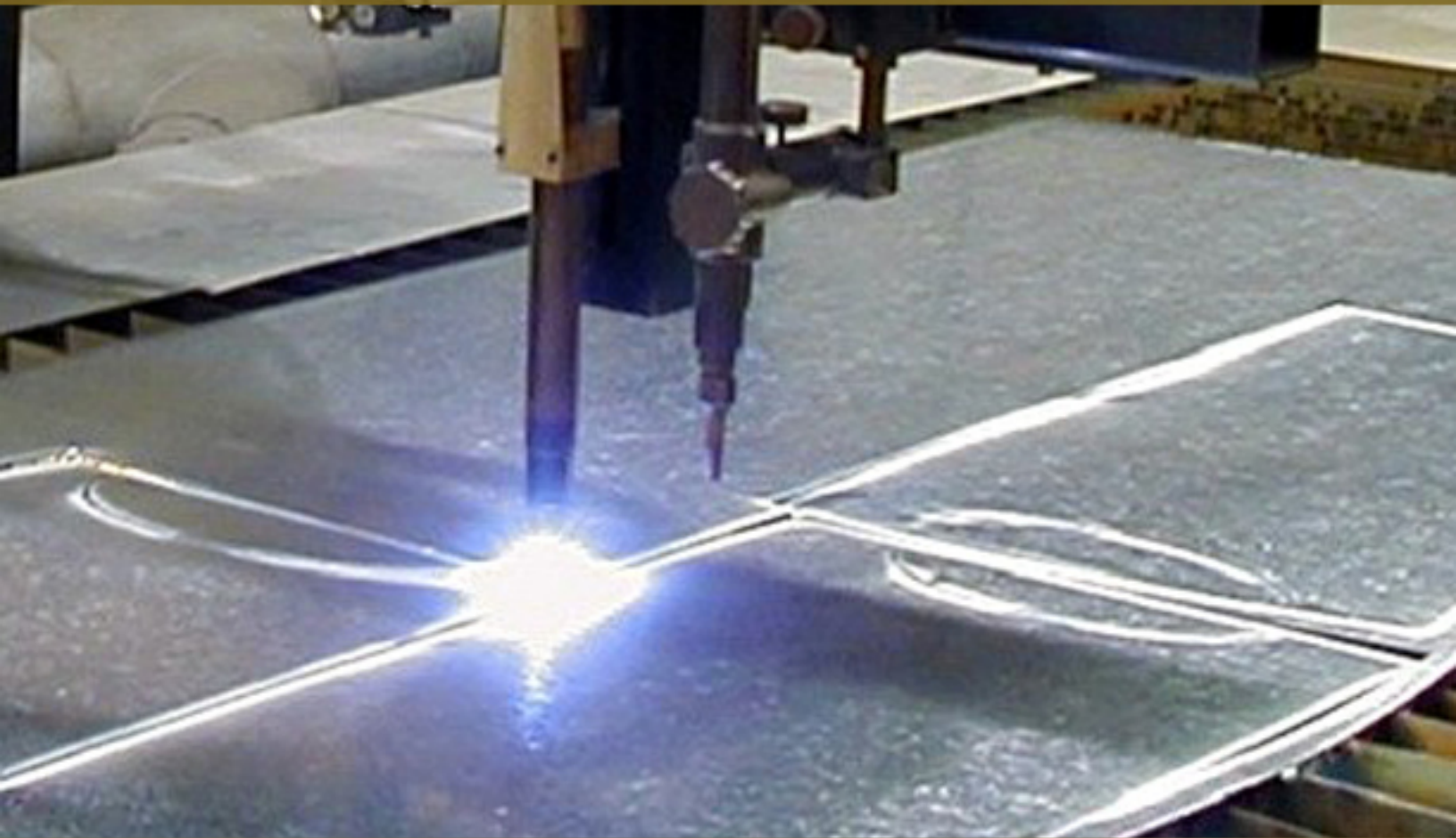


# Handbook of Metalworking and Welding Engineering



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## Chapter-1

# Metalworking



Machining a bar of metal on a lathe.

**Metalworking** is the process of working with metals to create individual parts, assemblies, or large scale structures. The term covers a wide range of work from large ships and bridges to precise engine parts and delicate jewelry. It therefore includes a correspondingly wide range of skills, processes, and tools.

Metalworking is a science, art, hobby, industry and trade. Its historical roots span cultures, civilizations, and millennia. Metalworking has evolved from the discovery of smelting various ores, producing malleable and ductile metal useful for tools and adornments. Modern metalworking processes, though diverse and specialized, can be

categorized as forming, cutting or joining processes. Today's machine shop includes a number of machine tools capable of creating a precise, useful workpiece.

## ***Prehistory***

Metalworking predates history. No one knows with any certainty where or when metalworking began. The earliest technologies were impermanent and were unlikely to leave evidence for long. The advance that brought metal into focus was the connection of fire and metals. Who accomplished this is as unknown as the when and where, but the Egyptians are thought to have been one of the first civilizations to work gold.

Not all metal required fire to obtain it or work it. Isaac Asimov speculated that gold was the "first metal." His reasoning is that gold by its chemistry is found in nature as nuggets of pure gold. In other words, gold, as rare as it is, is always found in nature as the metal that it is. There are a few other metals that sometimes occur natively, and as a result of meteors. Almost all other metals are found in ores, a mineral bearing rock, that require heat or some other process to liberate the metal. Another feature of gold is that it is workable as it is found, meaning that no technology beyond eyes to find a nugget and a hammer and an anvil to work the metal is needed. Stone hammer and stone anvil will suffice for technology. This is the result of gold's properties of malleability and ductility. The earliest tools were stone, bone, wood, and sinew. They sufficed to work gold.

At some unknown point the connection between heat and the liberation of metals from rock became clear, rocks rich in copper, tin, and lead came into demand. These ores were mined wherever they were recognized. Remnants of such ancient mines have been found all over what is today the Middle East. Metalworking was being carried out by the South Asian inhabitants of Mehrgarh between 7000–3300 BCE. The end of the beginning of metalworking occurs sometime around 6000 BCE when copper smelting became common in the Middle East.

The ancients knew of seven metals. Here they are arranged in order of their oxidation potential:

- Iron +0.44,
- Tin +0.14
- Lead +0.13
- Copper -0.34
- Mercury -0.79
- Silver -0.80
- Gold -1.50

The oxidation potential is important because it is one indicator of how tightly bound to the ore the metal is likely to be. As can be seen, iron is significantly higher than the other six metals while gold is dramatically lower than the six above it. Gold's low oxidation is one of the main reasons that gold is found in nuggets. These nuggets are relatively pure gold and are workable as they are found.

Copper ore, being relatively abundant, and tin ore became the next important players in the story of metalworking. Using heat to smelt copper from ore, a great deal of copper was produced. It was used for both jewelry and simple tools. However, copper by itself was too soft for tools requiring edges and stiffness. At some point tin was added into the molten copper and bronze was born. Bronze is an alloy of copper and tin. Bronze was an important advance because it had the edge-durability and stiffness that pure copper lacked. Until the advent of iron, bronze was the most advanced metal for tools and weapons in common use.

Looking beyond the Middle East, these same advances and materials were being discovered and used the world around. China and Britain jumped into the use of bronze with little time being devoted to copper. Japan began the use of bronze and iron almost simultaneously. In the Americas things were different. Although the peoples of the Americas knew of metals, it wasn't until the arrival of Europeans that metal for tools and weapons took off. Jewelry and art were the principal uses of metals in the Americas prior to European influence.

Around the date 2700 BCE, production of bronze was common in locales where the necessary materials could be assembled for smelting, heating, and working the metal. Iron was beginning to be smelted. Iron began its emergence as an important metal for tools and weapons. The Iron Age was dawning.

## History



A turret lathe operator machining parts for transport planes at the Consolidated Aircraft Corporation plant, Fort Worth, Texas, USA in the 1940s.

By the historical periods of the Pharaohs in Egypt, the Vedic Kings in India, the Tribes of Israel, and the Mayan Civilization in North America, among other ancient populations, precious metals began to have value attached to them. In some cases rules for ownership, distribution, and trade were created, enforced, and agreed upon by the respective peoples. By the above periods metalworkers were very skilled at creating objects of adornment, religious artifacts, and trade instruments of precious metals (non-ferrous), as well as weaponry usually of ferrous metals and/or alloys. These skills were finely honed and well executed. The techniques were practiced by artisans, blacksmiths, atharvavedic practitioners, alchemists, and other categories of metalworkers around the globe. For example, the ancient technique of granulation is found around the world in numerous ancient cultures before the historic record shows people traveled seas or overland to far regions of the earth to share this process that still being used by metalsmiths today.

As time progressed metal objects became more common, and ever more complex. The need to further acquire and work metals grew in importance. Skills related to extracting metal ores from the earth began to evolve, and metalsmiths became more knowledgeable. Metalsmiths became important members of society. Fates and economies of entire

civilizations were greatly affected by the availability of metals and metalsmiths. The metalworker depends on the extraction of precious metals to make jewelry, build more efficient electronics, and for industrial and technological applications from construction to shipping containers to rail, and air transport. Without metals, goods and services would cease to move around the globe on the scale we know today.

More individuals than ever before are learning metalworking as a creative outlet in the forms of jewelry making, hobby restoration of aircraft and cars, blacksmithing, tinsmithing, tinkering, and in other art and craft pursuits. Trade schools continue to teach welding in all of its forms, and there is a proliferation of schools of Lapidary and Jewelers arts and sciences at this- the beginning of the 21st Century AD.

### ***General metalworking processes***



A combination square used for transferring designs.



A caliper is used to precisely measure a short length.

Metalworking generally is divided into the following categories, *forming*, *cutting*, and, *joining*. Each of these categories contain various processes.

Compatibility chart of materials versus processes

	Material								
Process	Iron	Steel	Aluminium	Copper	Magnesium	Nickel	Refractory metals	Titanium	Zinc
Sand casting	X	X	X	X	X	X			0
Permanent mold casting	X	0	X	0	X	0			0
Die casting			X	0	X				X
Investment casting		X	X	X	0	0			
Closed-die forging		X	0	0	0	0	0	0	
Extrusion		0	X	X	X	0	0	0	
Cold heading		X	X	X		0			
Stamping		X	X	X	0	X		0	0

<b>&amp; deep drawing</b>									
<b>Screw machine</b>	0	X	X	X	0	X	0	0	0
<b>Powder metallurgy</b>	X	X	0	X		0	X	0	
Key: <b>X</b> = Routinely performed, <b>0</b> = Performed with difficulty, caution, or some sacrifice, <b>blank</b> = Not recommended									

Prior to most operations, the metal must be marked out and/or measured, depending on the desired finished product.

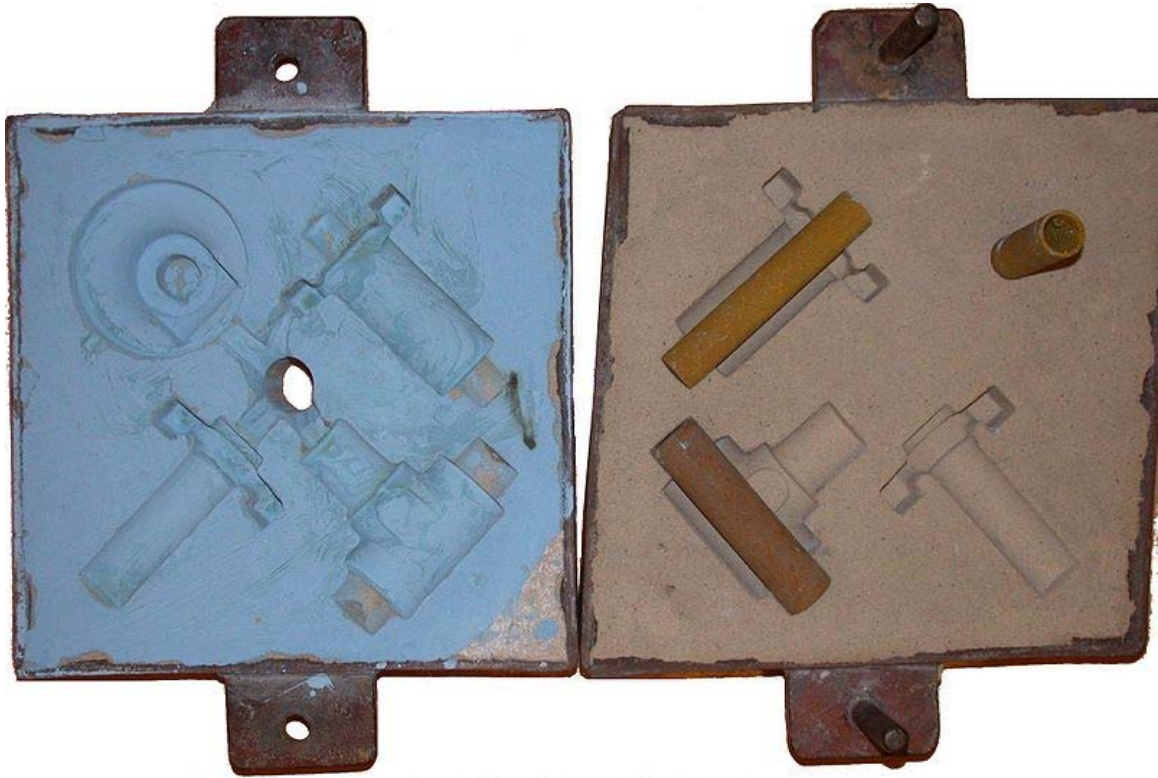
*Marking out* (also known as layout) is the process of transferring a design or pattern to a workpiece and is the first step in the handcraft of metalworking. It is performed in many industries or hobbies, although in the repetition industries the need to mark out every individual piece is eliminated. In the metal trades area, marking out consists of transferring the engineer's plan to the workpiece in preparation for the next step, machining or manufacture.

*Calipers* are hand tools designed to precisely measure the distance between two points. Most calipers have two sets of flat, perpendicular edges used for inner or outer diameter. These calipers can be accurate to within one-thousandth of an inch (25.4µm). Different types of calipers have different mechanisms for displaying the distance measured. Where larger objects need to be measured with less precision, a tape measure is often used.

### ***Forming processes***

These *forming* processes modify metal or workpiece by deforming the object, that is, without removing any material. Forming is done with heat and pressure, or with mechanical force, or both.

## Casting



A sand casting mold

Casting achieves a specific form by pouring molten metal into a mold and allowing it to cool, with no mechanical force. Forms of casting include:

- Investment casting (called lost wax casting in art)
- Centrifugal casting
- Die casting
- Sand casting
- Shell casting
- Spin casting

## Plastic deforming



A red-hot metal workpiece is inserted into a forging press.

Plastic deformation involves using heat or pressure to make a workpiece more conductive to mechanical force. Historically, this and casting were done by blacksmiths, though today the process has been industrialized.

- Cold sizing
- Extrusion
- Forging
- Hot metal gas forming
- Powder metallurgy

- Friction drilling

### Sheet metal forming



A metal spun brass vase

These types of forming process involve the application of mechanical force at room temperature.

- Bending
- Coining
- Decambering
- Deep drawing

- Drawing
- Spinning
- Flow turning
- Raising
- Roll forming
- Roll bending
- Repoussé and chasing
- Rolling
- Rubber pad forming
- Shearing
- Stamping
- Wheeling using an English wheel (wheeling machine)

### ***Cutting processes***



A CNC plasma cutting machining

*Cutting* is a collection of processes wherein material is brought to a specified geometry by removing excess material using various kinds of tooling to leave a finished part that meets specifications. The net result of cutting is two products, the waste or excess material, and the finished part. If this were a discussion of woodworking, the waste would be sawdust and excess wood. In cutting metals the waste is chips or swarf and excess metal. These processes can be divided into chip producing cutting, generally

known as machining. Burning or cutting with an oxyfuel torch is a welding process not machining. There are also miscellaneous specialty processes such as chemical milling.

Cutting is nearly fully represented by:

- Chip producing processes most commonly known as machining
- Burning, a set of processes which cut by oxidizing a kerf to separate pieces of metal
- Specialty processes

Drilling a hole in a metal part is the most common example of a chip producing process. Using an oxy-fuel cutting torch to separate a plate of steel into smaller pieces is an example of burning. Chemical milling is an example of a specialty process that removes excess material by the use of etching chemicals and masking chemicals.

There are many technologies available to cut metal, including:

- Manual technologies: saw, chisel, shear or snips
- Machine technologies: turning, milling, drilling, grinding, sawing
- Welding/burning technologies: burning by laser, oxy-fuel burning, and plasma
- Erosion technologies: by water jet or electric discharge.

Cutting fluid or coolant is used where there is significant friction and heat at the cutting interface between a cutter such as a drill or an end mill and the workpiece. Coolant is generally introduced by a spray across the face of the tool and workpiece to decrease friction and temperature at the cutting tool/workpiece interface to prevent excessive tool wear. In practice there are many methods of delivering coolant.

## Machining



A milling machine in operation, including coolant hoses.

*Milling* is the complex shaping of metal or other materials by removing material to form the final shape. It is generally done on a milling machine, a power-driven machine that in its basic form consists of a milling cutter that rotates about the spindle axis (like a drill), and a worktable that can move in multiple directions (usually two dimensions [x and y axis] relative to the workpiece). The spindle usually moves in the z axis. It is possible to raise the table (where the workpiece rests). Milling machines may be operated manually or under computer numerical control (CNC), and can perform a vast number of complex operations, such as slot cutting, planing, drilling and threading, rabbeting, routing, etc. Two common types of mills are the horizontal mill and vertical mill.

The pieces produced are usually complex 3D objects that are converted into x, y, and z coordinates that are then fed into the CNC machine and allow it to complete the tasks required. The milling machine can produce most parts in 3D, but some require the objects to be rotated around the x, y, or z coordinate axis (depending on the need). Tolerances are usually in the thousandths of an inch (Unit known as Thou), depending on the specific machine.

In order to keep both the bit and material cool, a high temperature coolant is used. In most cases the coolant is sprayed from a hose directly onto the bit and material. This coolant can either be machine or user controlled, depending on the machine.

Materials that can be milled range from aluminum to stainless steel and most everything in between. Each material requires a different speed on the milling tool and varies in the amount of material that can be removed in one pass of the tool. Harder materials are usually milled at slower speeds with small amounts of material removed. Softer materials vary, but usually are milled with a high bit speed.

The use of a milling machine adds costs that are factored into the manufacturing process. Each time the machine is used coolant is also used, which must be periodically added in order to prevent breaking bits. A milling bit must also be changed as needed in order to prevent damage to the material. Time is the biggest factor for costs. Complex parts can require hours to complete, while very simple parts take only minutes. This in turn varies the production time as well, as each part will require different amounts of time.

Safety is key with these machines. The bits are traveling at high speeds and removing pieces of usually scalding hot metal. The advantage of having a CNC milling machine is that it protects the machine operator.

## **Turning**



A lathe cutting material from a workpiece.

Turning is a metal cutting process for producing a cylindrical surface with a single point tool. The workpiece is rotated on a spindle and the cutting tool is fed into it radially, axially or both. Producing surfaces perpendicular to the workpiece axis is called facing. Producing surfaces using both radial and axial feeds is called profiling.

A *lathe* is a machine tool which spins a block or cylinder of material so that when abrasive, cutting, or deformation tools are applied to the workpiece, it can be shaped to produce an object which has rotational symmetry about an axis of rotation. Examples of objects that can be produced on a lathe include candlestick holders, table legs, bowls, baseball bats, crankshafts, camshafts, and bearing mounts.

Lathes have three main components: the headstock, the carriage, and the tailstock. The headstock's spindle secures the workpiece with a chuck, whose jaws (usually three or four) are tightened around the piece. The spindle rotates at high speed, providing the energy to cut the material. While historic lathes were powered by belts from the ceiling, modern examples use electric motors. The workpiece extends out of the spindle along the axis of rotation above the flat bed. The carriage is a platform that can be moved, precisely and independently, horizontally parallel and perpendicular to the axis of rotation. A hardened cutting tool is held at the desired height (usually the middle of the workpiece) by the toolpost. The carriage is then moved around the rotating workpiece, and the cutting tool gradually shaves material from the workpiece. The tailstock can be slid along the axis of rotation and then locked in place as necessary. It may hold centers to further secure the workpiece, or cutting tools driven into the end of the workpiece.

Other operations that can be performed with a single point tool on a lathe are:

**Chamfering:** Cutting an angle on the corner of a cylinder.

**Parting:** The tool is fed radially into the workpiece to cut off the end of a part.

**Threading:** A tool is fed along and across the outside or inside surface of rotating parts to produce external or internal threads.

**Boring:** A single-point tool is fed linearly and parallel to the axis of rotation.

**Drilling:** Feeding the drill into the workpiece axially.

**Knurling:** Produces a regular cross-hatched pattern in work surfaces intended to be gripped by hand.

Modern computer numerical control (CNC) lathes and (CNC) machining centres can do secondary operations like milling by using driven tools. When driven tools are used the work piece stops rotating and the driven tool executes the machining operation with a rotating cutting tool. The CNC machines use x, y, and z coordinates in order to control the turning tools and produce the product. Most modern day CNC lathes are able to produce most turned objects in 3D.

Materials appropriate for turning used are softer metals, although harder metals can be turned with a bit more time and effort.

The turning tool material must be harder than the material being turned in order for the process to work. Production rates for this process depend on the object being turned and the speed at which it can be done. More complex materials, therefore, will take more time.

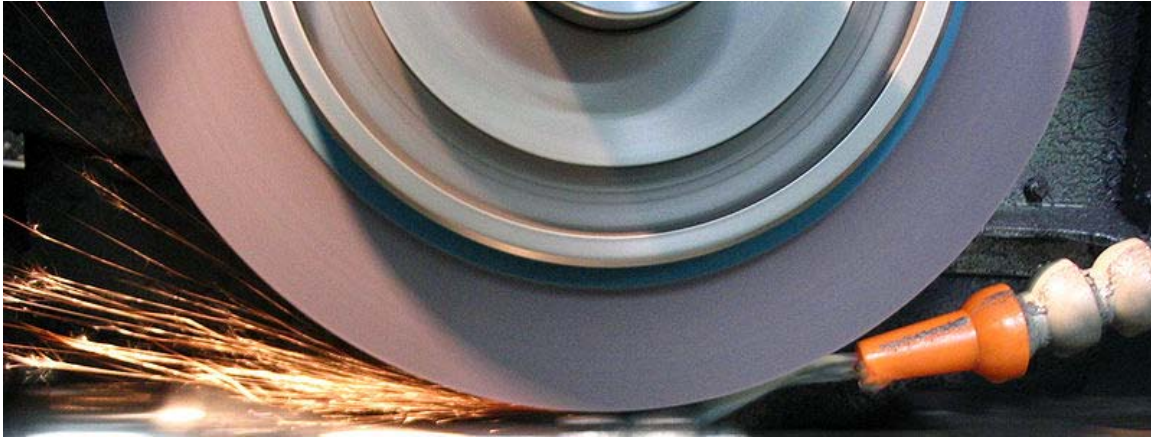
## Threading



Three different types and sizes of taps.

There are many threading processes including: cutting threads with a tap or die, thread milling, single-point thread cutting, thread rolling and forming, and thread grinding. A *tap* is used to cut a female thread on the inside surface of a pre-drilled hole, while a *die* cuts a male thread on a preformed cylindrical rod.

## Grinding



A surface grinder

*Grinding* uses an abrasive process to remove material from the workpiece. A **grinding machine** is a machine tool used for producing very fine finishes, making very light cuts, or high precision forms using an abrasive wheel as the cutting device. This wheel can be made up of various sizes and types of stones, diamonds or inorganic materials.

The simplest grinder is a bench grinder or a hand-held angle grinder, for deburring parts or cutting metal with a zip-disc.

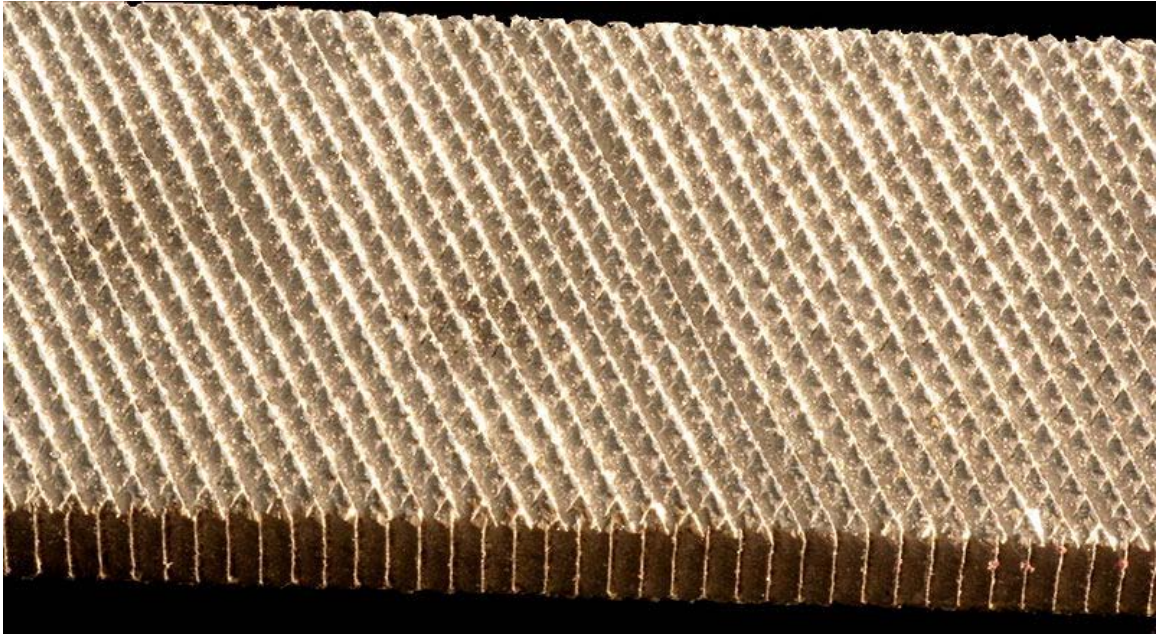
Grinders have increased in size and complexity with advances in time and technology. From the old days of a manual toolroom grinder sharpening endmills for a production shop, to today's 30000 RPM CNC auto-loading manufacturing cell producing jet turbines, grinding processes vary greatly.

Grinders need to be very rigid machines to produce the required finish. Some grinders are even used to produce glass scales for positioning CNC machine axis. The common rule is the machines used to produce scales be 10 times more accurate than the machines the parts are produced for.

In the past grinders were used for finishing operations only because of limitations of tooling. Modern grinding wheel materials and the use of industrial diamonds or other man-made coatings (cubic boron nitride) on wheel forms have allowed grinders to achieve excellent results in production environments instead of being relegated to the back of the shop.

Modern technology has advanced grinding operations to include CNC controls, high material removal rates with high precision, lending itself well to aerospace applications and high volume production runs of precision components.

## Filing



A file is an abrasive surface like this one that allows machinists to remove small, imprecise amounts of metal.

*Filing* is combination of grinding and saw tooth cutting using a file. Prior to the development of modern machining equipment it provided a relatively accurate means for the production of small parts, especially those with flat surfaces. The skilled use of a file allowed a machinist to work to fine tolerances and was the hallmark of the craft. Today filing is rarely used as a production technique in industry, though it remains as a common method of deburring.

## Other

Broaching is a machining operation used to cut keyways into shafts. Electron beam machining (EBM) is a machining process where high-velocity electrons are directed toward a work piece, creating heat and vaporizing the material. Ultrasonic machining uses ultrasonic vibrations to machine very hard or brittle materials.

## ***Joining processes***



Mig welding

## **Welding**

*Welding* is a fabrication process that joins materials, usually metals or thermoplastics, by causing coalescence. This is often done by melting the workpieces and adding a filler material to form a pool of molten material that cools to become a strong joint, but sometimes pressure is used in conjunction with heat, or by itself, to produce the weld.

Many different energy sources can be used for welding, including a gas flame, an electric arc, a laser, an electron beam, friction, and ultrasound. While often an industrial process,

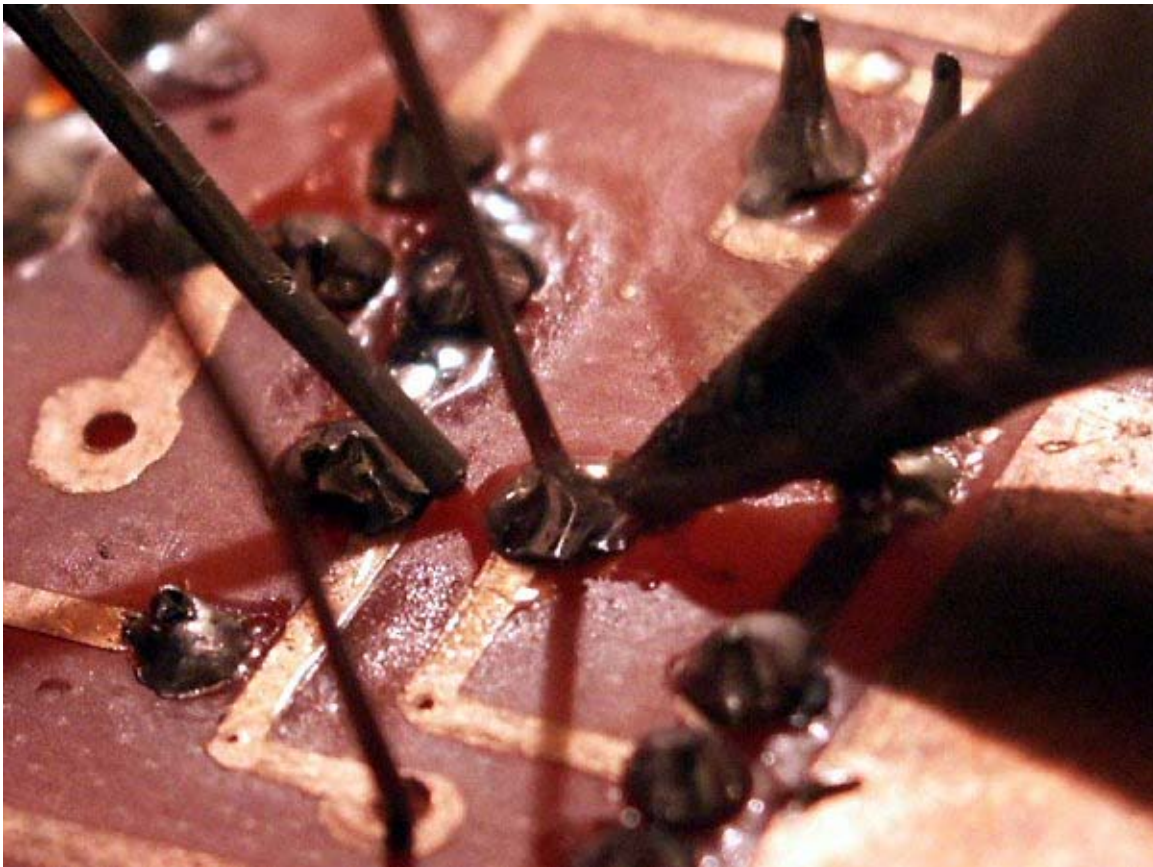
welding can be done in many different environments, including open air, underwater and in space. Regardless of location, however, welding remains dangerous, and precautions must be taken to avoid burns, electric shock, poisonous fumes, and overexposure to ultraviolet light.

## **Brazing**

*Brazing* is a joining process in which a filler metal is melted and drawn into a capillary formed by the assembly of two or more work pieces. The filler metal reacts metallurgically with the workpiece(s) and solidifies in the capillary, forming a strong joint. Unlike welding, the work piece is not melted. Brazing is similar to soldering, but occurs at temperatures in excess of 450 °C (842 °F). Brazing has the advantage of producing less thermal stresses than welding, and brazed assemblies tend to be more ductile than weldments because alloying elements can not segregate and precipitate.

Brazing techniques include, flame brazing, resistance brazing, furnace brazing, diffusion brazing, and inductive brazing.

## **Soldering**



Soldering a printed circuit board.

*Soldering* is a joining process that occurs at temperatures below 450 °C (842 °F). It is similar to brazing in the fact that a filler is melted and drawn into a capillary to form a joint, although at a lower temperature. Because of this lower temperature and different alloys used as fillers, the metallurgical reaction between filler and work piece is minimal, resulting in a weaker joint.

## **Riveting**

*Riveting* is one of the most ancient metalwork joining processes. Its use has declined markedly during the second half of the 20th century, but it still retains important uses in industry and construction into the 21st century. The earlier use of rivets is being superseded by improvements in welding and component fabrication techniques.

A rivet is essentially a two-headed and unthreaded bolt which holds two other pieces of metal together. Holes are drilled or punched through the two pieces of metal to be joined. The holes being aligned, a rivet is passed through the holes and permanent heads are formed onto the ends of the rivet utilizing hammers and forming dies (by either coldworking or hotworking). Rivets are commonly purchased with one head already formed.

When it is necessary to remove rivets, one of the rivet's heads is sheared off with a cold chisel. The rivet is then driven out with a hammer and punch.

## ***Associated processes***

While these processes are not primary metalworking processes, they are often performed before or after metalworking processes.

## **Heat treatment**

Metals can be heat treated to alter the properties of strength, ductility, toughness, hardness or resistance to corrosion. Common heat treatment processes include annealing, precipitation strengthening, quenching, and tempering. The **annealing** process softens the metal by allowing recovery of cold work and grain growth. **Quenching** can be used to harden alloy steels, or in precipitation hardenable alloys, to trap dissolved solute atoms in solution. **Tempering** will cause the dissolved alloying elements to precipitate, or in the case of quenched steels, improve impact strength and ductile properties.

Often, mechanical and thermal treatments are combined in what is known as thermo-mechanical treatments for better properties and more efficient processing of materials. These processes are common to high alloy special steels, super alloys and titanium alloys.

## **Plating**

Electroplating is a common surface-treatment technique. It involves bonding a thin layer of another metal such as gold, silver, chromium or zinc to the surface of the product. It is used to reduce corrosion as well as to improve the product's aesthetic appearance.

## **Thermal spraying**

Thermal spraying techniques are another popular finishing option, and often have better high temperature properties than electroplated coatings.

## Chapter-2

# Foundry



Glow of a foundry crucible

A **foundry** is a factory that produces metal castings. Metals are cast into shapes by melting them into a liquid, pouring the metal in a mold, and removing the mold material or casting after the metal has solidified as it cools. The most common metals processed are aluminum and cast iron. However, other metals, such as bronze, steel, magnesium, copper, tin, and zinc, are also used to produce castings in foundries.

## **Process**

### **Melting**

Melting is performed in a furnace. Virgin material, external scrap, internal scrap, and alloying elements are used to charge the furnace. Virgin material refers to commercially pure forms of the primary metal used to form a particular alloy. Alloying elements are either pure forms of an alloying element, like electrolytic nickel, or alloys of limited composition, such as ferroalloys or master alloys. External scrap is material from other forming processes such as punching, forging, or machining. Internal scrap consists of the gates, risers, or defective castings.

The process includes melting the charge, refining the melt, adjusting the melt chemistry and tapping into a transport vessel. Refining is done to remove deleterious gases and elements from the molten metal to avoid casting defects. Material is added during the melting process to bring the final chemistry within a specific range specified by industry and/or internal standards. During the tap, final chemistry adjustments are made.

### **Furnace**

Several specialised furnaces are used to melt the metal. Furnaces are refractory lined vessels that contain the material to be melted and provide the energy to melt it. Modern furnace types include electric arc furnaces (EAF), induction furnaces, cupolas, reverberatory, and crucible furnaces. Furnace choice is dependent on the alloy system and quantities produced. For ferrous materials, EAFs, cupolas, and induction furnaces are commonly used. Reverberatory and crucible furnaces are common for producing aluminum castings.

Furnace design is a complex process, and the design can be optimized based on multiple factors. Furnaces in foundries can be any size, ranging from mere ounces to hundreds of tons, and they are designed according to the type of metals that are to be melted. Also, furnaces must be designed around the fuel being used to produce the desired temperature. For low temperature melting point alloys, such as zinc or tin, melting furnaces may reach around 327 Celsius. Electricity, propane, or natural gas are usually used for these temperatures. For high melting point alloys such as steel or nickel based alloys, the furnace must be designed for temperatures over 3600 Celsius. The fuel used to reach these high temperatures can be electricity or coke.

The majority of foundries specialize in a particular metal and have furnaces dedicated to these metals. For example, an iron foundry (for cast iron) may use a cupola, induction furnace, or EAF, while a steel foundry will use an EAF or induction furnace. Bronze or brass foundries use crucible furnaces or induction furnaces. Most aluminum foundries use either an electric resistance or gas heated crucible furnaces or reverberatory furnaces.

## Degassing

In the case of aluminium alloys, a degassing step is usually necessary to reduce the amount of hydrogen in the liquid metal. If the hydrogen concentration in the melt is too high, the resulting casting will contain gas porosity that will deteriorate its mechanical properties.

An efficient way of removing hydrogen from the melt is to bubble argon or nitrogen. To do that, several different types of equipment are used by foundries. When the bubbles go up in the melt, they catch the dissolved hydrogen and bring it to the top surface. There are various equipment which measure the amount of hydrogen present in it. Alternatively, the density of the aluminum sample is calculated to check amount of hydrogen dissolved in it.

## Mould making



Many large foundries operate their own industrial railways

In the casting process a pattern is made in the shape of the desired part. This pattern is made out of wax, wood, plastic or metal. Simple designs can be made in a single piece or solid pattern. More complex designs are made in two parts, called split patterns. A split pattern has a top or upper section, called a cope, and a bottom or lower section called a drag. Both solid and split patterns can have cores inserted to complete the final part shape. Where the cope and drag separates is called the parting line.

# UNDERCUT



A diagram of an undercut in a mould.

# DRAFT

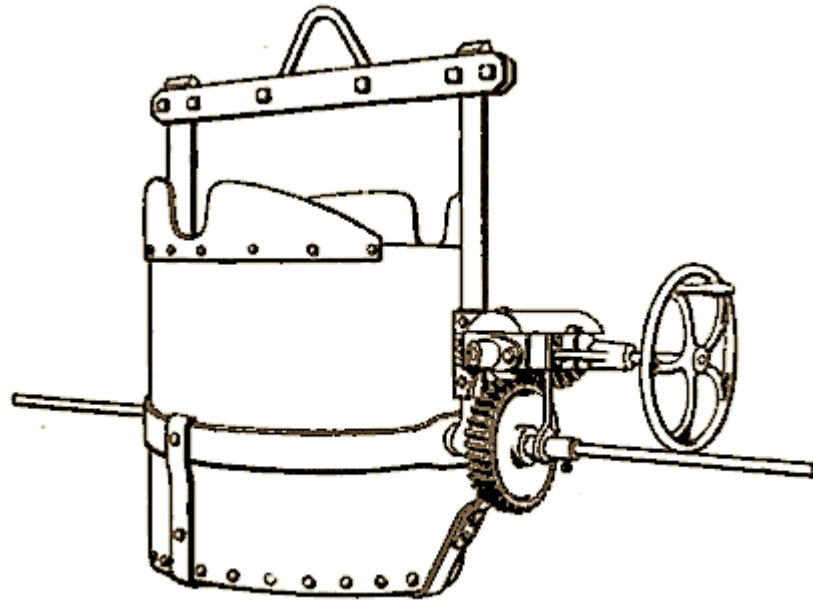


A diagram of draft on a pattern.

When making a pattern it is best to taper the edges so that the pattern can be removed without breaking the mold. This is called draft. The opposite of draft is an undercut where there is part of the pattern under the sand making it impossible to remove the pattern without damaging the mould. The molds are constructed by several different processes dependent upon the type of foundry, metal to be poured, quantity of parts to be produced, size of the casting and complexity of the casting. These mold processes include:

- Sand casting - Green or resin bonded sand mold.
- Lost-foam casting - Polystyrene pattern with a mixture of ceramic and sand mold.
- Investment casting - Wax or similar sacrificial pattern with a ceramic mold.
- Plaster casting - Plaster mold.
- V-Process casting - Vacuum is used in conjunction with thermoformed plastic to form sand molds. No moisture, clay or resin is needed for sand to retain shape.
- Billet (ingot) casting - Simple mold for producing ingots of metal normally for use in other foundries.

## Pouring



Geared Ladle.

An old geared ladle

In a foundry, molten metal is poured into molds. Pouring can be accomplished with gravity, or it may be assisted with a vacuum or pressurized gas. Many modern foundries use robots or automatic pouring machines for pouring molten metal. Traditionally, molds were poured by hand using ladles.

## Shakeout

The solidified metal component is then removed from its mold. Where the mold is sand based, this can be done by shaking or tumbling. This frees the casting from the sand, which is still attached to the metal runners and gates - which are the channels through which the molten metal traveled to reach the component itself.

## Degating

Degating is the removal of the heads, runners, gates, and risers from the casting. Runners, gates, and risers may be removed using cutting torches, bandsaws or ceramic cutoff blades. For some metal types, and with some gating system designs, the sprue, runners and gates can be removed by breaking them away from the casting with a hammer or specially designed knockout machinery. Risers must usually be removed using a cutting method but some newer methods of riser removal use knockout machinery with special designs incorporated into the riser neck geometry that allow the riser to break off at the right place.

The gating system required to produce castings in a mold yields leftover metal, including heads, risers and sprue, sometimes collectively called sprue, that can exceed 50% of the metal required to pour a full mold. Since this metal must be remelted as salvage, the yield of a particular gating configuration becomes an important economic consideration when designing various gating schemes, to minimize the cost of excess sprue, and thus melting costs.

## **Surface cleaning**

After degating, sand or other molding media may adhere to the casting. To remove this the surface is cleaned using a blasting process. This means a granular media will be propelled against the surface of the casting to mechanically knock away the adhering sand. The media may be blown with compressed air, or may be hurled using a shot wheel. The media strikes the casting surface at high velocity to dislodge the molding media (for example, sand, slag) from the casting surface. Numerous materials may be used as media, including steel, iron, other metal alloys, aluminum oxides, glass beads, walnut shells, baking powder among others. The blasting media is selected to develop the color and reflectance of the cast surface. Terms used to describe this process include cleaning, bead blasting, and sand blasting. Shot peening may be used to further work-harden and finish the surface.

## **Finishing**

The final step in the process usually involves grinding, sanding, or machining the component in order to achieve the desired dimensional accuracies, physical shape and surface finish.

Removing the remaining gate material, called a gate stub, is usually done using a grinder or sanding. These processes are used because their material removal rates are slow enough to control the amount of material. These steps are done prior to any final machining.

After grinding, any surfaces that require tight dimensional control are machined. Many castings are machined in CNC milling centers. The reason for this is that these processes have better dimensional capability and repeatability than many casting processes. However, it is not uncommon today for many components to be used without machining.

A few foundries provide other services before shipping components to their customers. Painting components to prevent corrosion and improve visual appeal is common. Some foundries will assemble their castings into complete machines or sub-assemblies. Other foundries weld multiple castings or wrought metals together to form a finished product.

More and more the process of finishing a casting is being achieved using robotic machines which eliminate the need for a human to physically grind or break parting lines, gating material or feeders. The introduction of these machines has reduced injury to workers, costs of consumables whilst also reducing the time necessary to finish a casting.

It also eliminates the problem of human error so as to increase repeatability in the quality of grinding. With a change of tooling these machines can finish a wide variety of materials including iron, bronze and aluminium.

## Chapter-3

# Polishing and Planing (shaping)

## Polishing

**Polishing** and **buffing** are finishing processes for smoothing a workpiece's surface using an abrasive and a work wheel. Technically *polishing* refers to processes that use an abrasive that is glued to the work wheel, while *buffing* uses a loose abrasive applied to the work wheel. Polishing is a more aggressive process while buffing is less harsh, which leads to a smoother, brighter finish. A common misconception is that a polished surface has a mirror bright finish, however most mirror bright finishes are actually buffed.

Polishing is often used to enhance the looks of an item, prevent contamination of medical instruments, remove oxidation, create a reflective surface, or prevent corrosion in pipes. In metallography and metallurgy, polishing is used to create a flat, defect-free surface for examination of a metal's microstructure under a microscope. Silicon-based polishing pads or a diamond solution can be used in the polishing process.

The removal of oxidization (tarnish) from metal objects is accomplished using a metal polish or tarnish remover; this is also called polishing. To prevent further unwanted oxidization, polished metal surfaces may be coated with wax, oil, or lacquer. This is of particular concern for copper alloy products such as brass and bronze.

### **Process**

Polishing is usually a multistage process. The first stage starts with a rough abrasive and each subsequent stage uses a finer abrasive until the desired finish is achieved. The rough pass removes surface defects like pits, nicks, lines and scratches. The finer abrasives leave very thin lines that are not visible to the naked eye. Lubricants like wax and kerosene may be used as lubricating and cooling media during these operations, although some polishing materials are specifically designed to be used "dry." Buffing may be done by hand with a stationary polisher or die grinder, or it may be automated using specialized equipment.

When buffing there are two types of buffing motions: the *cut motion* and the *color motion*. The cut motion is designed to give a uniform, smooth, semi-bright surface finish.

This is achieved by moving the workpiece against the rotation of the buffing wheel, while using medium to hard pressure. The color motion gives a clean, bright, shiny surface finish. This is achieved by moving the workpiece with the rotation of the buffing wheel, while using medium to light pressure.

When polishing brass, there are often minute marks in the metal caused by impurities. To overcome this, the surface is polished with a very fine (600) grit, copper plated, then buffed to a mirror finish with an airflow mop.

Polishing operations for items such as chisels, hammers, screwdrivers, wrenches, etc., are given a fine finish but not plated. In order to achieve this finish four operations are required: roughing, dry fining, greasing, and coloring. Note that roughing is usually done on a solid grinding wheel and for an extra fine polish the greasing operation may be broken up into two operations: rough greasing and fine greasing. However, for inexpensive items money is saved by only performing the first two operations.

Polishing knives and cutlery is known as fine glazing or blue glazing. Sand buffing, when used on German silver, white metal, etc., is technically a buffing operation because it uses a loose abrasive, but removes a significant amount of material, like polishing.

## **Equipment**

Aluminium oxide abrasives are used on high tensile strength metals, such as carbon and alloy steel, tough iron, and nonferrous alloys. Silicon carbide abrasives are used on hard and brittle substances, such as grey iron and cemented carbide, and low tensile strength metals, such as brass, aluminium, and copper.

Polishing wheels come in a wide variety of types to fulfill a wide range of needs. The most common materials used for polishing wheels are wood, leather, canvas, cotton cloth, plastic, felt, paper, sheepskin, impregnated rubber, canvas composition, and wool; leather and canvas are the most common. Wooden wheels have emery or other abrasives glued onto them and are used to polish flat surfaces and maintained good edges. There are many types of cloth wheels. Cloth wheels that are cemented together are very hard and used for rough work, whereas other cloth wheels that are sewn and glued together are not as aggressive. There are cloth wheels that are not glued or cemented, instead these are sewed and have metal side plates for support. Solid felt wheels are popular for fine finishes. Hard roughing wheels can be made by cementing together strawboard paper disks. Softer paper wheels are made from felt paper. Most wheels are run at approximately 7500 surface feet per minute (SFM), however muslin, felt and leather wheels are usually run at 4000 SFM.

Buffing wheels, also known as mops, are either made from cotton or wool cloth and come bleached or unbleached. Specific types include: sisal, spiral sewn, loose cotton, canton flannel, domet flannel, denim, treated spiral sewn, cushion, treated vented, untreated vented, string buff, finger buff, sisal rope, mushroom, facer, tampered,

scrubbing mushroom, hourglass buff, rag, "B", climax, swansdown, airflow, coolair, and bullet.

The following chart will help in deciding which wheels and compounds to use when polishing different materials. This chart is a starting point and experienced polishers may vary the materials used to suit different applications.

Common buffing compound and wheel combinations															
	Silver, gold & thin plates			Nickel & chrome plating			Copper, brass, aluminium, pot metal & soft metals			Steel & iron			Stainless steel		
Buff type	Rough	Initial buff	Final buff	Rough	Initial buff	Final buff	Rough	Initial buff	Final buff	Rough	Initial buff	Final buff	Rough	Initial buff	Final buff
Sisal							X			X			X		
Spiral sewn					X			X			X			X	
Loose									X			X			X
Canton flannel			X			X									
String															
Compound															
Black							X			X			X		
Brown								X							
White					X				X		X				
Blue			X			X						X			
Green														X	X
Red			X			X						X			

**BLACK** = Emery Compound, a coarse abrasive material for removal of scratches, pits, paint, rust etc.

**BROWN** = Tripoli compound used for general purpose cut and color on most soft metals.

**WHITE** = Blizzard compound, used for color and final finish of harder metals, has a cutting action.

**RED** = Jeweller's Rouge, designed to polish without any cutting action. Safe on thin plates. Use on its own wheel.

**BLUE** = A dryer, almost greaseless wheel - designed to polish without any cutting action. Safe on thin plates. Use on its own wheel.

**GREEN** = Used exclusively for Stainless Steel.

## Applications

Polishing may be used to enhance the looks of certain parts on cars, motorbikes, handrails, cookware, kitchenware, and architectural metal applications. Pharmaceutical, dairy, and water pipes are buffed to maintain hygienic conditions and prevent corrosion. Buffing is used to manufacture of high-quality lighting reflectors.

# Planing (shaping)

**Planing** is a manufacturing process of material removal in which the workpiece reciprocates against a stationary single-point cutting tool producing a plane or sculpted surface. Planing is analogous to shaping. The main difference between these two processes is that in shaping the tool reciprocates across the stationary workpiece. Planing motion is the opposite of shaping. Both planing and shaping are rapidly being replaced by milling.

The mechanism used for this process is known as a planer. The size of the planer is determined by the largest workpiece that can be machined on it. The cutting tools are usually carbide tipped or made of high speed steel and resemble those used in facing and turning.

## ***Process Characteristics***

- Uses single-point cutting tools
- Involves a reciprocating motion between the tool and workpiece
- Produces plane or sculpted surfaces
- Leaves parallel feed marks

## ***Process***

In shaping, the tool is brought into position with the workpiece. The tool then repeatedly moves in a straight line while the workpiece is incrementally fed into the line of motion of the tool, this produces a flat, smooth, and sculpted surface. For shaped pieces the tool reciprocates across the stationary workpiece. The tools are usually tilted or lifted after each stroke. This is done hydraulically or manually in order to prevent the tool surface from chipping when the workpiece travels back across.

## ***Workpiece Geometry***

Planing can be used to produce flat surfaces, as well as cross-sections with grooves and notches, are produced along the length of workpiece. Shaping is basically the same as planing, except the workpiece is usually smaller, and it is the tool that moves and not the workpiece. Planing can be used to produce horizontal, vertical, or inclined flat surfaces on workpieces usually too large for shaping. Shaping is used not only for flat surfaces, but also for external or internal surfaces (either horizontal or inclined). Curved and irregular surfaces can also be produced by using special attachments

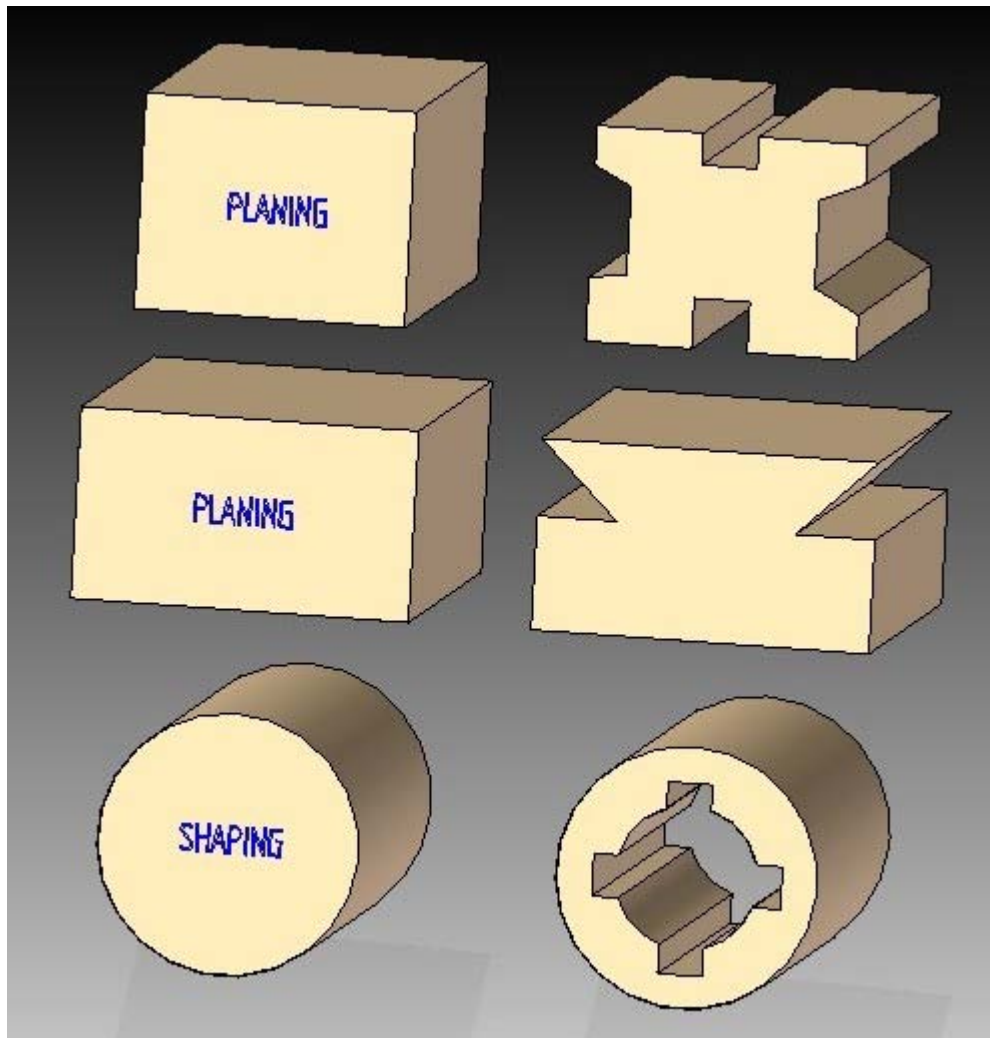
## ***Setup and Equipment***

Flat, angular, and contoured surfaces are made by horizontal shapers. Concerning shaping, the device that holds the piece being worked on has a very heavy movable jaw

to withstand cutting forces. The size of the planer needed is determined by the workpiece. Depending on the size of the workpiece many clamps and supporting devices may be used to hold it on the planer.

### ***Typical Tools and Geometry Produced***

The tools for shaping/planing are usually made of high speed steel or carbide tipped. Except for some slight angle difference, cutting tools resemble those used in facing and turning. Some advantages of using single-point cutting tools over multipoint tools is that they are more easily sharpened and fabricated. Internal shapes can be made by using a special extension tool.



Before and after geometry

## ***Material Properties***

Although the most common material to be planed or shaped is wood, there are planers and shaping machines capable of processing anything from metal pieces to plastic objects.

## Chapter-4

# Parts Cleaning

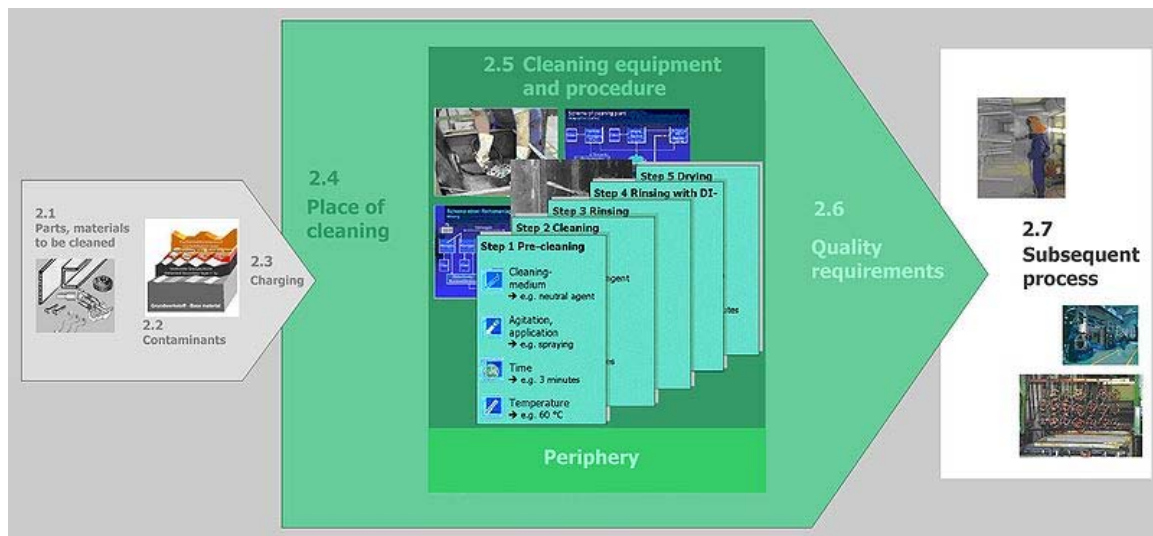
**Parts cleaning** is essential to many industrial processes, as a prelude to surface finishing or to protect sensitive components. Electroplating is particularly sensitive to part cleanliness, since molecular layers of oil can prevent adhesion of the coating. ASTM B322 is a standard guide for cleaning metals prior to electroplating. Cleaning processes include solvent cleaning, hot alkaline detergent cleaning, electrocleaning, and acid etch. The most common industrial test for cleanliness is the waterbreak test, in which the surface is thoroughly rinsed and held vertical. Hydrophobic contaminants such as oils cause the water to bead and break up, allowing the water to drain rapidly. Perfectly clean metal surfaces are hydrophilic and will retain an unbroken sheet of water that does not bead up or drain off. ASTM F22 describes a version of this test. This test does not detect hydrophilic contaminants, but the electroplating process can displace these easily since the solutions are water-based. Surfactants such as soap reduce the sensitivity of the test, so these must be thoroughly rinsed off.

### ***Definitions and classifications***

For the activities described here the following terms are often found: metal cleaning, metal surface cleaning, component cleaning, degreasing, parts washing, parts cleaning. These are well established in technical language usage but they have their shortcomings. Metal cleaning can easily be mixed up with refinement of unpurified metals. Metal surface cleaning and metal cleaning do not consider the increasing usage of plastics and composite materials in this sector. The term component cleaning leaves out the cleaning of steel sections and sheets and finally degreasing only describes a part of the topic as in most cases also chips, fines, particles, salts etc. have to be removed.

The terms 'commercial and industrial parts cleaning', 'parts cleaning in craft and industry' or 'commercial parts cleaning' probably best describe this field of activity. There are some specialists who prefer the term 'industrial parts cleaning', because they want to exclude maintenance of buildings, rooms, areas, windows, floors, tanks, machinery, hygiene, hands washing, showers etc.

## Elements and their interactions



### Factors

Cleaning activities in this sector can only be characterised sufficiently by a description of a number of different factors. These are outlined in illustration 1.

### Parts and materials to be cleaned

First, consider the parts to be cleaned. They may consist of non- or hardly-processed sections, sheets and wires. But also machined parts or assembled components needing cleaning. Therefore, they may be composed of different metals or different combinations of metals. Plastics and composite materials can frequently be found and indeed are on the increase because e.g. the automobile industry as well as others uses more and more lighter materials.

Mass and size can be very important for the selection of cleaning methods, for example big shafts for ships are usually cleaned manually, whereas tiny shafts for electrical appliances are often cleaned in bulk in highly automated plants.

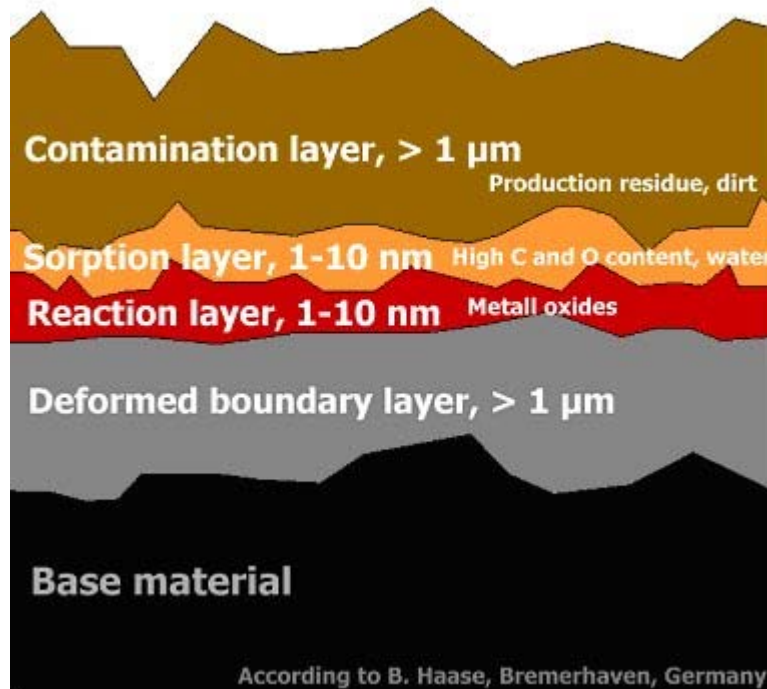
Similarly important is the geometry of the parts. Long, thin, branching, threaded holes, which could contain jammed chips, feature among the greatest challenges in this technical field. High pressure and the power wash process are one way to remove these chips as well as robots, which are programmed to exactly flush the drilled holes under high pressure.

### Contaminations

The parts are usually covered by unwanted substances, the contaminations or soiling. The definition used is quite varied. In certain cases these coverings may be desired: e.g. one

may not wish to remove a paint layer but only the material on top. In another case, where crack proofing is necessary one has to remove the paint layer and it is regarded as an unwanted substance.

The classification of soiling follows the layer structure starting from the base material:



Structure of a metallic surface

- Deformed boundary layer, > 1 µm
- Reaction layer, 1 - 10 nm
- Sorption layer, 1 - 10 nm
- Contamination layer, > 1 µm

See illustration 2: Structure of a metallic surface

The nearer the layers are to the substrate surface, the more energy is needed to remove them. Correspondingly the cleaning itself can be structured according to the type of energy input :

- mechanical - abrasive: blasting, grinding
- mechanical - non-abrasive: stirring, mixing, ultrasound, spraying
- thermal - reactive: heat treatment much above 100°C in reactive gases
- thermal - non-reactive: temperature below 100°C, increased bath temperature, vapour degreasing

- chemical - abrasive/reactive: pickling in liquids, plasma-assisted, sputter-cleaning, elektropolishing
- chemical - non-reactive: organic solvents, aqueous solutions, supercritical CO<sub>2</sub>

The contamination layer may then be further classified according to:

- Origin
- Composition: e.g. cooling lubricants may be composed very differently, thereby single components may account for big problems especially for job shop cleaners, who have no control over prior processes and thus don't know the contaminants. For example silicates may obstruct nitriding.
- State of aggregation
- Chemical and physical properties

The American Society for Testing and Materials (ASTM) presents six groups of contaminations in their manual "Choosing a cleaning process" and relates them to the most common cleaning methods, thereby the suitability of cleaning methods for the removal of a given contaminate is discussed in detail. In addition they list exemplary cleaning processes for different typical applications. Since one has to consider very many different aspects when choosing a process, this can only serve as a first orientation. The groups of contaminants are stated as follows:

- Pigmented drawing compounds
- Unpigmented oil and grease
- Chips and cutting fluids
- Polishing and buffing compounds
- Rust and scale
- Others

## **Charging**

In order to select suitable equipment and media it should be known also which amount and which throughput has to be handled. Small amounts can hardly be cleaned economically in larger plants. Also the type of charging has to be ascertained. Sensitive parts sometimes need to be fixed in boxes. Very economically when dealing with large amounts is bulk charging, but it is quite difficult to achieve a sufficient level of cleanliness with flat pieces clinging together. Also drying can be difficult in these cases.

## **Place of cleaning**

Another consideration is the place of cleaning. E.g. is the cleaning to be done on site, which can be the case with repair and maintenance work.

Usually the cleaning takes place in a workshop. Several common methods are solvent degreasing, vapor degreasing and using an aqueous parts washer. Companies often want

the charging, loading and unloading to be integrated into the production line, which is much more demanding as regards size and throughput ability of the cleaning system.

Such cleaning systems often exactly match the requirements regarding parts, contaminants and charging methods (special production). Nonetheless central cleaning equipment, often built as multi task systems, are commonly used. These systems can suit different cleaning requirements. Typical examples are the wash stands or the small cleaning machines which are found in many industrial plants.

## **Cleaning equipment and procedure**

First, one can differentiate between the following techniques:

- Manual
- Mechanical
- Automatic
- Robot supported

The process may be performed in one step, which is especially true for the manual cleaning, but typically it requires several steps. Therefore, it is not uncommon to find 10 to 20 steps in large plants e.g. for the medical and optical industry. This can be especially complex because non-cleaning steps may be integrated in such plants like application of corrosion protection layers or phosphating. Cleaning can also be simple, the cleaning processes are integrated into other processes as it is the case with electroplating or galvanising, where it usually serves as a pre-treatment step.

The following procedure is quite common:

1. Pre cleaning
2. Main cleaning
3. Rinsing
4. Rinsing with deionised water
5. Rinsing with corrosion protection
6. Drying

Each of these steps may take place in its own bath or chamber or in case of spray cleaning in its own zone (line or multi-chamber equipment). But quite often these steps may have a single chamber into which the respective media are pumped in (single chamber plant).

Besides equipment and procedure, cleaning media plays an important role as it removes the contaminants from the substrate.

For liquid media the following cleaners are in use: aqueous agents, semi-aqueous agents (an emulsion of solvents and water), hydrocarbon based solvents and halogenated solvents. Usually the latter are referred to as chlorinated agents, but there are also

brominated and fluorated substances in (limited) use, that is why we have chosen the higher level classification. The hazardous traditionally used chlorinated agents TCI and PCE are nowadays only applied in airtight plants and the modern volume shift systems limits any emissions.

Aqueous cleaners are mostly a combination of various substances like Alkaline builders, surfactants, sequestering agents, etc. Their use is on the rise as their results have proven to be in many cases as good or better than hydrocarbon cleaners. Additionally, the wastes generated are less hazardous resulting in less costly disposal. In the group of hydrocarbon based solvents, there are some newly developed agents like fatty acid esters made of natural fats and oils, modified alcohols and dibasic esters.

Aqueous cleaners have advantages as regards to particle and polar contaminants and only require higher inputs of mechanical and thermal energy to be effective, whereas solvents easily remove oils and greases but have health and environmental risks. In addition most solvents are flammable and create fire and explosion hazards. Now days, with the proper equipment, it is generally accepted that aqueous cleaners remove oil and grease as easily as solvents.

Another approach is with solid cleaning media (blasting) which constitutes of the CO<sub>2</sub> dry ice process: For tougher requirements pellets are used while for more sensitive materials or components CO<sub>2</sub> in form of snow is applied. One draw back is the high energy consumption required to make dry ice.

Last but not least there are processes without any media like vibration, laser, brushing and blow/exhaust systems.

All cleaning steps are characterised by media and applied temperatures and their individual agitation/application (mechanical impact). There is a wide range of different methods and combinations of these methods:

- Sprinkling
- Spraying
- Power Wash Process
- Blasting
- Flooding
- Movement of parts (turning, oscillating, pivoting)
- Circulation of bath
- Gas or air injection into bath
- Boiling under pressure
- Injection flooding
- Pressure flooding
- Hydroson
- Ultrasonic
- Megasonic

Finally, every cleaning step is described by the time which the parts to be cleaned spends in the respective zone, bath or chamber and thus medium, temperature and agitation can impact on the contamination.

Every cleaning equipment needs a so-called periphery. This term describes measures and equipment on the one hand side to maintain and control baths and on the other hand side to protect human beings and the environment.

In most plants the cleaning agents are circulated until their cleaning power has eventually decreased and reached the maximum tolerable contaminant level. In order to delay the necessary bath exchange as much as possible there are sophisticated treatment attachments in use, removing contaminants and the used up agents from the system. At the same time fresh cleaning agents or parts thereof have to be supplemented, which requires a bath control. The latter is more and more facilitated online and thus allows a computer aided adjustment of the bath. With the help of oil separators, demulsifying agents and evaporators aqueous processes can be conducted 'waste water free'. Complete exchange of baths becomes only necessary every 3 to 12 months.

When using organic solvents the preferred method to achieve a long operating bath life is distillation, an especially effective method to separate contaminants and agents.

The periphery also includes measures to protect the workers like encapsulation, automatic shut off of power supply, automatic refill and sharpening of media (e.g. gas shuttle technique), explosion prevention measures, exhaust ventilation etc., and also measures to protect the environment, e.g. capturing of volatile solvents, impounding basins, extraction, treatment and disposal of resulting wastes. Solvents based cleaning processes have the advantage that the dirt and the cleaning agent can be more easily separated, whereas in aqueous processes is more complex.

In processes without cleaning media like laser ablation and vibration cleaning, only the removed dirt has to be disposed of as there is no cleaning agent. Quite little waste is generated in processes like CO<sub>2</sub> blasting and automatic brush cleaning at the expense of higher energy costs.

## **Quality requirements**

A standardisation of the quality requirements for cleaned surfaces regarding the following process (e.g. coating, heat treatment) or from the point of view of technical functionality is difficult. However it is possible to use general classifications. In Germany it was attempted to define cleaning as a sub category of metal treatment (DIN 8592: Cleaning as sub category of cutting processes), but this does not cope with all the complexities of cleaning.

The rather general rules includes the classification in intermediate cleaning, final cleaning, precision cleaning and critical cleaning (s. table), in practice seen only as a general guideline.

Terms	Max. allowed dirt	Soils removed	Explanations
Intermediate cleaning			E.g. in metal cutting manufacturing
Final cleaning	$\leq 500 \text{ mg / m}^2$ (1)	Mil-sized particles and residues thicker than a monolayer	E.g. before assembling or coating
<ul style="list-style-type: none"> <li>Parts for phosphating, painting, enamelling</li> </ul>	<ul style="list-style-type: none"> <li><math>500 - \leq 5 \text{ mg C / m}^2</math> (2)</li> </ul>		
<ul style="list-style-type: none"> <li>Parts for case-hardening, nitriding, nitrocarburising resp. vacuum treatment</li> </ul>	<ul style="list-style-type: none"> <li><math>500 - \leq 5 \text{ mg C / m}^2</math> (2)</li> </ul>		
<ul style="list-style-type: none"> <li>Parts for electroplating, electronic parts</li> </ul>	<ul style="list-style-type: none"> <li><math>20 - \leq 5 \text{ mg C / m}^2</math> (2)</li> </ul>		
Precision cleaning	$\leq 50 \text{ mg / m}^2$ (1)	Supermicrometre particles and residues <i>thinner</i> than a monolayer	Controlled environment (Durkee)
Critical cleaning	$\leq 5 \text{ mg / m}^2$ (1)	Sub-micrometre particles and non-volatile residue measured in Angstroms	cleanroom (Durkee)

(1) Related to the total dirt; (2) Only related to Carbon

Thus in practice the rule of thumb is still followed, stating that the quality requirements are met, if the subsequent process does not cause any problems, for example a paint coating does not flake off before the guarantee period ends.

Where this is not sufficient, especially in case of external orders, because of missing standards there are often specific customer requirements regarding remaining contamination, corrosion protection, spots and gloss level etc.

Measuring methods to ensure quality therefore do not play a bigger role in the workshops, although there exist a broad scale of different methods, from visual control over simple testing methods (among other things water break test, wipe test, measurement of contact angle, test inks, tape test) to complex analysis methods (among others gravimetric test, particle counting, infrared spectroscopy, glow discharge spectroscopy, energy dispersive X-ray analysis, scanning electron microscopy and electrochemical methods). Nevertheless there are only few methods, which can be applied directly in the line and which offer reproducible and comparable results. It was not until recently that bigger advancements in this area have been made

The general situation has changed meanwhile, because of dramatically rising cleanliness requirements for certain components in the automotive industry. For example brake systems and fuel-injection systems need to be fitted with increasingly smaller diameters and they have to withstand increasingly higher pressures. Therefore, a very minor particle contamination may lead to big problems. Due to the rising innovation speed, the industry cannot afford to identify possible failures at a relatively late stage. Therefore, the standard VDA 19/ISO 16232 'Road Vehicles – Cleanliness of Components of Fluid Circuits' was developed which describes methods that can control the compliance with the cleanliness requirements.

### **Subsequent process**

When choosing cleaning techniques, cleaning agents and cleaning processes, the subsequent processes, i.e. the further processing of the cleaned parts is of special interest.

The classification follows basically the metal work theory:

- machining
- cutting
- joining
- coating
- heat treatment
- assembling
- measuring, testing
- repairing, maintenance.

In the course of time empirical values were established, how efficient the cleaning has to be, to assure the processes for the particular guarantee period and beyond. Choosing the cleaning method often starts from here.

### ***Challenges and trends***

The details above illustrate how extremely complex this specific field is. Already small changes in the requirements can necessitate completely different processes. Thus it defies scientific technical determination. On the other hand it becomes more and more important to receive the required degree of cleanliness as cost-effective as possible and with continuously minimised health and environmental risks, because cleaning has become of central importance for the supply chain in manufacturing . Applying companies usually rely on their suppliers, who—due to a big experience base—suggest adequate equipment and processes, which are then adapted to the detailed requirements in tests stations at the supplier's premises. However they are limited to their scope of technology. To put practitioners in a position to consider all relevant possibilities meeting their requirements, some institutes have developed different tools:

**SAGE:** Unfortunately no longer in operation the comprehensive expert system for parts cleaning and degreasing provided a graded list with relatively general processes of possible solvent and process alternatives. Developed by the Surface Cleaning Programme at the Research Triangle Institute, Raleigh, North Carolina, USA, in cooperation with the U.S. EPA.

**Cleantool:** A 'Best Practice' database in seven languages with comprehensive and specific processes, directly recorded in companies. It contains furthermore an integrated evaluation tool, which covers the areas technology, quality, health and safety at work, environmental protection as well as costs. Also included is a comprehensive glossary.

**Bauteilreinigung:** A selection system for component cleaning developed by the University of Dortmund, assisting the users to analyse their cleaning tasks with regard to the suitable cleaning processes and cleaning agents.

**TURI, Toxic Use Reduction Institute:** A department of the University of Lowell, Massachusetts (USA). TURI's laboratory has been conducting evaluations on alternative cleaning products since 1993. A majority of these products were designed for metal surface cleaning. The results of these tests are available on-line through the Institute's laboratory database.

## Chapter-5

# Hot Working and Hot Pressing

## Hot working



A forge fire for hot working of metal

**Hot working** refers to processes where metals are plastically deformed above their recrystallization temperature. Being above the recrystallization temperature allows the material to recrystallize during deformation. This is important because recrystallization keeps the materials from strain hardening, which ultimately keeps the yield strength and hardness low and ductility high. This contrasts with cold working.

## **Temperature**

The lower limit of the hot working temperature is determined by its recrystallization temperature. As a guideline, the lower limit of the hot working temperature of a material is 0.6 times its melting temperature (on an absolute temperature scale). The upper limit for hot working is determined by various factors, such as: excessive oxidation, grain growth, or an undesirable phase transformation. In practice materials are usually heated to the upper limit first to keep forming forces as low as possible and to maximize the amount of time available to hot work the workpiece.

The most important aspect of any hot working process is controlling the temperature of the workpiece. Of 90% of the energy imparted into the workpiece is converted into heat. Therefore, if the deformation process is quick enough the temperature of the workpiece should rise, however, this does not usually happen in practice. Most of the heat is lost through the surface of the workpiece into the cooler tooling. This causes temperature gradients in the workpiece, usually due to non-uniform cross-sections where the thinner sections are cooler than the thicker sections. Ultimately, this can lead to cracking in the cooler, less ductile surfaces. One way to minimize the problem is to heat the tooling. The hotter the tooling the less heat lost to it, but as the tooling temperature rises, the tool life decreases. Therefore the tooling temperature must be compromised; commonly, hot working tooling is heated to 500–850 °F (325–450 °C).

<b>Metal</b>	<b>Temperature</b>
Tin	Room temperature
Steel	2,000 °F (1,090 °C)
Tungsten	4,000 °F (2,200 °C)

## **Advantages & disadvantages**

The advantages are:

- Decrease in yield strength, therefore it is easier to work and uses less energy or force
- Increase in ductility
- Elevated temperatures increase diffusion which can remove or reduce chemical inhomogeneities
- Pores may reduce in size or close completely during deformation
- In steel, the weak, ductile, face-centered-cubic austenite microstructure is deformed instead of the strong body-centered-cubic ferrite microstructure found at lower temperatures

Usually the initial workpiece that is hot worked was originally cast. The microstructure of cast items does not optimize the engineering properties, from a microstructure standpoint.

Hot working improves the engineering properties of the workpiece because it replaces the microstructure with one that has fine spherical shaped grains. These grains increase the strength, ductility, and toughness of the material.

The engineering properties can also be improved by reorienting the inclusions (impurities). In the cast state the inclusions are randomly oriented, which, when intersecting the surface, can be a propagation point for cracks. When the material is hot worked the inclusions tend to flow with the contour of the surface, creating *stringers*. As a whole the strings create a *flow structure*, where the properties are anisotropic (different based on direction). With the stringers oriented parallel to the surface it strengthens the workpiece, especially with respect to fracturing. The stringers act as "crack-arrestors" because the crack will want to propagate through the stringer and not along it.

The disadvantages are:

- Undesirable reactions between the metal and the surrounding atmosphere (scaling or rapid oxidation of the workpiece)
- Less precise tolerances due to thermal contraction and warping from uneven cooling
- Grain structure may vary throughout the metal for various reasons
- Requires a heating unit of some kind such as a gas or diesel furnace or an induction heater, which can be very expensive

## Hot pressing

**Hot pressing** is a high-pressure, low-strain-rate powder metallurgy process for forming of a powder or powder compact at a temperature high enough to induce sintering and creep processes. This is achieved by the simultaneous application of heat and pressure.

Hot pressing is mainly used to fabricate hard and brittle materials. One large use is in the consolidation of diamond-metal composite cutting tools and technical ceramics. The densification works through particle rearrangement and plastic flow at the particle contacts. The loose powder or the pre-compacted part is in most of the cases filled to a graphite mould that allows induction or resistance heating up to temperatures of typically 2,400 °C (4,350 °F). Pressures of up to 50 MPa (7,300 psi) can be applied.

Within hot pressing technology, three distinctly different types of heating can be found in use: induction heating, indirect resistance heating, and direct hot pressing.

## ***Inductive heating***

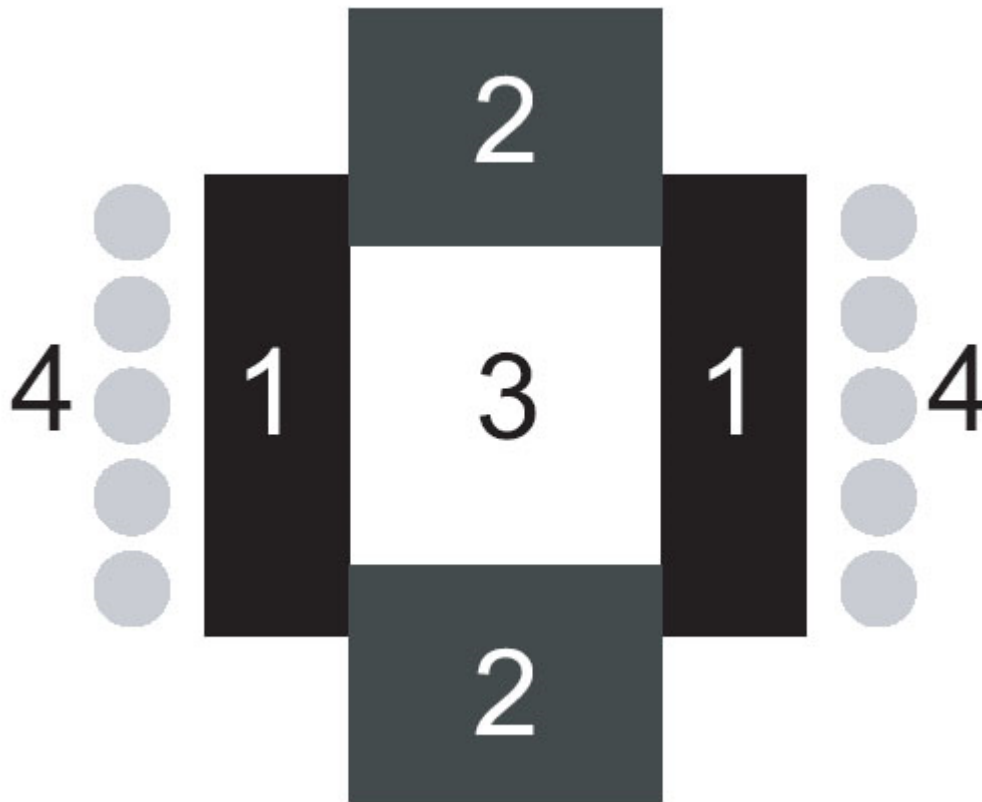


Figure I: Conventional inductive heating

In this process heat is produced within the mould when it is subjected to a high frequency electromagnetic field, generated by using an induction coil coupled to an electronic generator. The mould is made out of graphite or steel, and pressure is applied by one or two cylinders onto the punches. The mould is positioned within the induction coil. The advantage here is that the pressure and the inductive power are completely independent. Even powders with a liquid phase are amenable to this process and low pressures are possible, too. Among the disadvantages are the expense of a high-frequency generator and the need for proper alignment. If the mould is placed off centre, the heat distribution is uneven. But the main disadvantage is the dependence of the process on good inductive coupling and thermal conductivity of the mould. The magnetic field can penetrate the mould only 0.5mm to 3mm. From there on, the heat has to be "transported" into the mould by the thermal conductivity of the mould material. Uniform heating is much more difficult if the air gap between the mould and the inductive coil is not the same all along the mould profile. Another potential problem is heating rate. Too high a heat up rate will result in high temperature differences between the surface and core that can destroy the mould.

## ***Indirect resistance heating***

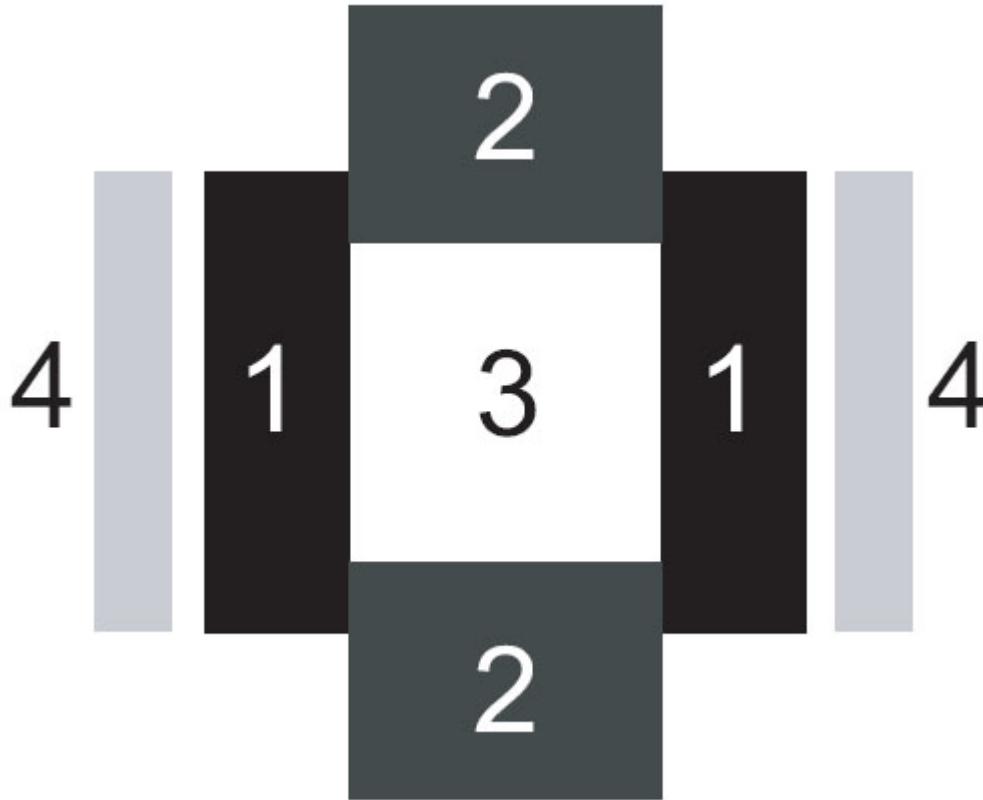


Figure II: Indirect resistance heating

With indirect resistance heating technology, the mould is placed in a heating chamber. The chamber is heated by graphite heating elements. These elements are heated by electrical current. The heat is then transferred into the mould by convection. As the electrical energy heats the heating elements that then heat the mould in a secondary manner, the process is called indirect resistance heating.

Advantages are high achievable temperatures, independent from the conductivity of the mould and independent from heat and pressure. Main disadvantage is the time that it takes to heat up the mould. It takes relatively long for heat transfer to take place from the furnace atmosphere to the mould surface and subsequently through out the cross-section of the mould.

## ***Direct hot pressing***

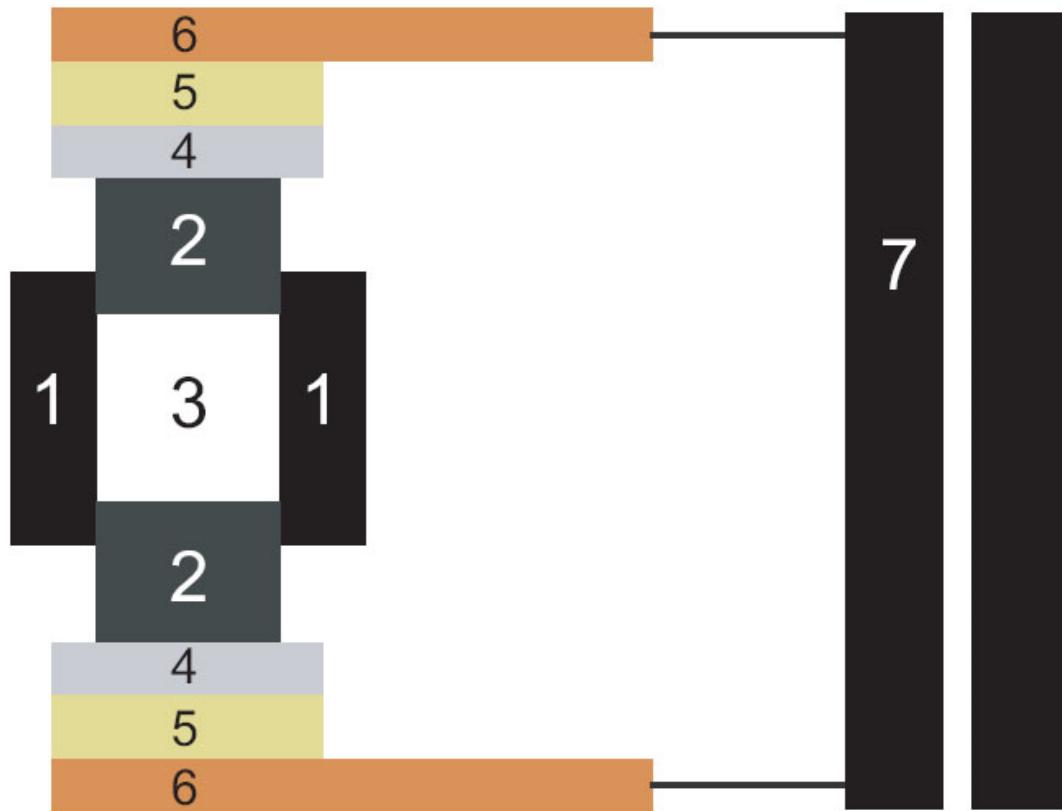


Figure III: Direct hot pressing

The basic idea of sintering with electric current going through the mould is quite old. Resistance heating of cemented carbide powders was patented by Taylor as early as 1933. This method is currently undergoing renewed interest. When applying a standard (unpulsed) AC or DC current, it is referred to as Direct Hot-Pressing (DHP) which is a common term in many industries. When applying a pulsed DC current, it is referred to as Spark Plasma Sintering (SPS) or Field Assisted Sintering Technique (FAST). The compelling reason for shortening the cycle time then was to avoid grain growth and also save energy. In direct hot pressing, the mould is directly connected to electrical power. The resistance of the mould and the powder part generates the heat directly in the mould. This results in very high heating rates. Additionally, this leads to significant increase in the sintering activity of fine metal powder aggregates which makes short cycle times of a few minutes possible. Further, this process lowers the threshold sintering temperature and pressure compared to that required in conventional sintering processes. The previous two methods are both closely dependent on the an intrinsic property of the mould material, i.e., its thermal conductivity. With direct resistance heating, however, the heat is generated where it is needed.

Recently, the manufacture of such critical items as sputtering targets and high-performance ceramic components, such as boron carbide, titanium diboride, and sialon, have been achieved. Using metal powder, the conductivity of the mould is ideal for fast heating of the work-piece. Moulds that have a big diameter and relatively small height can be heated up very fast. The process is especially suitable for applications that need high heating rates, e.g. for materials that should not be kept at high temperatures too long or for processes that require fast heating rates for high productivity.

With the direct hot pressing technology, materials can be sintered to their final density. The near net-shape precision achieved is very high and saves in many cases mechanical reworking of the high grade materials that are often difficult to process.

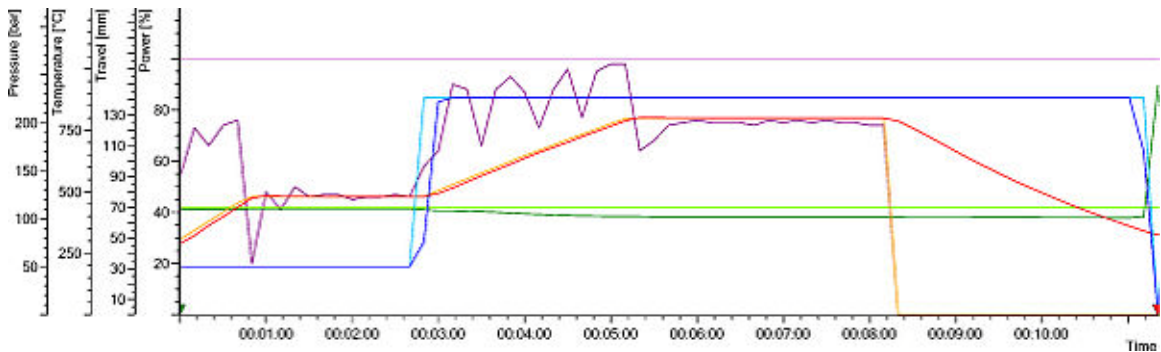


Figure IV: Process layout of the co-sintering process; total cycle time 11.5 mins Key:  
 Red/orange line: actual/set temperature Green line: densification of powder/green compact Dark blue/light blue: actual/set pressure

## Chapter-6

# Forge



A blacksmith's coal forge



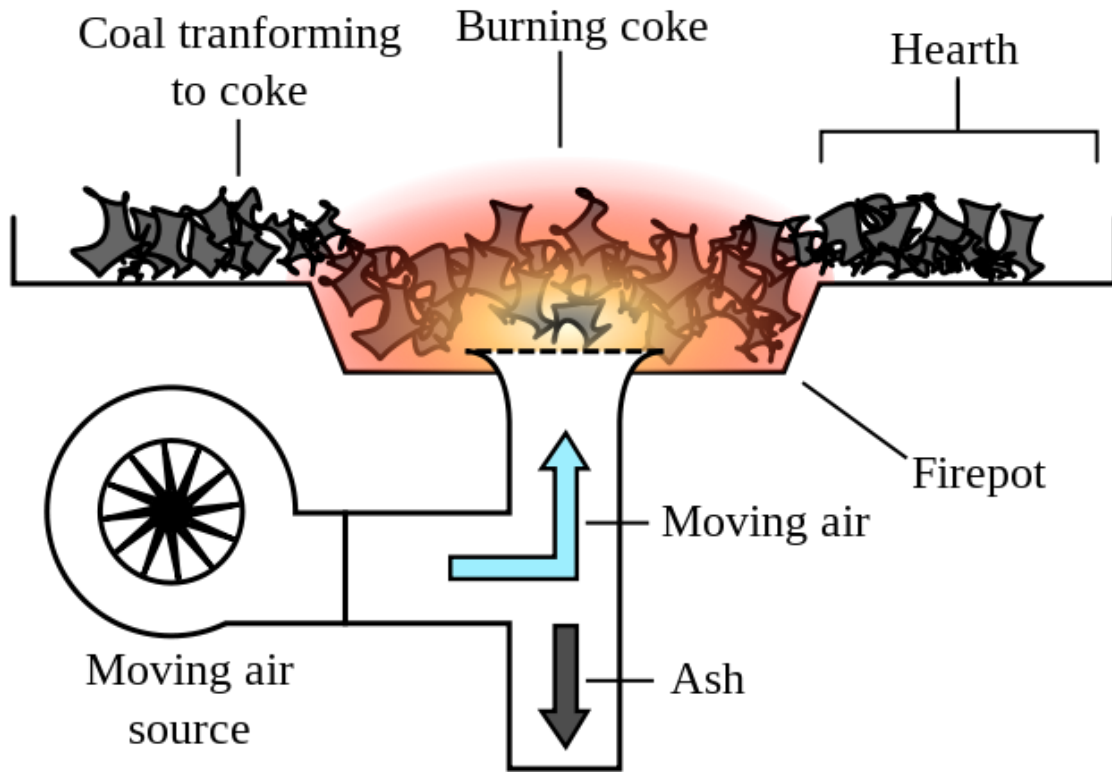
Wooden smithy in Opole, Upper Silesia

A **forge** is a hearth used for forging. The term "forge" can also refer to the workplace of a smith or a blacksmith, although the term **smithy** is then more commonly used.

The basic smithy contains a forge, also known as a hearth, for heating metals. The forge heats the workpiece to a malleable temperature (a temperature where the metal becomes easier to shape) or to the point where work hardening no longer occurs. The workpiece is transported to and from the forge using tongs. The tongs are also used to hold the workpiece on the smithy's anvil while the smith works it with a hammer. Finally the workpiece is transported to the slack tub, which rapidly cools the workpiece in a large body of water. The slack tub also provides water to control the fire in the forge.

## ***Types of forges***

### **Coal/coke/charcoal forge**



Standard coal forge

A forge typically uses bituminous coal, industrial coke or charcoal as the fuel to heat metal. The designs of these forges have varied over time, but whether the fuel is coal, coke or charcoal the basic design has remained the same.

A forge of this type is essentially a hearth or fireplace designed to allow a fire to be controlled such that metal introduced to the fire may be brought to a malleable state or to bring about other metallurgical effects (hardening, annealing, and drawing temper as examples). The forge fire in this type of forge is controlled in three ways: amount of air, volume of fuel, and shape of the fuel/fire.



A forge fire for hot working of metal

Over thousands of years of forging, these devices have evolved in one form or another as the essential features of this type of forge:

- Tuyere — a pipe through which air can be forced into the fire
- Bellows or blower — a means for forcing air into the tuyere
- Firepot or hearth — a place where the burning fuel can be contained over or against the tuyere opening.

During operation, fuel is placed in or on the hearth and ignited. A source of moving air, such as a fan or bellows, introduces additional air into the fire through the tuyere. With additional air, the fire consumes more fuel and burns hotter.



A typical Scottish smithy at Auchentiber, North Ayrshire, Scotland.

A blacksmith balances the fuel and air in the fire to suit particular kinds of work. Often this involves adjusting and maintaining the shape of the fire.

In a typical, but by no means universal, coal forge, a firepot will be centered in a flat hearth. The tuyere will enter the firepot at the bottom. In operation, the hot core of the fire will be a ball of burning coke in and above the firepot. The heart of the fire will be surrounded by a layer of hot but not burning coke. Around the unburnt coke will be a transitional layer of coal being transformed into coke by the heat of the fire. Surrounding all is a ring or horseshoe-shaped layer of raw coal, usually kept damp and tightly packed to maintain the shape of the fire's heart and to keep the coal from burning directly so that it "cooks" into coke first.

If a larger fire is necessary, the smith increases the air flowing into the fire as well as feeding and deepening the coke heart. The smith can also adjust the length and width of the fire in such a forge to accommodate different shapes of work.

The major variation from the forge and fire just described is a 'back draft' where there is no fire pot, and the tuyere enters the hearth horizontally from the back wall.

Coke and charcoal may be burned in the same forges that use coal, but since there is no need to convert the raw fuel at the heart of the fire (as with coal), the fire is handled differently.

Individual smiths and specialized applications have fostered development of a variety of forges of this type, from the coal forge described above, to simpler constructions amounting to a hole in the ground with a pipe leading into it.

## **Gas forge**

A gas forge typically uses propane or natural gas as the fuel. One common, efficient design uses a cylindrical forge chamber and a burner tube mounted at a right angle to the body. The chamber is typically lined with refractory materials, preferably a hard castable refractory ceramic. The burner mixes fuel and air which are ignited at the tip, which protrudes a short way into the chamber lining. The air pressure, and therefore heat, can be increased with a mechanical blower or by taking advantage of the Venturi effect.

Gas forges vary in size and construction, from large forges using a big burner with a blower or several atmospheric burners to forges built out of a coffee can utilizing a cheap, simple propane torch. A small forge can even be carved out of a single soft firebrick.

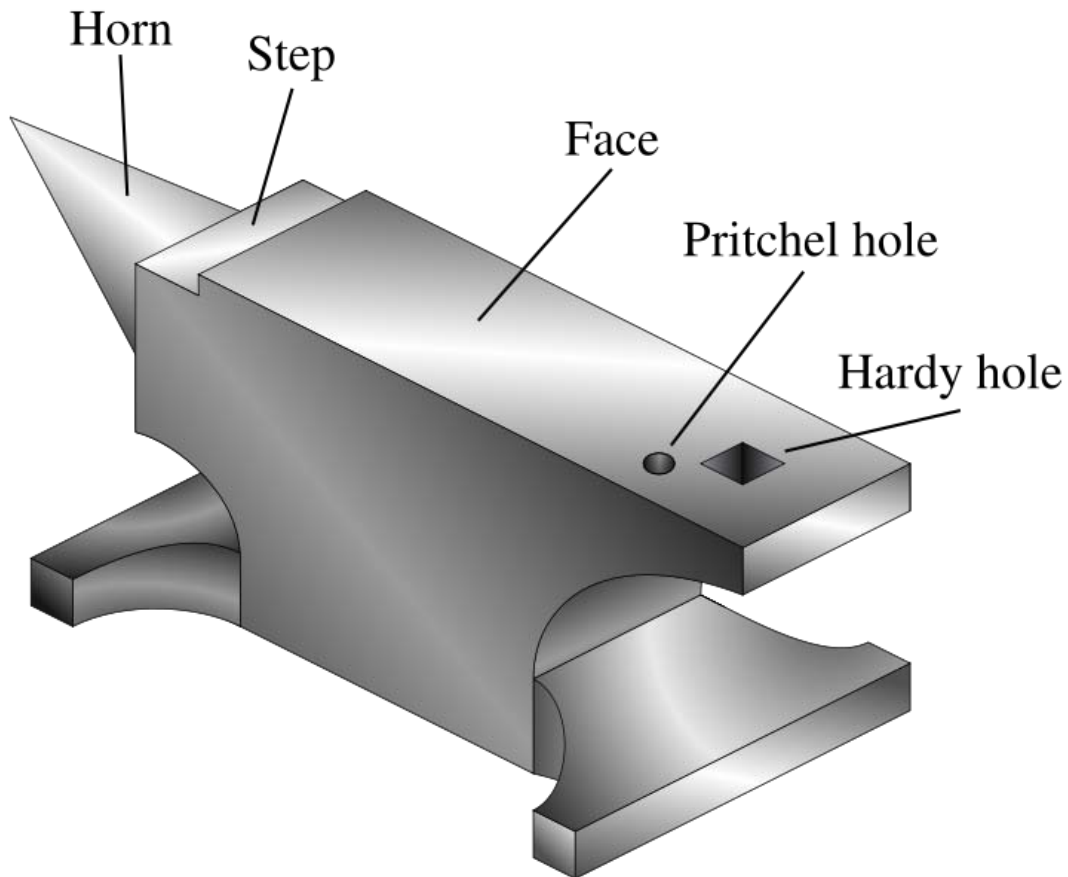
The primary advantage of a gas forge is ease of use, particularly for a novice. A gas forge is simple to operate compared to coal forges, and the fire produced is clean and consistent. They are less versatile, as the fire cannot be reshaped to accommodate large or unusually shaped pieces; It is also difficult to heat a small section of a piece. A common misconception is that gas forges cannot produce enough heat to enable forge-welding, but a well designed gas forge is hot enough for any task.

## **Finery forge**

A finery forge is a water-powered mill where pig iron is refined into wrought iron.

## ***Forging equipment***

### **Anvil**



The anvil serves as a work bench for the blacksmith, where the metal to be beaten is placed. Anvils are made of cast or wrought iron with a tool steel face welded on or of a single piece of cast or forged tool steel. The flat top has two holes; the wider one is called the hardy hole, where the square shank of the hardy fits. The smaller hole is called the punch hole, used as clearance when punching holes in hot metal.

### **Chisel**

Chisels are made of high carbon steel. They are hardened and tempered at the cutting edge while the head is left soft so it will not crack when hammered. Chisels are of two types, hot and cold chisels. The cold chisel is used for cutting cold metals while the hot chisel is for hot metals. Usually hot chisels are thinner and therefore cannot be substituted with cold chisels.

## **Tongs**

Tongs are used by the blacksmith for holding hot metals securely. The mouths are custom made by the smith in various shapes to suit the gripping of various shapes of metal.

## **Fuller**

Fullers are forming tools of different shapes used in making grooves or hollows. They are often used in pairs, the bottom fuller has a square shank which fits into the hardy hole in the anvil while the top fuller has a handle. The work is placed on the bottom fuller and the top is placed on the work and struck with a hammer. The top fuller is also used for finishing round corners and for stretching or spreading metal.

## **Hardy**

The hardy is a cutting tool similar to the chisel. It is used as a chisel or hammer for cutting both hot and cold metals. It has a square shank that fits into the hardy hole in the anvil, with the cutting edge facing upwards. The metal to be cut is placed on the cutting edge and struck with a hammer. They are also used with set tools which are placed over the workpiece and struck.

## **Slack tub**

A *slack tub* is usually a large container full of water, brine, or oil used by a blacksmith to quench hot metal. The term is believed to derive from the word "slake", as in slaking the heat.

## ***Types of Forging***

### **Drop Forging**

Drop forging is a process used to shape metal into complex shapes by dropping heated metal into a punch and die which compresses to gradually change the shape of the metal.

### **Process**

The workpiece is placed into a die and punch, then the impact of a ram on the punch causes the heated material, which is very malleable, to conform to the shape of the punch and die cavities. Typically only one ram is needed to completely form the part. The extra space between the die and punch is called the flash. It acts as a relief valve for the extreme pressure produced by the closing of the die halves but is eventually trimmed off of the finished part.

## **Equipment**

The equipment used in the drop forming process is commonly known as a power or drop hammer. These may be powered by air, hydraulics, or mechanics. Depending on how the machine is powered, the mass of the ram, and the drop height, the striking force can be anywhere from 11,000 to 425,000 pounds. The tools that are used, dies and punches, come in many different shapes and sizes, as well as materials. Examples of these shapes are flat and v-shaped which are used for open-die forging, and single or multiple-impression dies used for closed die-forging. The designs for the dies have many aspects to them that must be considered. They all must be properly aligned, they must be designed so the metal and the flash will flow properly and fill all the grooves, and special considerations must be made for supporting webs and ribs and the parting line location. The materials must also be selected carefully. Some factors that go into the material selection are cost, their ability to harden, their ability to withstand high pressures, hot abrasion, heat cracking, and other such things. The most common materials used for the tools are carbon steel and, in some cases, nickel based alloys.

## **Workpiece Materials**

The materials that are used most commonly in drop forging are aluminum, copper, nickel, mild steel, stainless steel, and magnesium. Mild steel is the best choice, and magnesium generally performs pretty poorly as a drop forging material.



Forge fire



Brake Drum Coal Forge

## Chapter-7

# Cutting Fluid



Thin-wall milling of aluminum using a water-based cutting fluid on the milling cutter.

**Cutting fluid** is a type of coolant and lubricant designed specifically for metalworking and machining processes. There are various kinds of cutting fluids, which include oils, oil-water emulsions, pastes, gels, aerosols (mists), and air or other gases. They may be

made from petroleum distillates, animal fats, plant oils, water and air, or other raw ingredients. Depending on context and on which type of cutting fluid is being considered, it may be referred to as **cutting fluid**, **cutting oil**, **cutting compound**, **coolant**, or **lubricant**.

Most metalworking and machining processes can benefit from the use of cutting fluid, depending on workpiece material. A common exception to this is machining cast iron or brass, which are machined dry.

The properties that are sought after in a good cutting fluid are the ability to:

- keep the workpiece at a stable temperature (critical when working to close tolerances). Very warm is OK, but extremely hot or alternating hot-and-cold are avoided.
- maximize the life of the cutting tip by lubricating the working edge and reducing tip welding.
- ensure safety for the people handling it (toxicity, bacteria, fungi) and for the environment upon disposal.
- prevent rust on machine parts and cutters.

## ***Functions***

### **Cooling**

Metal cutting operations involve generation of heat due to friction between the tool and the pieces and due to energy lost deforming the material. The surrounding air alone is a rather poor coolant for the cutting tool, because the rate of heat transfer is low. Ambient-air cooling is adequate for light cuts with periods of rest in between, such as are typical in maintenance, repair and operations (MRO) work or hobbyist contexts. However, for heavy cuts and constant use, such as in production work, more heat is produced per time period than ambient-air cooling can remove. It is not acceptable to introduce long idle periods into the cycle time to allow the air-cooling of the tool to "catch up" when the heat-removal can instead be accomplished with a flood of liquid, which can "keep up" with the heat generation.

### **Lubrication**

Besides cooling, cutting fluids also aid the cutting process by lubricating the interface between the tool's cutting edge and the chip. By preventing friction at this interface, some of the heat generation is prevented. This lubrication also helps prevent the chip from being welded onto the tool, which interferes with subsequent cutting.

Extreme pressure additives are often added to cutting fluids to further reduce tool wear.

## ***Delivery methods***

Every conceivable method of applying cutting fluid (e.g., flooding, spraying, dripping, misting, brushing) can be used, with the best choice depending on the application and the equipment available. For many metal cutting applications the ideal has long been high-pressure, high-volume pumping to force a stream of liquid (usually an oil-water emulsion) directly into the tool-chip interface, with walls around the machine to contain the splatter and a sump to catch, filter, and recirculate the fluid. This type of system is commonly employed, especially in manufacturing. It is often not a practical option for MRO or hobbyist metalcutting, where smaller, simpler machine tools are used. Fortunately it is also not necessary in those applications, where heavy cuts, aggressive speeds and feeds, and constant, all-day cutting are not vital.

As technology continually advances, the flooding paradigm is no longer always the clear winner. It has been complemented since the 2000s by new permutations of liquid, aerosol, and gas delivery, such as MQL and through-the-tool-tip cryogenic cooling.

## ***Types***

### **Liquids**

There are generally three types of liquids: mineral, semi-synthetic, and synthetic. Semi-synthetic and synthetic cutting fluids try to blend the best properties of oil into the best properties of water. They basically achieve this by allowing oil to emulsify into water. Some of these properties are: rust inhibition, tolerance of a wide range of water hardness (maintain pH stability around 9 to 10), ability to work with many metals, resist thermal breakdown, and environmental safety.

Water is a great conductor of heat but has drawbacks as a cutting fluid. It boils easily, promotes rusting of machine parts, and does not lubricate well. Therefore, other ingredients are necessary to create an optimal cutting fluid.

Mineral oils, which are petroleum-based, began in the late 19th century. They vary from the thick, dark, sulfur-rich cutting oils used in heavy industry to light, clear oils.

Semi-synthetic coolants are an emulsion or microemulsion of water with mineral oil. They began in the 1930s. A typical CNC usually uses emulsified coolant, which consists of a small amount of oil emulsified into a larger amount of water through the use of a detergent.

Synthetic coolants originated in the late 1950s and are usually water-based.

A hand-held refractometer is used to determine the mix ratio (also called concentration) of water soluble coolants. Numerous other test equipment are used to determine such things as acidity, and amount of conductivity.

Others include:

- Kerosene, rubbing alcohol, and 3-In-One Oil often give good results when working on aluminium.
- WD-40
- Dielectric fluid is the cutting fluid used in Electrical discharge machines (EDMs). It is usually deionized water or a high-flash-point kerosene. Intense heat is generated by the cutting action of the electrode (or wire) and the fluid is used to stabilise the temperature of the workpiece, along with flushing any eroded particles from the immediate work area. The dielectric fluid is nonconductive.
- Liquid- (water- or petroleum oil-) cooled water tables are used with the plasma arc cutting (PAC) process.

### **Pastes or gels**

Cutting fluid may also take the form of a paste or gel when used for some applications, in particular hand operations such as drilling and tapping. In sawing metal with a bandsaw, it is common to periodically run a stick of paste against the blade. This product is similar in form factor to lipstick or beeswax. It comes in a cardboard tube, which gets slowly consumed with each application.

### **Aerosols (mists)**

Some cutting fluids are used in aerosol (mist) form (air with tiny droplets of liquid scattered throughout). The main problems with mists have been that they are rather bad for the workers, who have to breathe the surrounding mist-tainted air, and that they often don't even work very well. Both of those problems come from the imprecise delivery that often puts the mist everywhere and all the time except at the cutting interface, during the cut—the one place and time where it's wanted. However, a newer form of aerosol delivery, MQL (minimum quantity of lubricant), avoids both of those problems. The delivery of the aerosol is directly through the flutes of the tool (it arrives directly through or around the insert itself—an ideal type of cutting fluid delivery that traditionally has been unavailable outside of a few contexts such as gun drilling or expensive, state-of-the-art liquid delivery in production milling). MQL's aerosol is delivered in such a precisely targeted way (with respect to both location and timing) that the net effect seems almost like dry machining from the operators' perspective. The chips generally seem like dry-machined chips, requiring no draining, and the air is so clean that machining cells can be stationed closer to inspection and assembly than before.

### **Air or other gases (e.g., nitrogen)**

Ambient air, of course, was the original machining coolant. Compressed air, supplied through pipes and hoses from an air compressor and discharged from a nozzle aimed at the tool, is sometimes a useful coolant. The force of the decompressing air stream blows chips away, and the decompression itself has a slight degree of cooling action ( $pV=nRT$ ; lowering the pressure lowers the temperature).

Liquid nitrogen, supplied in pressurized steel bottles, is sometimes used in similar fashion. In this case, the decompression is enough to provide a powerful refrigerating effect. For years this has been done (in limited applications) by flooding the work zone. Since 2005, this mode of coolant has been applied in a manner comparable to MQL (with through-the-spindle and through-the-tool-tip delivery). This refrigerates the body and tips of the tool to such a degree that it acts as a "thermal sponge", sucking up the heat from the tool–chip interface. This new type of nitrogen cooling is still under patent. Tool life has been increased by a factor of 10 in the milling of tough metals such as titanium and inconel.

## **Past practice**

- In 19th-century machining practice, it was not uncommon to use plain water. This was simply a practical expedient to keep the cutter cool, regardless of whether it provided any lubrication at the cutting edge–chip interface. When one considers that high-speed steel (HSS) had not been developed yet, the need to cool the tool becomes all the more apparent. (HSS retains its hardness at high temperatures; other carbon tool steels do not.) An improvement was soda water, which better inhibited the rusting of machine slides. These options are generally not used today because better options are available.
- Lard was very popular in the past. It is used infrequently today, because of the wide variety of other options, but it is still an option.
- Old machine shop training texts speak of using red lead and white lead, often mixed into lard or lard oil. This practice is obsolete due to the toxicity of lead.
- From the mid-20th century to the 1990s, 1,1,1-trichloroethane was used as an additive to make some cutting fluids more effective. In shop-floor slang it was referred to as "one-one-one". It has been phased out because of its ozone-depleting and central nervous system-depressing properties.

## **Safety concerns**

Cutting fluids present some mechanisms for causing illness or injury in workers. These mechanisms are based on the external (skin) or internal contact involved in machining work, including touching the parts and tooling; being splattered or splashed by the fluid; or having mist settle on the skin or enter the mouth and nose in the normal course of breathing.

The mechanisms include the chemical toxicity or physical irritating ability of:

- the fluid itself
- the metal particles (from previous cutting) that are borne in the fluid
- the bacterial or fungal populations that naturally tend to grow in the fluid over time
- the biocides that are added to inhibit those life forms
- the corrosion inhibitors that are added to protect the machine and tooling

- the tramp oils that result from the way oils (the lubricants for the slideways) inevitably finding their way into the coolant

The toxicity or irritating ability is usually not high, but it is sometimes enough to cause problems for the skin or for the tissues of the respiratory tract or alimentary tract (e.g., the mouth, larynx, esophagus, trachea, or lungs).

Some of the diagnoses that can result from the mechanisms explained above include irritant contact dermatitis; allergic contact dermatitis; occupational acne; tracheitis; esophagitis; bronchitis; asthma; allergy; hypersensitivity pneumonitis (HP); and worsening of pre-existing respiratory problems.

Safer cutting fluid formulations provide a resistance to tramp oils, allowing improved filtration separation without removing the base additive package. Room ventilation, splash guards on machines, and personal protective equipment (PPE) (such as safety glasses, respirator masks, and gloves) can mitigate hazards related to cutting fluids.

Bacterial growth is predominant in semi-synthetic and synthetic fluids. Tramp oil along with human hair or skin oil are some of the debris during cutting which accumulates and forms a layer on the top of the liquid; anaerobic bacteria proliferate due to a number of factors. An early sign of the need for replacement is the "Monday-morning smell" (due to lack of usage from Friday to Monday). Antiseptics are sometimes added to the fluid to kill bacteria. Such use must be balanced against whether the antiseptics will harm the cutting performance, workers' health, or the environment. Maintaining as low a fluid temperature as practical will slow the growth of microorganisms.

The discussion above could leave a reader with the mistaken idea that cutting fluid is "often extremely dangerous". That would be an exaggeration. In reality, cutting fluid exposure is like many exposures in life, such as second-hand tobacco smoke; ethanol ingestion; paint and thinner fumes; kitchen or bakery smoke; smoke from smelting, casting, forging, or welding; contact with animal manure in farming, veterinary work, or pest control work; or contact with sewage in plumbing or sewer work. Such exposures only cause acute illness or injury in occasional cases where some situational factor was "out of normal bounds". Rather, the main health risk is that of chronic illness from long-term occupational exposure. Most machinists work around cutting fluids for years without adverse effects. They generally don't worry about casual contact, and they use PPE to minimize it.

### ***Degradation, replacement, and disposal***

Cutting fluids degrade over time due to contaminants entering the lubrication system. A common type of degradation is the formation of *tramp oil*, also known as *sump oil*, which is unwanted oil that has mixed with cutting fluid. It originates as lubrication oil that seeps out from the slideways and washes into the coolant mixture, as the protective film with which a steel supplier coats bar stock to prevent rusting, or as hydraulic oil leaks. In

extreme cases it can be seen as a film or skin on the surface of the coolant or as floating drops of oil.

Skimmers are used to separate the tramp oil from the coolant. These are typically slowly rotating vertical discs that are partially submerged below the coolant level in the main reservoir. As the disc rotates the tramp oil clings to each side of the disc to be scraped off by two wipers, before the disc passes back through the coolant. The wipers are in the form a channel that then redirects the tramp oil to a container where it is collected for disposal. Floating weir skimmers are also used in these situation where temperature or the amount of oil on the water becomes excessive.

Since the introduction of CNC additives, the tramp oil in these systems can be managed more effectively through a continuous separation effect. The tramp oil accumulation separates from the aqueous or oil based coolant and can be easily removed with an absorbent.

Old, used cutting fluid must be disposed of when it is fetid or chemically degraded and has lost its usefulness. As with used motor oil or other wastes, its impact on the environment should be mitigated. Legislation and regulation specify how this mitigation should be achieved. Modern cutting fluid disposal involves techniques such as ultrafiltration using polymeric or ceramic membranes which concentrates the suspended and emulsified oil phase.

One shop's total costs for each instance of cutting fluid replacement came to USD 373, which included 2 hours of machine downtime (accounted at USD 50 per hour); 2 hours of labor (accounted at USD 12 per hour); USD 69 worth of new coolant concentrate (which is then mixed with water); and USD 3 per U.S. gallon for proper disposal of about 60 gallons (about 225 L) of coolant. Clearly, fluid formulations and machining practices that extend the working lifespan of each batch of coolant can be worth the costs of developing them.

## Chapter-8

# Architectural Metals and Mass Finishing

## Architectural metals

**Architectural metals** used in buildings and structures comprise several distinctive metallic materials. Metals serve a wide variety of uses in the built landscape, including structural features, such as nails and trusses, as well as decorative features, such as doorknobs and cladding. Some metals discovered by early civilizations are still in use today. Scientific study has brought a greater understanding of the performance and limits of the various types of metals used in buildings.

### *Metal Types*

#### **Lead**

The low melting point of lead permitted its use on a wide scale throughout human history. Water pipes were frequently constructed of lead, until its health hazards were publicized in the late 19th century.

Lead has been a popular roofing material for centuries, being used for roofing, flashing, gutters, downspouts, and conductor heads. Lead was best suited for low-pitched roofs, as steep roofs experienced creep. Lead roofs in regions with large temperature fluctuations, such as the mid-Atlantic states, experienced deterioration from constant expansion and contraction, called fatigue. Beginning in the 19th century, a roofing material called “terne” or “terneplate” was used, consisting of sheet iron or sheet steel coated with a lead-tin alloy. It is frequently confused with tinplate.

Lead was also frequently used for window comes, for use in skylights and stained glass. It was also used for small pieces of sculpture and garden ornamentation. Finally, lead was frequently added to paint, with red lead used as an anti-corrosive pigment for iron, and white lead used as paint for wooden houses. Lead-based paint was one of the most durable materials developed as a protective exterior coating. The use of lead paint has been restricted on most buildings, due to concerns of lead poisoning.

## **Tin**

The principal architectural uses of tin fall into two categories: the alloying of tin with other metals such as copper to form bronze, and the coating of tin on harder metals, such as tinned iron or steel. Architectural bronzes usually contain about 90% copper and 10% tin, although the content may vary widely. The term “tin ceiling” is a misnomer, as these decorative sheets were never tinned; they were almost always painted sheet iron or steel.

Tinplate was a type of architectural material consisting of sheet iron coated with tin. “Tin roofs,” a type of tinplate, was originally used for armor but eventually as a roofing material. Tinplate was also used for decoration, such as ornamental windows and door lintels. Although tinplate is still available today for roofing and flashing, it is generally considered expensive since the initial cost is more than that for common modern roofing types such as asphalt shingles or built-up roofs. However, since a well-maintained tinplate roof typically lasts several times longer than either of these types of roofing, it is more economical when the cost is prorated over the longer lifespan.

## **Zinc**

Pure zinc was used for roofing in Belgium, France and Germany, where it replaced more expensive copper and lead in roofing. Starting in the 1820s, Belgian sheet zinc was imported in America, used by builders in New York City and elsewhere. Pure zinc is subject to creep at ordinary temperatures.

Zinc-coated metals were first patented in 1837, separately by M. Sorel in France and H. W. Crawford in England. The methods employed a “hot dipping” process to coat sheet iron with zinc. By 1839 “galvanized” sheet iron roofing was being used in New York City. The Merchant's Exchange in Manhattan was one of the first buildings to have both a galvanized roof and galvanized gutters. Some galvanized sheet roofing was pressed with designs, a mode very popular in the Victorian era.

Zinc was also cast for sculptures and decorative elements in Germany as early as 1832. Decorative architectural elements were frequently cast in zinc, since it molded readily, was inexpensive compared to stone, and could be painted to imitate more expensive metals.

Zinc oxide paints were nontoxic and resistant to pollution. They became commercially successful and readily available in America in about 1850 and used widely starting around the 1870s. They had the added benefit of being good inhibitors against rust on iron and steel.

During the early decades of the 20th century, the use of pure zinc roofing and ornament decreased in use in the United States. It is now back on the upswing and gaining popularity in its pure form (99.95%) for building materials. Zinc is still used in alloys such as brass and nickel silver, and in the electroplating of steel as well. Today,

galvanized steel and pure zinc material, usually Double Locked Standing Seam panels, are used for roofing a variety of buildings. Creep has been reduced by the introduction of titanium in most architectural zinc available in North America. Galvanized nails and sheet metal ducts are also common.

## **Copper and Copper Alloys**

The “cupric” metals include copper and its alloys, especially bronze, an alloy of copper and tin, and brass, an alloy of copper and zinc. Copper is a very durable metal, withstanding corrosion when forming a green patina, copper sulfate. Sheet copper used as roofing is lighter than wooden shingles and much lighter than slate, tile, or lead. Roofing copper can be folded readily into waterproof seams, or shaped over curved frameworks for cupolas and domes.

The initial cost of copper was traditionally high, but its length of service more than compensated for the price. Copper could also be shaped to the bends and angles around chimneys and at roof edges and dormers. All nails, screws, bolts, and cleats used with sheet copper had to be made of copper or a copper alloy; otherwise “galvanic” action between the dissimilar metals would occur, causing deterioration.

Copper was also used for decorative purposes, including architectural ornaments or sculptures. A very famous example of this is the Statue of Liberty.

With aging it turns a deep light green color.

## **Nickel and Nickel Alloys**

Although somewhat rare, nickel has been used for plating architectural details. Nickel is most frequently used for building components in the form of alloys: nickel silver, Monel metal, and stainless steel.

Nickel silver was originally called “German Silver,” until World War I. It has been called “white brass” but probably should be termed “nickel brass,” because it generally contains 75% copper, 20% nickel, and 5% zinc. Different percentages result in a range of colors, including silvery-white, yellow, slight blue, green or pink. Nickel silver hardware was popular in the United States during the Art Deco and Depression Modern periods. Architects and designers preferred nickel silver because it could take and retain appropriate finishes, and it resisted corrosion.

Monel metal is an alloy of approximately two-thirds nickel and one-third copper. It is similar to platinum in color. Monel pioneered many of the present uses of stainless steel. The first architectural use of Monel was for roofing of the Pennsylvania Railroad Terminal in New York City in 1909. In 1936, the copper roof on the New York City Public Library at Fifth Avenue and 42nd Street was replaced with a Monel metal roof. Its advantages as a roofing material included its ability to be brazed, welded, or soldered in place to provide a watertight, continuous cover. Monel was popular during the Art Deco

periods. During World War II, however, large quantities of nickel and copper had to be diverted to the war effort and the supply of Monel was greatly reduced. Following the war, stainless steel and aluminium replaced Monel because of lower production costs.

## **Iron and Iron Alloys**

Iron has become an important architectural building component. It has been used in four common forms: wrought iron, cast iron, sheet iron, and steel.

Wrought iron was used for minor structural and decorative elements starting in the 18th century. Until the mid-19th century, the use of wrought iron in buildings was generally limited to small items such as tie rods, straps, nails, and hardware, or to decorative ironwork in balconies, railings fences and gates. Around 1850 its structural use became more widespread as iron mills began to roll rails, bulb-tees, and eventually I-beams. It was also used for decorative purposes, such as ornamental balconies or hardware. Since wrought iron is handmade, no two pieces are identical.

Cast iron was a major 19th century building material of the Industrial Revolution. Although brittle, it is remarkably strong in compression. It was frequently used for structural purposes, such as columns,, building fronts, domes and light courts. Decorative uses have included stairs, elevators, lintels, grilles, verandas, balconies, railings, fences, streetlights, and tombs. The Bradbury Building is one example of extensive decorative cast iron use. Today, cast iron is used for plumbing fixtures and piping in new construction, and its structural and decorative use is used occasionally through historic preservation practices.

Sheet iron can be subject to rapid corrosion, forming rust. Sheet iron was used throughout the 19th century, although it is not clear how widespread sheet iron roofs became. Pressed decorative sheet iron used for ceilings was frequently called a “tin ceiling,” although tin was generally not present for indoor uses.

Steel was introduced to the construction industry at the end of the 19th century. The development of structural steel in the mid-19th century allowed tall buildings to be constructed. Builders and manufacturers turned to steel, which was stronger than cast iron in compression and wrought iron in tension. when the Bessemer process was developed in England in 1856, and the open-hearth process was invented, steel was produced in a quantity that allowed it to be economical. Bridges, railroad companies, and skyscrapers were among the first large-scale uses of structural steel. Although iron and steel are not combustible, they lose strength in a fire if they are not protected from the heat. Almost all structural steel has to be “fireproofed” in some manner, utilizing a cladding of terra-cotta, tile, plaster- poured concrete, sprayed concrete, or sprayed insulation. Ferro concrete, also called reinforced concrete, was developed in the late 19th century when steel wire was added to concrete.

Decorative steels used in buildings include:

- Stainless steel, a chromium-nickel steel, developed between 1903 and 1912. Its most important property is its resistance to corrosion. It contains about 18% chromium and 8-12% nickel. Stainless steel is expensive, so it was used primarily as a nonstructural metal or where there is a high potential for corrosion. One of the most extensive early uses of stainless steel was in the Chrysler Building.
- Copper-bearing steels, containing from .15% to .25% copper, develop increased resistance to atmospheric corrosion, when compared to ordinary steel, by forming a protective oxide coating, having a uniform deep brown color and texture. Eero Saarinen experimented with the material in the Deere and Company building in 1964.

## Aluminum

Aluminum was not available at a reasonable price or in sufficient quantities for general architectural use until after the beginning of the 20th century. Architectural use of aluminum increased in the 1920s, mainly for decorative detailing. It was used for roofing, flashing, gutters, downspouts, wall panels, and spandrels. Art Deco designs frequently used aluminum for ornamental features. The first extensive use of aluminum in construction was the Empire State Building, where the entire tower portion is aluminum, as well as many decorative features, such as the entrances, elevator doors, ornamental trim, and some 6,000 window spandrels. Today, aluminum is used frequently in construction except major structural members.

## Mass finishing

**Mass finishing** is a group of manufacturing processes that allow large quantities of parts to be simultaneously finished. The goal of this type of finishing is to burnish, deburr, clean, radius, de-flash, descale, remove rust, polish, brighten, surface harden, prepare parts for further finishing, or break off die cast runners. The two main types of mass finishing are tumble finishing, also known as barrel finishing, and vibratory finishing. Both involve the use of a cyclical action to create grinding contact between surfaces. Sometimes the workpieces are finished against each other; however, usually a finishing medium is used. Mass finishing can be performed dry or wet; wet processes have liquid lubricants, cleaners, or abrasives, while dry processes do not. Cycle times can be as short as 10 minutes for nonferrous workpieces or as long as 2 hours for hardened steel.

Mass finishing processes can be configured as either batch systems, in which batches of workpieces are added, run, and removed before the next batch is run, or as continuous systems, in which the workpieces enter at one end and leave at the other end in the finished state. They may also be sequenced, which involves running the workpieces through multiple different mass finishing processes; usually, the finish becomes

progressively finer. Due to the random action of the processes, mass finishing is as much an art as it is a science.

## **Media**

Media are designed for four things:

### Cut

Media which cut can remove burrs and can smooth surfaces. As a carrier of abrasive grain, the large medium pieces effectively increase the impact force of the abrasive on the metal part to be cut, thereby improving the efficiency of the abrasive. Cutting media develop dull, matte surfaces.

### Luster

Some grades of medium are designed to promote luster on the surface of metal parts. These products are generally non-abrasive or have a very low degree of abrasiveness. They deburr by peening, rather than actually removing the burr. Media selection, therefore, will control the degree of surface luster, making the part bright and shiny or developing a very matte, dull surface characterized by a completely random scratch pattern, or anything in between.

### Part separation

A very important function of the medium is to separate parts during the deburring, cutting, surface improving or burnishing operations. The media:parts volume ratio is normally used to control the amount of part-on-part contact which will occur in a vibratory or tumble finishing operation. At low ratios, considerable part-on-part contact occurs, while at higher ratios part-on-part contact is limited.

### Surface scrubbing

Media have the unique ability to scrub surfaces and physically assist compounds in their cleaning function. Both abrasive and non-abrasive media are effective in this. They can remove organic soils, scale, and other inorganic residues.

Media come in a wide range of materials in order to fulfill various needs.

### Aluminum media

Aluminium media are typically cast parts and are available in a wide variety of shapes and sizes. Aluminum scrubs parts and can work in conjunction with cleaning compounds to clean parts. Since aluminum is fairly nonabrasive it tends to remove surface impurities without affecting the part's surface qualities. Its cost is typically higher than other cast media. Wear rates are lower than ceramic but higher than steel media.

### Preformed ceramic media

Ceramic media are manufactured by mixing clay-like materials and water with abrasives, forming the mud into shapes, drying the shapes, and firing them at high temperatures to vitrify the binder. Many of these binders are porcelain-like in nature. Variability in these products occur both with the type of binder used, firing temperatures, the amount, size and type of abrasive grains they contain, and their uniformity of firing. This type of media today is the general workhorse of

mass finishing systems and is the type of medium generally used, because of its availability in a variety of shapes and sizes, low cost, and low wear rate.

#### Preformed resin-bonded media

Plastic or resin-bonded media utilize a wider range of abrasive types and sizes than preformed ceramics. The most popular grades are those using quartz as an abrasive. Aluminum oxide, silicon carbide and other abrasives are also used. Usually, low-cost polyester resins are employed as the binder and the various shapes are produced by casting. Resin bonded media is good for preparing a metal surface for plating.

#### Steel

Case hardened, stress-relieved steel preformed shapes are available in a variety of sizes and configurations. Balls, balls with flat spots, ovoids (footballs), diagonally cut wire similar to angle-cut cylinders, ball cones and cones (both of which are different than the general concept of cones) and pins are the most commonly used. Steel media weigh approximately 300 pounds per cubic foot and are expensive for initial installation, but, because of their minimal attrition rate and extreme cleanliness, are being more widely used for light deburring applications and cleaning. Compounds are available to keep steel burnishing media clean and bright for extended periods.

#### Synthetic random-shaped media

The most popular synthetic random media is fused aluminum oxide, which is available in a number of grades. The more loosely bound, coarse-grained materials are characterized by fast cut and high depreciation rates. Because of the dark color of fused aluminum oxide, the soil generated by this material is excessive in many applications. Fine-grained fused aluminum oxide is generally employed for burnishing and in this respect is unexcelled in many applications with the possible exception of steel. Where some light cutting is required, fine-grained aluminum oxide can develop a better luster on stainless steels and other hard surfaces than can be achieved with steel burnishing media.

#### Natural random-shaped media

River rock, granite, quartz, limestone, emery and other naturally occurring abrasive materials are also used in vibratory and tumble finishing applications. In general, these media are not very efficient in vibratory equipment because of their high attrition rates.

#### Cobmeal, walnut-shell flour, and related materials

These are used for drying applications because of the natural ability of these materials to absorb water from metal surfaces. These can also be blended with abrasives and used for fine-polishing applications in vibratory, barrel, or spindle finishing equipment.

#### Other

Shoe pegs, leather, carpet tacks, and many other solid materials have been used at one time or another in tumble or vibratory finishing for certain applications.

## ***Compounds***

Compounds are added to mass finishing processes to assist in deburring, burnishing, cutting, cleaning, descaling, and inhibiting corrosion. They may be liquids or dry powders. They are usually broken up into four types: deburring and finishing, burnishing, cleaning, and water stabilizing.

### Deburring and finishing

These compounds are mainly designed to suspend the small particles created when deburring and abrading parts. They are also designed to keep workpieces clean and inhibit corrosion.

### Burnishing

Burnishing compounds are designed to enhance brightness and to develop certain colors after mass finishing.

### Cleaning

These compounds are usually dilute acids or soaps designed to remove soil, grease, or oil from the incoming parts. They also provide corrosion resistance for ferrous and non-ferrous parts.

### Water stabilizers

These are used in conjunction with water to maintain a consistent water hardness and level of metal ions. This helps ensure consistent results from batch to batch.

## Chapter-9

# Abrasive

An **abrasive** is a material, often a mineral, that is used to shape or finish a workpiece through rubbing which leads to part of the workpiece being worn away. While finishing a material often means polishing it to gain a smooth, reflective surface it can also involve roughening as in satin, matte or beaded finishes.

Abrasives are extremely commonplace and are used very extensively in a wide variety of industrial, domestic, and technological applications. This gives rise to a large variation in the physical and chemical composition of abrasives as well as the shape of the abrasive. Common uses for abrasives include grinding, polishing, buffing, honing, cutting, drilling, sharpening, lapping, and sanding.

Files act by abrasion but are not classed as abrasives as they are a shaped bar of metal. However, diamond files are a form of coated abrasive (as they are metal rods coated with diamond powder).

### ***Mechanics of abrasion***

Abrasives generally rely upon a difference in hardness between the abrasive and the material being worked upon, the abrasive being the harder of the two substances. However, this is not necessary as any two solid materials that repeatedly rub against each other will tend to wear each other away (such as softer shoe soles wearing away wooden or stone steps over decades or centuries or glaciers abrading stone valleys).

Typically, materials used as abrasives are either hard minerals (rated at 7 or above on Mohs scale of mineral hardness) or are synthetic stones, some of which may be chemically and physically identical to naturally occurring minerals but which cannot be called minerals as they did not arise naturally. (While useful for comparative purposes, the Mohs scale is of limited value to materials engineers as it is an arbitrary, ordinal, irregular scale.) Diamond, a common abrasive, for instance occurs both naturally and is industrially produced, as is corundum which occurs naturally but which is nowadays more commonly manufactured from bauxite. However, even softer minerals like calcium carbonate are used as abrasives, such as "polishing agents" in toothpaste.



Grit size ranging from 2 mm (the large grain) (about F 10 using FEPA standards) to about 40 micrometres (about F 240 or P 360).

These minerals are either crushed or are already of a sufficiently small size (anywhere from macroscopic grains as large as about 2 mm to microscopic grains about 0.001 mm in diameter) to permit their use as an abrasive. These grains, commonly called grit, have rough edges, often terminating in points which will decrease the surface area in contact and increase the localised contact pressure. The abrasive and the material to be worked are brought into contact while in relative motion to each other. Force applied through the grains causes fragments of the worked material to break away while simultaneously smoothing the abrasive grain and/or causing the grain to work loose from the rest of the abrasive.

Some factors which will affect how quickly a substance is abraded include:

- Difference in hardness between the two substances: a much harder abrasive will cut faster and deeper
- Grain size (grit size): larger grains will cut faster as they also cut deeper
- Adhesion between grains, between grains and backing, between grains and matrix: determines how quickly grains are lost from the abrasive and how soon fresh grains, if present, are exposed

- Contact force: more force will cause faster abrasion
- Loading: worn abrasive and cast off work material tends to fill spaces between abrasive grains so reducing cutting efficiency while increasing friction
- Use of lubricant/coolant/metalworking fluid: Can carry away swarf (preventing loading), transport heat (which may affect the physical properties of the workpiece or the abrasive), decrease friction (with the substrate or matrix), suspend worn work material and abrasives allowing for a finer finish, conduct stress to the workpiece.

## ***Abrasive minerals***

Abrasives may be classified as either natural or synthetic. When discussing sharpening stones, natural stones have long been considered superior but advances in material technology are seeing this distinction become less distinct. Many synthetic abrasives are effectively identical to a natural mineral, differing only in that the synthetic mineral has been manufactured rather than been mined. Impurities in the natural mineral may make it less effective.

Some naturally occurring abrasives are:

- Calcite (calcium carbonate)
- Emery (impure corundum)
- Diamond dust (synthetic diamonds are used extensively)
- Novaculite
- Pumice dust
- Rouge
- Sand

Some abrasive minerals (such as zirconia alumina) occur naturally but are sufficiently rare or sufficiently more difficult/costly to obtain such that a synthetic stone is used industrially. These and other artificial abrasives include:

- Borazon (cubic boron nitride or CBN)
- Ceramic
- Ceramic aluminium oxide
- Ceramic iron oxide
- Corundum (alumina or aluminium oxide)
- Dry ice
- Glass powder
- Steel abrasive
- Silicon carbide (carborundum)
- Zirconia alumina

## ***Manufactured abrasives***

Abrasives are shaped for various purposes. Natural abrasives are often sold as dressed stones, usually in the form of a rectangular block. Both natural and synthetic abrasives are commonly available in a wide variety of shapes, often coming as bonded or coated abrasives, including blocks, belts, discs, wheels, sheets, rods and loose grains.

### **Bonded abrasives**



Assorted grinding wheels as examples of bonded abrasives.



A grinding wheel with a reservoir to hold water as a lubricant and coolant.

A **bonded abrasive** is composed of an abrasive material contained within a matrix, although very fine aluminium oxide abrasive may comprise sintered material. This matrix is called a binder and is often a clay, a resin, a glass or a rubber. This mixture of binder and abrasive is typically shaped into blocks, sticks, or wheels. The most usual abrasive used is aluminium oxide. Also common are silicon carbide, tungsten carbide and garnet. Artificial sharpening stones are often a bonded abrasive and are readily available as a two sided block, each side being a different grade of grit.

Grinding wheels are cylinders that are rotated at high speed. While once worked with a foot pedal or hand crank, the introduction of electric motors has made it necessary to construct the wheel to withstand greater radial stress to prevent the wheel flying apart as

it spins. Similar issues arise with cutting wheels which are often structurally reinforced with impregnated fibres. High relative speed between abrasive and workpiece often makes necessary the use of a lubricant of some kind. Traditionally they were called coolants as they were used to prevent frictional heat build up which could damage the workpiece (such as ruining the temper of a blade). Some research suggests that the heat transport property of a lubricant is less important when dealing with metals as the metal will quickly conduct heat from the work surface. More important are their effects upon lessening tensile stresses while increasing some compressive stresses and reducing "thermal and mechanical stresses during chip formation".

Various shapes are also used as heads on rotary tools used in precision work, such as scale modelling.

Bonded abrasives need to be trued and dressed after they are used. Dressing is cleaning the waste material (swarf and loose abrasive) from the surface and exposing fresh grit. Depending upon the abrasive and how it was used, dressing may involve the abrasive being simply placed under running water and brushed with a stiff brush for a soft stone or the abrasive being ground against another abrasive, such as aluminium oxide used to dress a grinding wheel.

Truing is restoring the abrasive to its original surface shape. Wheels and stones tend to wear unevenly, leaving the cutting surface no longer flat (said to be "dished out" if it is meant to be a flat stone) or no longer the same diameter across the cutting face. This will lead to uneven abrasion and other difficulties.

## Coated abrasives

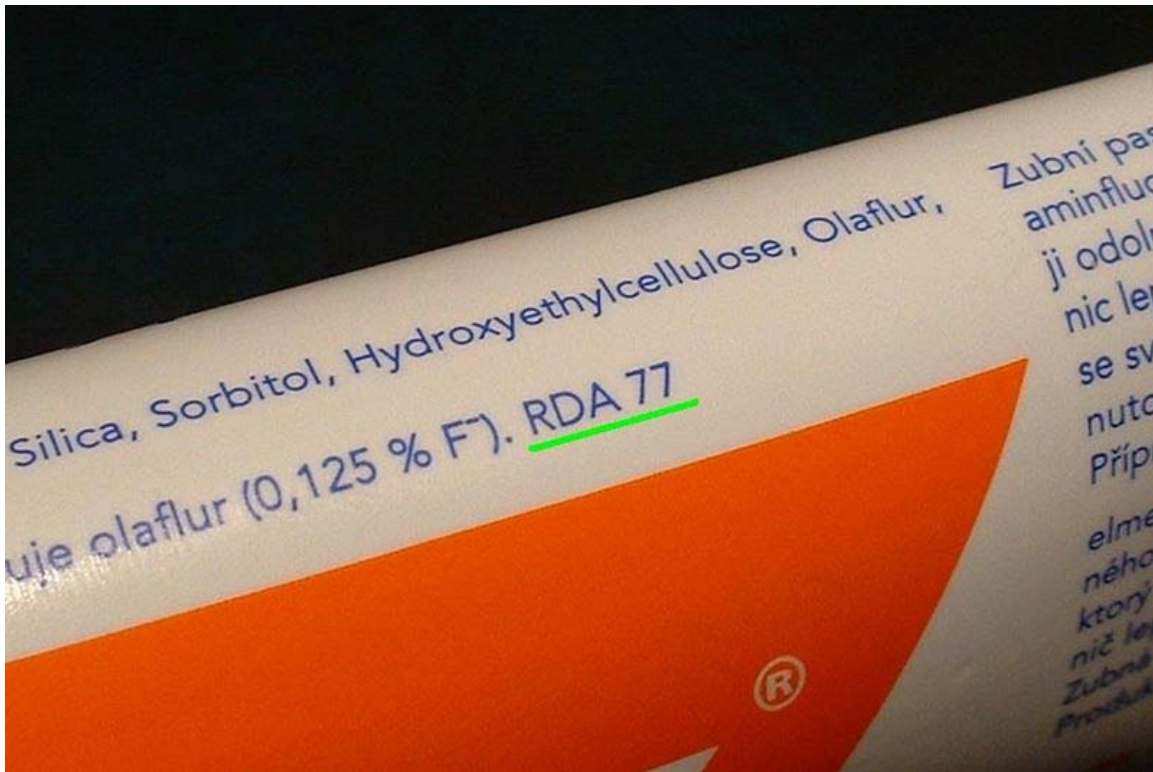


A German sandpaper showing its backing and FEPA grit size.

A *coated abrasive* comprises an abrasive fixed to a backing material such as paper, cloth, rubber, resin, polyester or even metal, many of which are flexible. Sandpaper is a very common coated abrasive. Coated abrasives are commonly the same minerals as are used for bonded abrasives. A bonding agent (often some sort of adhesive or resin) is applied to the backing to provide a flat surface to which the grit is then subsequently adhered. A woven backing may also use a filler agent (again, often a resin) to provide additional resilience.

Coated abrasives may be shaped for use in rotary and orbital sanders, for wrapping around sanding blocks, as handpads, as closed loops for use on belt grinders, as striking surfaces on matchboxes, on diamond plates and diamond steels. Diamond tools, though for cutting, are often abrasive in nature.

## Other abrasives and their uses



Here the abrasiveness of toothpaste is detailed by its Relative Dentin Abrasivity (RDA)

Sand, glass beads, metal pellets copper slag and dry ice may all be used for a process called sandblasting (or similar, such as the use of glass beads which is "bead blasting"). Dry ice will sublimate leaving behind no residual abrasive.

Cutting compound used on automotive paint is an example of an abrasive suspended in a liquid, paste or wax, as are some polishing liquids for silverware and optical media. The liquid, paste or wax acts as a binding agent that keeps the abrasive attached to the cloth which is used to as a backing to move the abrasive across the workpiece. On cars in particular, wax may serve as both a protective agent by preventing exposure of the paint of metal to air and also act as an optical filler to make scratches less noticeable.

Toothpaste contains calcium carbonate or silica as a "polishing agent" to remove plaque and other matter from teeth as the hardness of calcium carbonate is less than that of tooth enamel but more than that of the contaminating agent.

Very fine rouge powder was commonly used for grinding glass, being somewhat replaced by modern ceramics, and is still used in jewellery making for a highly reflective finish.

Cleaning products may also contain abrasives suspended in a paste or cream. They are chosen to be reasonably safe on some linoleum, tile, metal or stone surfaces. However, many laminate surfaces and ceramic topped stoves are easily damaged by these abrasive

compounds. Even ceramic/pottery tableware or cookware can damage these surfaces, particularly the bottom of the tableware which is often unglazed in part or in whole and acts as simply another bonded abrasive.

Metal pots and stoves are often scoured with abrasive cleaners, typically in the form of the aforementioned cream or paste or of steel wool and non woven scouring pads which holds fine grits abrasives.

Human skin is also subjected to abrasion in the form of exfoliation. Abrasives for this can be much softer and more exotic than for other purposes and may include things like almond and oatmeal. Dermabrasion and microdermabrasion are now rather commonplace cosmetic procedures which use mineral abrasives.

Scratched compact discs and DVDs may sometimes be repaired through buffing with a very fine compound, the principle being that a multitude of small scratches will be more optically transparent than a single large scratch. However, this does take some skill and will eventually cause the protective coating of the disc to be entirely eroded (especially if the original scratch is deep), after which the data surface will be destroyed if abrasion continues.

### ***Choice of abrasive***

The shape, size and nature of the workpiece and the desired finish will influence the choice of the abrasive used. A bonded abrasive grind wheel may be used to commercially sharpen a knife (producing a hollow grind), but an individual may then sharpen the same knife with a natural sharpening stone or an even flexible coated abrasive (like a sandpaper) stuck to a soft, non-slip surface to make achieving a convex grind easier. Similarly, a brass mirror may be cut with a bonded abrasive, have its surface flattened with a coated abrasive to achieve a basic shape, and then have finer grades of abrasive successively applied culminating in a wax paste impregnated with rouge to leave a sort of "grainless finish" called, in this case, a "mirror finish".

Also, different shapes of adhesive may make it harder to abrade certain areas of the workpiece. Health hazards can arise from any dust produced (which may be ameliorated through the use of a lubricant) which could lead to silicosis (when the abrasive or workpiece is a silicate) and the choice of any lubricant. Besides water, oils are the most common lubricants. These may present inhalation hazards, contact hazards and, as friction necessarily produces heat, flammable material hazards.

An abrasive which is too hard or too coarse can remove too much material or leave undesired scratch marks. Besides being unsightly, scratching can have other, more serious effects. Excessive abrasion or the presence of scratches may:

- diminish or destroy usefulness (as in the case of scratched optics and compact discs or a dull knife);
- trap dirt, water, or other material;

- increase surface area (permitting greater chemical reactivity such as increased rusting which is also affected by matter caught in scratches);
- erode or penetrate a coating (such as a paint or a chemical or wear resistant coating);
- overly quickly cause an object to wear away (such as a blade or a gemstone);
- increase friction (as in jeweled bearings and pistons).

A finer or softer abrasive will tend to leave much finer scratch marks which may even be invisible to the naked eye (a "grainless finish"); a softer abrasive may not even significantly abrade a certain object. A softer or finer abrasive will take longer to cut as tends to cut less deeply than a coarser, harder material. Also, the softer abrasive may become less effective more quickly as the abrasive is itself abraded. This allows fine abrasives to be used in the polishing of metal and lenses where the series of increasingly fine scratches tends to take on a much more shiny or reflective appearance or greater transparency. Very fine abrasives may be used to coat the strop for a cut-throat razors, however, the purpose of stropping is not to abrade material but to straighten the burr on an edge. The final stage of sharpening Japanese swords is called polishing and may be a form of superfinishing.

Different chemical or structural modifications may be made to alter the cutting properties of the abrasive.

Other very important considerations are price and availability. Diamond, for a long time considered the hardest substance in existence, is actually softer than fullerite and even harder aggregated diamond nanorods, both of which have been synthesised in laboratories but no commercial process has yet been developed. Diamond itself is expensive due to scarcity in nature and the cost of synthesising it. Bauxite is a very common ore which, along with corundum's reasonably high hardness, contributes to corundum's status as a common, inexpensive abrasive.

Thought must be given to the desired task about using an appropriately hard abrasive. At one end, using an excessively hard abrasive wastes money by wearing it down when a cheaper, less hard abrasive would suffice. At the other end, if too soft, abrasion does not take place in a timely fashion, effectively wasting the abrasive as well as any accruing costs associated with loss of time.

### ***Other instances of abrasion***

Aside from the aforementioned uses of shaping and finishing, abrasives may also be used to prepare surfaces for application of some sort of paint or adhesive. An excessively smooth surface may prevent paint and adhesives from adhering as strongly as an irregular surface could allow. Inflatable tyre repair kits (which, on bicycles particularly, are actually patches for the inner tube rather than the tyre) require use of an abrasive so that the self-vulcanising cement will stick strongly.

Inadvertently, people who use knives on glass or metal cutting boards are abrading their knife blades. The pressure at the knife edge can easily create microscopic (or even macroscopic) cuts in the board. This cut is a ready source of abrasive material as well as a channel full of this abrasive through which the edge slides. For this reason—without regard for the health benefits—wooden boards are much more desirable. A similar occurrence arises with glass-cutters. Glass-cutters have circular blades that are designed to roll not slide. They should never retrace an already effected cut.

Undesired abrasion may result from the presence of carbon in internal combustion engines. While smaller particles are readily transported by the lubrication system, larger carbon particles may abrade components with close tolerances. The carbon arises from the excessive heating of engine oil or from incomplete combustion. This soot may contain fullerenes which are noted for their extreme hardness—and small size and limited quantity which would tend to limit their effect.

## Chapter-10

# Welding



Gas metal arc welding

**Welding** is a fabrication or sculptural process that joins materials, usually metals or thermoplastics, by causing coalescence. This is often done by melting the workpieces and adding a filler material to form a pool of molten material (the *weld pool*) that cools to become a strong joint, with pressure sometimes used in conjunction with heat, or by itself, to produce the weld. This is in contrast with soldering and brazing, which involve melting a lower-melting-point material between the workpieces to form a bond between them, without melting the workpieces.

Many different energy sources can be used for welding, including a gas flame, an electric arc, a laser, an electron beam, friction, and ultrasound. While often an industrial process, welding can be done in many different environments, including open air, under water and in outer space. Regardless of location, welding remains dangerous, and precautions are taken to avoid burns, electric shock, eye damage, poisonous fumes, and overexposure to ultraviolet light.

Until the end of the 19th century, the only welding process was forge welding, which blacksmiths had used for centuries to join iron and steel by heating and hammering them. Arc welding and oxyfuel welding were among the first processes to develop late in the century, and resistance welding followed soon after. Welding technology advanced quickly during the early 20th century as World War I and World War II drove the demand for reliable and inexpensive joining methods. Following the wars, several modern welding techniques were developed, including manual methods like shielded metal arc welding, now one of the most popular welding methods, as well as semi-automatic and automatic processes such as gas metal arc welding, submerged arc welding, flux-cored arc welding and electroslag welding. Developments continued with the invention of laser beam welding and electron beam welding in the latter half of the century. Today, the science continues to advance. Robot welding is becoming more commonplace in industrial settings, and researchers continue to develop new welding methods and gain greater understanding of weld quality and properties.

## ***History***



The iron pillar of Delhi

The history of joining metals goes back several millennia, with the earliest examples of welding from the Bronze Age and the Iron Age in Europe and the Middle East. Welding was used in the construction of the iron pillar in Delhi, India, erected about 310 AD and weighing 5.4 metric tons.

The Middle Ages brought advances in forge welding, in which blacksmiths pounded heated metal repeatedly until bonding occurred. In 1540, Vannoccio Biringuccio published *De la pirotechnia*, which includes descriptions of the forging operation.

Renaissance craftsmen were skilled in the process, and the industry continued to grow during the following centuries.

In 1802, Russian scientist Vasily Petrov discovered the electric arc and subsequently proposed its possible practical applications, including welding. In 1881–82 a Russian inventor Nikolai Benardos created the first electric arc welding method known as carbon arc welding, using carbon electrodes. The advances in arc welding continued with the invention of metal electrodes in the late 1800s by a Russian, Nikolai Slavyanov (1888), and an American, C. L. Coffin (1890). Around 1900, A. P. Strohmenger released a coated metal electrode in Britain, which gave a more stable arc. In 1905 Russian scientist Vladimir Mitkevich proposed the usage of three-phase electric arc for welding. In 1919, alternating current welding was invented by C. J. Holslag but did not become popular for another decade.

Resistance welding was also developed during the final decades of the 19th century, with the first patents going to Elihu Thomson in 1885, who produced further advances over the next 15 years. Thermite welding was invented in 1893, and around that time another process, oxyfuel welding, became well established. Acetylene was discovered in 1836 by Edmund Davy, but its use was not practical in welding until about 1900, when a suitable blowtorch was developed. At first, oxyfuel welding was one of the more popular welding methods due to its portability and relatively low cost. As the 20th century progressed, however, it fell out of favor for industrial applications. It was largely replaced with arc welding, as metal coverings (known as flux) for the electrode that stabilize the arc and shield the base material from impurities continued to be developed.

World War I caused a major surge in the use of welding processes, with the various military powers attempting to determine which of the several new welding processes would be best. The British primarily used arc welding, even constructing a ship, the *Fulagar*, with an entirely welded hull. Arc welding was first applied to aircraft during the war as well, as some German airplane fuselages were constructed using the process. Also noteworthy is the first welded road bridge in the world, designed by Stefan Bryła of the Warsaw University of Technology in 1927, and built across the river Słudwia Maurzyce near Łowicz, Poland in 1929.

During the 1920s, major advances were made in welding technology, including the introduction of automatic welding in 1920, in which electrode wire was fed continuously. Shielding gas became a subject receiving much attention, as scientists attempted to protect welds from the effects of oxygen and nitrogen in the atmosphere. Porosity and brittleness were the primary problems, and the solutions that developed included the use of hydrogen, argon, and helium as welding atmospheres. During the following decade, further advances allowed for the welding of reactive metals like aluminum and magnesium. This in conjunction with developments in automatic welding, alternating current, and fluxes fed a major expansion of arc welding during the 1930s and then during World War II.

During the middle of the century, many new welding methods were invented. 1930 saw the release of stud welding, which soon became popular in shipbuilding and construction. Submerged arc welding was invented the same year and continues to be popular today. In 1932 a Russian, Konstantin Khrenov successfully implemented the first underwater electric arc welding. Gas tungsten arc welding, after decades of development, was finally perfected in 1941, and gas metal arc welding followed in 1948, allowing for fast welding of non-ferrous materials but requiring expensive shielding gases. Shielded metal arc welding was developed during the 1950s, using a flux-coated consumable electrode, and it quickly became the most popular metal arc welding process. In 1957, the flux-cored arc welding process debuted, in which the self-shielded wire electrode could be used with automatic equipment, resulting in greatly increased welding speeds, and that same year, plasma arc welding was invented. Electroslag welding was introduced in 1958, and it was followed by its cousin, electrogas welding, in 1961. In 1953 the Soviet scientist N. F. Kazakov proposed the diffusion bonding method.

Other recent developments in welding include the 1958 breakthrough of electron beam welding, making deep and narrow welding possible through the concentrated heat source. Following the invention of the laser in 1960, laser beam welding debuted several decades later, and has proved to be especially useful in high-speed, automated welding. In 1991 friction stir welding was invented in the UK and found high-quality applications all over the world. All of these three new processes continue to be quite expensive due the high cost of the necessary equipment, and this has limited their applications.

## **Processes**

### **Arc**

These processes use a welding power supply to create and maintain an electric arc between an electrode and the base material to melt metals at the welding point. They can use either direct (DC) or alternating (AC) current, and consumable or non-consumable electrodes. The welding region is sometimes protected by some type of inert or semi-inert gas, known as a shielding gas, and filler material is sometimes used as well.

### **Power supplies**

To supply the electrical energy necessary for arc welding processes, a number of different power supplies can be used. The most common welding power supplies are constant current power supplies and constant voltage power supplies. In arc welding, the length of the arc is directly related to the voltage, and the amount of heat input is related to the current. Constant current power supplies are most often used for manual welding processes such as gas tungsten arc welding and shielded metal arc welding, because they maintain a relatively constant current even as the voltage varies. This is important because in manual welding, it can be difficult to hold the electrode perfectly steady, and as a result, the arc length and thus voltage tend to fluctuate. Constant voltage power supplies hold the voltage constant and vary the current, and as a result, are most often used for automated welding processes such as gas metal arc welding, flux cored arc

welding, and submerged arc welding. In these processes, arc length is kept constant, since any fluctuation in the distance between the wire and the base material is quickly rectified by a large change in current. For example, if the wire and the base material get too close, the current will rapidly increase, which in turn causes the heat to increase and the tip of the wire to melt, returning it to its original separation distance.

The type of current used in arc welding also plays an important role in welding. Consumable electrode processes such as shielded metal arc welding and gas metal arc welding generally use direct current, but the electrode can be charged either positively or negatively. In welding, the positively charged anode will have a greater heat concentration, and as a result, changing the polarity of the electrode has an impact on weld properties. If the electrode is positively charged, the base metal will be hotter, increasing weld penetration and welding speed. Alternatively, a negatively charged electrode results in more shallow welds. Nonconsumable electrode processes, such as gas tungsten arc welding, can use either type of direct current, as well as alternating current. However, with direct current, because the electrode only creates the arc and does not provide filler material, a positively charged electrode causes shallow welds, while a negatively charged electrode makes deeper welds. Alternating current rapidly moves between these two, resulting in medium-penetration welds. One disadvantage of AC, the fact that the arc must be re-ignited after every zero crossing, has been addressed with the invention of special power units that produce a square wave pattern instead of the normal sine wave, making rapid zero crossings possible and minimizing the effects of the problem.

## **Processes**

One of the most common types of arc welding is shielded metal arc welding (SMAW); it is also known as manual metal arc welding (MMA) or stick welding. Electric current is used to strike an arc between the base material and consumable electrode rod, which is made of steel and is covered with a flux that protects the weld area from oxidation and contamination by producing carbon dioxide (CO<sub>2</sub>) gas during the welding process. The electrode core itself acts as filler material, making a separate filler unnecessary.



Shielded metal arc welding

The process is versatile and can be performed with relatively inexpensive equipment, making it well suited to shop jobs and field work. An operator can become reasonably proficient with a modest amount of training and can achieve mastery with experience. Weld times are rather slow, since the consumable electrodes must be frequently replaced and because slag, the residue from the flux, must be chipped away after welding. Furthermore, the process is generally limited to welding ferrous materials, though special electrodes have made possible the welding of cast iron, nickel, aluminum, copper, and other metals.

Gas metal arc welding (GMAW), also known as metal inert gas or MIG welding, is a semi-automatic or automatic process that uses a continuous wire feed as an electrode and an inert or semi-inert gas mixture to protect the weld from contamination. Since the electrode is continuous, welding speeds are greater for GMAW than for SMAW.

A related process, flux-cored arc welding (FCAW), uses similar equipment but uses wire consisting of a steel electrode surrounding a powder fill material. This cored wire is more expensive than the standard solid wire and can generate fumes and/or slag, but it permits even higher welding speed and greater metal penetration.

Gas tungsten arc welding (GTAW), or tungsten inert gas (TIG) welding, is a manual welding process that uses a nonconsumable tungsten electrode, an inert or semi-inert gas mixture, and a separate filler material. Especially useful for welding thin materials, this

method is characterized by a stable arc and high quality welds, but it requires significant operator skill and can only be accomplished at relatively low speeds.

GTAW can be used on nearly all weldable metals, though it is most often applied to stainless steel and light metals. It is often used when quality welds are extremely important, such as in bicycle, aircraft and naval applications. A related process, plasma arc welding, also uses a tungsten electrode but uses plasma gas to make the arc. The arc is more concentrated than the GTAW arc, making transverse control more critical and thus generally restricting the technique to a mechanized process. Because of its stable current, the method can be used on a wider range of material thicknesses than can the GTAW process and it is much faster. It can be applied to all of the same materials as GTAW except magnesium, and automated welding of stainless steel is one important application of the process. A variation of the process is plasma cutting, an efficient steel cutting process.

Submerged arc welding (SAW) is a high-productivity welding method in which the arc is struck beneath a covering layer of flux. This increases arc quality, since contaminants in the atmosphere are blocked by the flux. The slag that forms on the weld generally comes off by itself, and combined with the use of a continuous wire feed, the weld deposition rate is high. Working conditions are much improved over other arc welding processes, since the flux hides the arc and almost no smoke is produced. The process is commonly used in industry, especially for large products and in the manufacture of welded pressure vessels. Other arc welding processes include atomic hydrogen welding, electroslag welding, electrogas welding, and stud arc welding.

## **Gas**

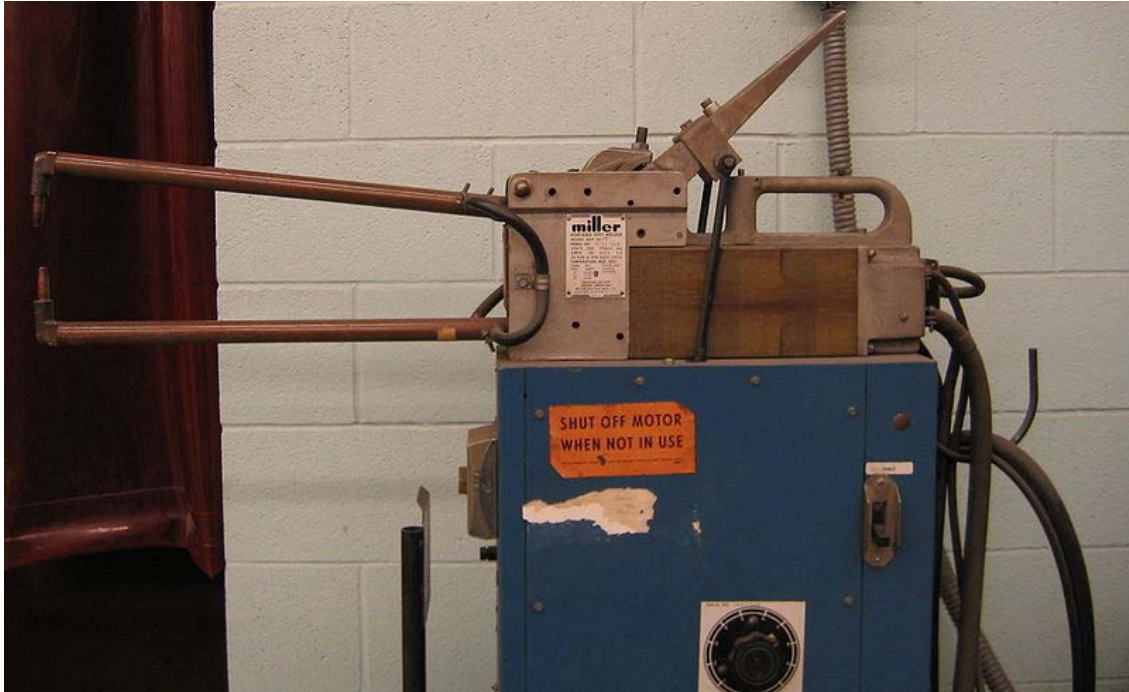
The most common gas welding process is oxyfuel welding, also known as oxyacetylene welding. It is one of the oldest and most versatile welding processes, but in recent years it has become less popular in industrial applications. It is still widely used for welding pipes and tubes, as well as repair work.

The equipment is relatively inexpensive and simple, generally employing the combustion of acetylene in oxygen to produce a welding flame temperature of about 3100 °C. The flame, since it is less concentrated than an electric arc, causes slower weld cooling, which can lead to greater residual stresses and weld distortion, though it eases the welding of high alloy steels. A similar process, generally called oxyfuel cutting, is used to cut metals.

## **Resistance**

Resistance welding involves the generation of heat by passing current through the resistance caused by the contact between two or more metal surfaces. Small pools of molten metal are formed at the weld area as high current (1000–100,000 A) is passed through the metal. In general, resistance welding methods are efficient and cause little

pollution, but their applications are somewhat limited and the equipment cost can be high.



Spot welder

Spot welding is a popular resistance welding method used to join overlapping metal sheets of up to 3 mm thick. Two electrodes are simultaneously used to clamp the metal sheets together and to pass current through the sheets. The advantages of the method include efficient energy use, limited workpiece deformation, high production rates, easy automation, and no required filler materials. Weld strength is significantly lower than with other welding methods, making the process suitable for only certain applications. It is used extensively in the automotive industry—ordinary cars can have several thousand spot welds made by industrial robots. A specialized process, called shot welding, can be used to spot weld stainless steel.

Like spot welding, seam welding relies on two electrodes to apply pressure and current to join metal sheets. However, instead of pointed electrodes, wheel-shaped electrodes roll along and often feed the workpiece, making it possible to make long continuous welds. In the past, this process was used in the manufacture of beverage cans, but now its uses are more limited. Other resistance welding methods include butt welding, flash welding, projection welding, and upset welding.

### **Energy beam**

Energy beam welding methods, namely laser beam welding and electron beam welding, are relatively new processes that have become quite popular in high production

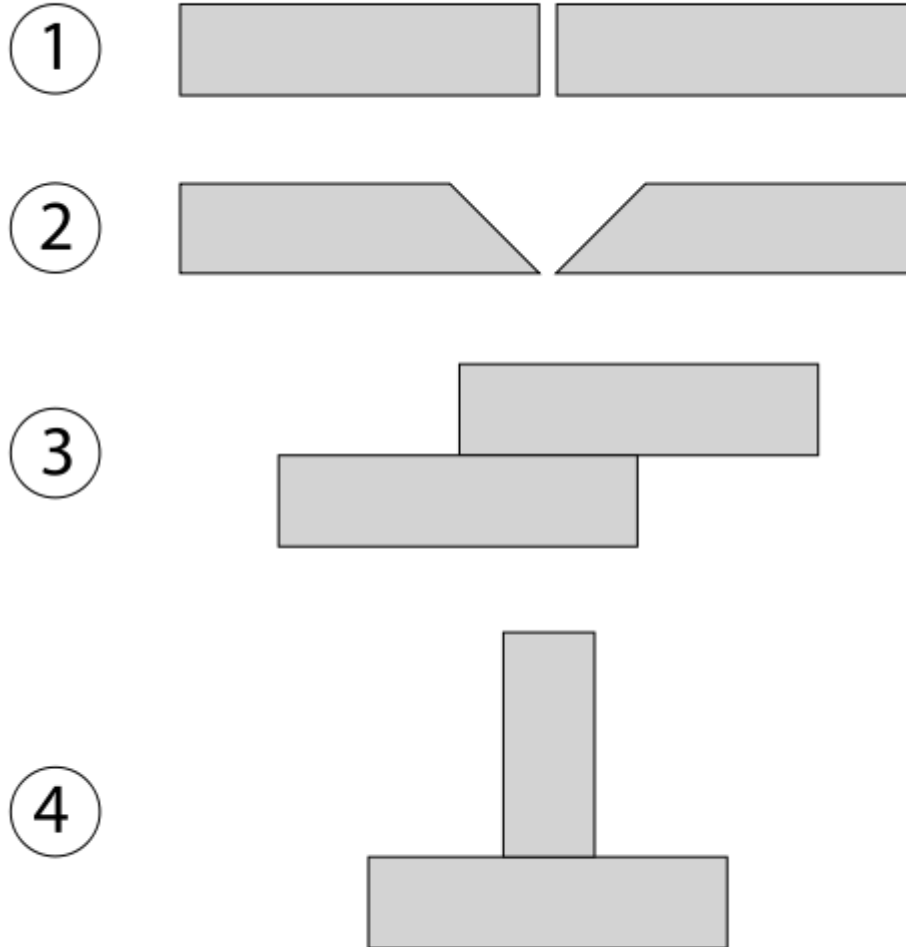
applications. The two processes are quite similar, differing most notably in their source of power. Laser beam welding employs a highly focused laser beam, while electron beam welding is done in a vacuum and uses an electron beam. Both have a very high energy density, making deep weld penetration possible and minimizing the size of the weld area. Both processes are extremely fast, and are easily automated, making them highly productive. The primary disadvantages are their very high equipment costs (though these are decreasing) and a susceptibility to thermal cracking. Developments in this area include laser-hybrid welding, which uses principles from both laser beam welding and arc welding for even better weld properties, and X-ray welding.

## **Solid-state**

Like the first welding process, forge welding, some modern welding methods do not involve the melting of the materials being joined. One of the most popular, ultrasonic welding, is used to connect thin sheets or wires made of metal or thermoplastic by vibrating them at high frequency and under high pressure. The equipment and methods involved are similar to that of resistance welding, but instead of electric current, vibration provides energy input. Welding metals with this process does not involve melting the materials; instead, the weld is formed by introducing mechanical vibrations horizontally under pressure. When welding plastics, the materials should have similar melting temperatures, and the vibrations are introduced vertically. Ultrasonic welding is commonly used for making electrical connections out of aluminum or copper, and it is also a very common polymer welding process.

Another common process, explosion welding, involves the joining of materials by pushing them together under extremely high pressure. The energy from the impact plasticizes the materials, forming a weld, even though only a limited amount of heat is generated. The process is commonly used for welding dissimilar materials, such as the welding of aluminum with steel in ship hulls or compound plates. Other solid-state welding processes include friction welding (including friction stir welding), electromagnetic pulse welding, co-extrusion welding, cold welding, diffusion welding, exothermic welding, high frequency welding, hot pressure welding, induction welding, and roll welding.

## Geometry

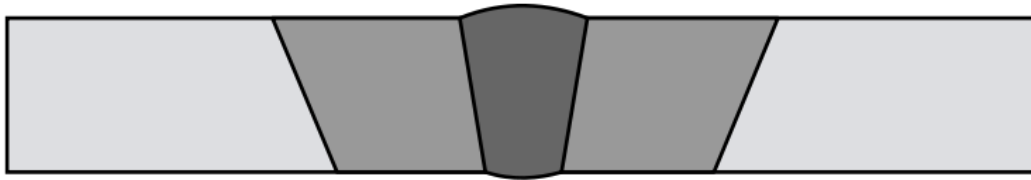


Common welding joint types – (1) Square butt joint, (2) V butt joint, (3) Lap joint, (4) T-joint

Welds can be geometrically prepared in many different ways. The five basic types of weld joints are the butt joint, lap joint, corner joint, edge joint, and T-joint (a variant of this last is the cruciform joint). Other variations exist as well—for example, double-V preparation joints are characterized by the two pieces of material each tapering to a single center point at one-half their height. Single-U and double-U preparation joints are also fairly common—instead of having straight edges like the single-V and double-V preparation joints, they are curved, forming the shape of a U. Lap joints are also

commonly more than two pieces thick—depending on the process used and the thickness of the material, many pieces can be welded together in a lap joint geometry.

Many welding processes require the use of a particular joint designs; for example, resistance spot welding, laser beam welding, and electron beam welding are most frequently performed on lap joints. Other welding methods, like shielded metal arc welding, are extremely versatile and can weld virtually any type of joint. Some processes can also be used to make multipass welds, in which one weld is allowed to cool, and then another weld is performed on top of it. This allows for the welding of thick sections arranged in a single-V preparation joint, for example.



The cross-section of a welded butt joint, with the darkest gray representing the weld or fusion zone, the medium gray the heat-affected zone, and the lightest gray the base material.

After welding, a number of distinct regions can be identified in the weld area. The weld itself is called the fusion zone—more specifically, it is where the filler metal was laid during the welding process. The properties of the fusion zone depend primarily on the filler metal used, and its compatibility with the base materials. It is surrounded by the heat-affected zone, the area that had its microstructure and properties altered by the weld. These properties depend on the base material's behavior when subjected to heat. The metal in this area is often weaker than both the base material and the fusion zone, and is also where residual stresses are found.

## **Quality**



The blue area results from oxidation at a corresponding temperature of 600 °F (316 °C). This is an accurate way to identify temperature, but does not represent the HAZ width. The HAZ is the narrow area that immediately surrounds the welded base metal.

Many distinct factors influence the strength of welds and the material around them, including the welding method, the amount and concentration of energy input, the weldability of the base material, filler material, and flux material, the design of the joint, and the interactions between all these factors. To test the quality of a weld, either destructive or nondestructive testing methods are commonly used to verify that welds are free of defects, have acceptable levels of residual stresses and distortion, and have acceptable heat-affected zone (HAZ) properties. Types of welding defects include cracks, distortion, gas inclusions (porosity), non-metallic inclusions, lack of fusion, incomplete

penetration, lamellar tearing, and undercutting. Welding codes and specifications exist to guide welders in proper welding technique and in how to judge the quality of welds.

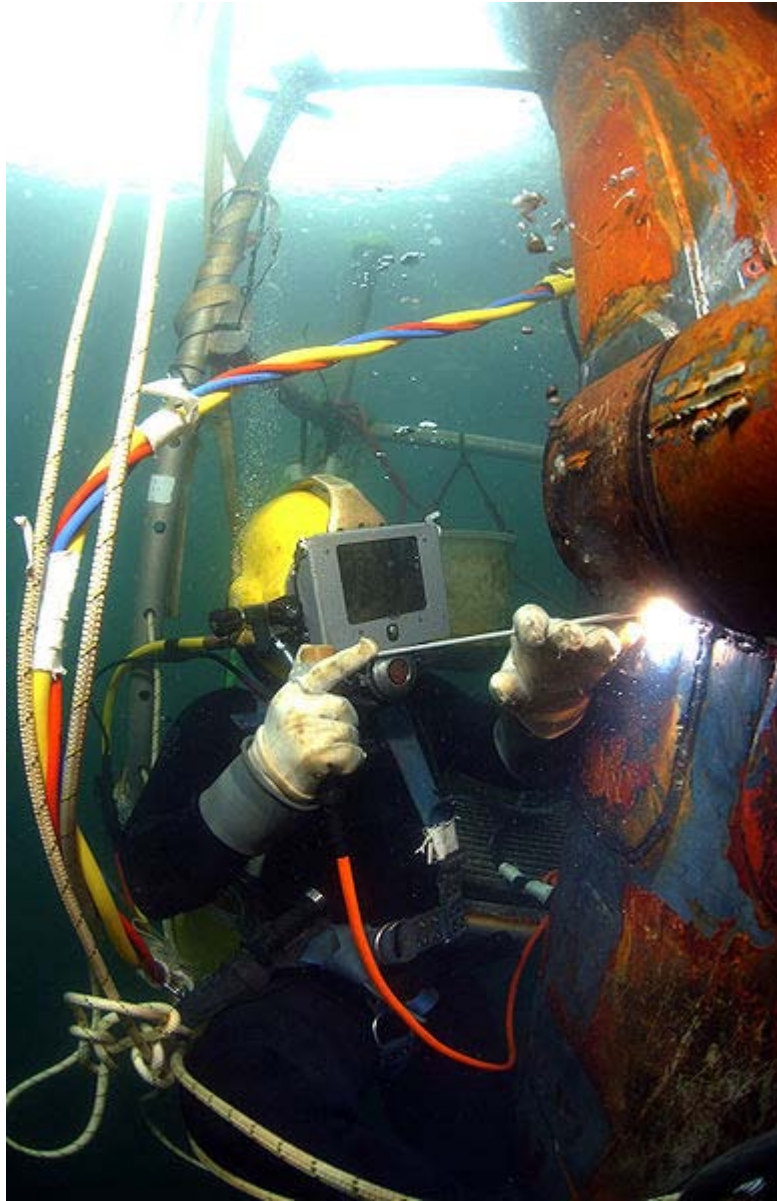
### **Heat-affected zone**

The effects of welding on the material surrounding the weld can be detrimental—depending on the materials used and the heat input of the welding process used, the HAZ can be of varying size and strength. The thermal diffusivity of the base material plays a large role—if the diffusivity is high, the material cooling rate is high and the HAZ is relatively small. Conversely, a low diffusivity leads to slower cooling and a larger HAZ. The amount of heat injected by the welding process plays an important role as well, as processes like oxyacetylene welding have an unconcentrated heat input and increase the size of the HAZ. Processes like laser beam welding give a highly concentrated, limited amount of heat, resulting in a small HAZ. Arc welding falls between these two extremes, with the individual processes varying somewhat in heat input. To calculate the heat input for arc welding procedures, the following formula can be used:

$$Q = \left( \frac{V \times I \times 60}{S \times 1000} \right) \times \textit{Efficiency}$$

where  $Q$  = heat input (kJ/mm),  $V$  = voltage (V),  $I$  = current (A), and  $S$  = welding speed (mm/min). The efficiency is dependent on the welding process used, with shielded metal arc welding having a value of 0.75, gas metal arc welding and submerged arc welding, 0.9, and gas tungsten arc welding, 0.8.

## ***Unusual conditions***



Underwater welding

While many welding applications are done in controlled environments such as factories and repair shops, some welding processes are commonly used in a wide variety of conditions, such as open air, underwater, and vacuums (such as space). In open-air applications, such as construction and outdoors repair, shielded metal arc welding is the most common process. Processes that employ inert gases to protect the weld cannot be readily used in such situations, because unpredictable atmospheric movements can result in a faulty weld. Shielded metal arc welding is also often used in underwater welding in the construction and repair of ships, offshore platforms, and pipelines, but others, such as flux cored arc welding and gas tungsten arc welding, are also common. Welding in space is also possible—it was first attempted in 1969 by Russian cosmonauts, when they

performed experiments to test shielded metal arc welding, plasma arc welding, and electron beam welding in a depressurized environment. Further testing of these methods was done in the following decades, and today researchers continue to develop methods for using other welding processes in space, such as laser beam welding, resistance welding, and friction welding. Advances in these areas may be useful for future endeavours similar to the construction of the International Space Station, which could rely on welding for joining in space the parts that were manufactured on Earth.

### ***Safety issues***



Arc welding with a welding helmet, gloves, and other protective clothing

Welding, without the proper precautions, can be a dangerous and unhealthy practice. However, with the use of new technology and proper protection, risks of injury and death associated with welding can be greatly reduced. Because many common welding procedures involve an open electric arc or flame, the risk of burns and fire is significant; this is why it is classified as a hot work process. To prevent them, welders wear personal protective equipment in the form of heavy leather gloves and protective long sleeve jackets to avoid exposure to extreme heat and flames. Additionally, the brightness of the weld area leads to a condition called arc eye or flash burns in which ultraviolet light causes inflammation of the cornea and can burn the retinas of the eyes. Goggles and welding helmets with dark face plates are worn to prevent this exposure, and in recent years, new helmet models have been produced that feature a face plate that self-darkens

upon exposure to high amounts of UV light. To protect bystanders, translucent welding curtains often surround the welding area. These curtains, made of a polyvinyl chloride plastic film, shield nearby workers from exposure to the UV light from the electric arc, but should not be used to replace the filter glass used in helmets.

Welders are also often exposed to dangerous gases and particulate matter. Processes like flux-cored arc welding and shielded metal arc welding produce smoke containing particles of various types of oxides. The size of the particles in question tends to influence the toxicity of the fumes, with smaller particles presenting a greater danger. This is due to the fact that smaller particles have the ability to cross the blood brain barrier. Additionally, many processes produce fumes and various gases, most commonly carbon dioxide, ozone and heavy metals, that can prove dangerous without proper ventilation and training. Exposure to manganese welding fumes, for example, even at low levels ( $<0.2 \text{ mg/m}^3$ ), may lead to neurological problems or to damage to the lungs, liver, kidneys, or central nervous system. Furthermore, because the use of compressed gases and flames in many welding processes poses an explosion and fire risk, some common precautions include limiting the amount of oxygen in the air and keeping combustible materials away from the workplace.

### ***Costs and trends***

As an industrial process, the cost of welding plays a crucial role in manufacturing decisions. Many different variables affect the total cost, including equipment cost, labor cost, material cost, and energy cost. Depending on the process, equipment cost can vary, from inexpensive for methods like shielded metal arc welding and oxyfuel welding, to extremely expensive for methods like laser beam welding and electron beam welding. Because of their high cost, they are only used in high production operations. Similarly, because automation and robots increase equipment costs, they are only implemented when high production is necessary. Labor cost depends on the deposition rate (the rate of welding), the hourly wage, and the total operation time, including both time welding and handling the part. The cost of materials includes the cost of the base and filler material, and the cost of shielding gases. Finally, energy cost depends on arc time and welding power demand.

For manual welding methods, labor costs generally make up the vast majority of the total cost. As a result, many cost-saving measures are focused on minimizing operation time. To do this, welding procedures with high deposition rates can be selected, and weld parameters can be fine-tuned to increase welding speed. Mechanization and automation are often implemented to reduce labor costs, but this frequently increases the cost of equipment and creates additional setup time. Material costs tend to increase when special properties are necessary, and energy costs normally do not amount to more than several percent of the total welding cost.

In recent years, in order to minimize labor costs in high production manufacturing, industrial welding has become increasingly more automated, most notably with the use of robots in resistance spot welding (especially in the automotive industry) and in arc

welding. In robot welding, mechanized devices both hold the material and perform the weld and at first, spot welding was its most common application, but robotic arc welding increases in popularity as technology advances. Other key areas of research and development include the welding of dissimilar materials (such as steel and aluminum, for example) and new welding processes, such as friction stir, magnetic pulse, conductive heat seam, and laser-hybrid welding. Furthermore, progress is desired in making more specialized methods like laser beam welding practical for more applications, such as in the aerospace and automotive industries. Researchers also hope to better understand the often unpredictable properties of welds, especially microstructure, residual stresses, and a weld's tendency to crack or deform.

## Chapter-11

# Fabrication (Metal)



A typical steel fabrication shop



A set of six-axis welding robots.

**Fabrication** as an industrial term refers to building metal structures by cutting, bending, and assembling. The cutting part of fabrication is via sawing, shearing, or chiseling (all with manual and powered variants); torching with handheld torches (such as oxy-fuel torches or plasma torches); and via CNC cutters (using a laser, torch, or water jet). The bending is via hammering (manual or powered) or via press brakes and similar tools. The assembling (joining of the pieces) is via welding, binding with adhesives, riveting, threaded fasteners, or even yet more bending in the form of a crimped seam. Structural steel and sheet metal are the usual starting materials for fabrication, along with the welding wire, flux, and fasteners that will join the cut pieces. As with other manufacturing processes, both human labor and automation are commonly used. The product resulting from (the process of) fabrication may be called a fabrication. Shops that specialize in this type of metal work are called *fab shops*. The end products of other common types of metalworking, such as machining, metal stamping, forging, and casting, may be similar in shape and function, but those processes are not classified as fabrication.

Fabrication comprises or overlaps with various metalworking specialties:

- Fabrication shops and machine shops have overlapping capabilities, but fabrication shops generally concentrate on metal preparation and assembly as described above. By comparison, machine shops also cut metal, but they are more

concerned with the machining of parts on machine tools. Firms that encompass both fab work and machining are also common.

- Blacksmithing has always involved fabrication, although it was not always called by that name.
- The products produced by welders, which are often referred to as weldments, are an example of fabrication.
- Boilermakers originally specialized in boilers, leading to their trade's name, but the term as used today has a broader meaning.
- Similarly, millwrights originally specialized in setting up grain mills and saw mills, but today they may be called upon for a broad range of fabrication work.
- Ironworkers, also known as steel erectors, also engage in fabrication. Often the fabrications for structural work begin as prefabricated segments in a fab shop, then are moved to the site by truck, rail, or barge, and finally are installed by erectors.

## ***Metal fabrication***

Metal fabrication is a value added process that involves the construction of machines and structures from various raw materials. A fab shop will bid on a job, usually based on the engineering drawings, and if awarded the contract will build the product.

Fabrication shops are employed by contractors, OEM's and VAR's. Typical projects include; loose parts, structural frames for buildings and heavy equipment, and hand railings and stairs for buildings.

## **Engineering**

The fabricator may employ or contract out steel detailers to prepare shop drawings, if not provided by the customer, which the fabricating shop will use for manufacturing. Manufacturing engineers will program CNC machines as needed.

## **Raw materials**

Standard raw materials used by metal fabricators are;

- plate metal
- formed and expanded metal
  - tube stock, CDSM
  - square stock
  - sectional metals (I beams, W beams, C-channel...)
- welding wire
- hardware
- castings
- fittings

## **Cutting and burning**

The raw material has to be cut to size. This is done with a variety of tools.

The most common way to cut material is by Shearing (metalworking);

Special band saws designed for cutting metal have hardened blades and a feed mechanism for even cutting. Abrasive cut-off saws, also known as chop saws, are similar to miter saws but with a steel cutting abrasive disk. Cutting torches can cut very large sections of steel *with little effort*.

Burn tables are CNC cutting torches, usually natural gas powered. Plasma and laser cutting tables, and Water jet cutters, are also common. Plate steel is loaded on a table and the parts are cut out as programmed. The support table is made of a grid of bars that can be replaced. Some very expensive burn tables also include CNC punch capability, with a carousel of different punches and taps. Fabrication of structural steel by plasma and laser cutting introduces robots to move the cutting head in three dimensions around the material to be cut.

## **Forming**

Hydraulic brake presses with v-dies are the most common method of forming metal. The cut plate is placed in the press and a v-shaped die is pressed a predetermined distance to bend the plate to the desired angle. Wing brakes and hand powered brakes are sometimes used.

Tube bending machines have specially shaped dies and mandrels to bend tubular sections without kinking them.

Rolling machines are used to form plate steel into a round section.

English Wheel or Wheeling Machines are used to form complex double curvature shapes using sheet metal.

## **Machining**

Fab shops will generally have a limited machining capability including; metal lathes, mills, magnetic based drills along with other portable metal working tools.

## **Welding**

Welding is the main focus of steel fabrication. The formed and machined parts will be assembled and tack welded into place then re-checked for accuracy. A fixture may be used to locate parts for welding if multiple weldments have been ordered.

The welder then completes welding per the engineering drawings, if welding is detailed, or per his own judgment if no welding details are provided.

Special precautions may be needed to prevent warping of the weldment due to heat. These may include re-designing the weldment to use less weld, welding in a staggered fashion, using a stout fixture, covering the weldment in sand during cooling, and straightening operations after welding.

Straightening of warped steel weldments is done with an Oxy-acetylene torch and is somewhat of an art. Heat is selectively applied to the steel in a slow, linear sweep. The steel will have a net contraction, upon cooling, in the direction of the sweep. A highly skilled welder can remove significant warpage using this technique.

Steel weldments are occasionally annealed in a low temperature oven to relieve residual stresses.

### **Final assembly**

After the weldment has cooled it is generally sand blasted, primed and painted. Any additional manufacturing specified by the customer is then completed. The finished product is then inspected and shipped.

### ***Specialities***

Many fabrication shops have speciality processes which they develop or invest in, based on their customers needs and their expertise:

- brazing
- casting
- chipping
- drawing
- extrusion
- forging
- heat treatment
- hydroforming
- oven soldering
- plastic fabrication
- powder coating
- powder metallurgy
- punching
- shearing
- spinning
- English wheeling
- welding

And higher-level specializations such as:

- electrical
- hydraulics
- prototyping/machine design/technical drawing
- sub-contract manufacturing

## Chapter-12

# Electron Beam Welding and Friction Welding

## Electron beam welding

**Electron beam welding (EBW)** is a fusion welding process in which a beam of high-velocity electrons is applied to the materials being joined. The workpieces melt as the kinetic energy of the electrons is transformed into heat upon impact, and the filler metal, if used, also melts to form part of the weld. The welding is often done in conditions of a vacuum to prevent dispersion of the electron beam. The process was developed by German physicist Karl-Heinz Steigerwald, who was at the time working on various electron beam applications, perceived and developed the first practical electron beam welding machine which began operation in 1958.

### ***Operation***

The three primary methods of EBW are each applied in different welding environments.

### **Vacuum welding**

The method first developed requires that the welding chamber be at a hard vacuum. Material as thick as 15 cm (6 in) can be welded, and the distance between the welding gun and workpiece (the *stand-off distance*) can be as great as 0.7 m (30 in). While the most efficient of the three modes, disadvantages include the amount of time required to properly evacuate the chamber and the cost of the entire machine.

### **Low pressure welding**

As electron beam gun technology advanced, it became possible to perform EBW in a soft vacuum, under pressure of 0.1 torr. This allows for larger welding chambers and reduces the time and equipment required to attain evacuate the chamber, but reduces the maximum stand-off distance by half and decreases the maximum material thickness to 5 cm (2 in).

## **In-air welding**

The third EBW mode is called nonvacuum or out-of-vacuum EBW, since it is performed at atmospheric pressure. The stand-off distance must be diminished to 4 cm (1.5 in), and the maximum material thickness is about 5 cm (2 in). However, it allows for workpieces of any size to be welded, since the size of the welding chamber is no longer a factor. A schematic drawing may be helpful.

## **Equipment**

The electron beam gun used in EBW both produces the electrons and accelerates them, using a hot cathode emitter made of tungsten that emits electrons when heated. (Steigerwald also experimented with tantalum filaments because of the lower work function). The electrons are then accelerated to a hollow anode inside the gun column by means of a high voltage differential. They pass through the anode at high speed (approx 1/2 the speed of light) and are then directed to the workpiece with magnetic forces resulting from focusing and deflection coils. These components are all housed in an electron beam gun column, in which a hard vacuum (about 0.00001 torr) is maintained.

The EBW power supply pulls a low current (usually less than 1 A), but provides a voltage as high as 60 kV in low-voltage machines, or 200 kV in high-voltage machines. High-voltage machines supply a current as low as 40 mA, and can provide a weld depth-to-width ratio of 25:1, whereas the ratio with a low-voltage machine is around 12:1. The beam power of a power supply is an indicator of its ability to do work, and determines the power density (generally 40-4000 kW/cm<sup>2</sup> or 100-10,000 kW/in<sup>2</sup>).

The welding chamber walls and doors must be thick enough to act as X-ray shielding.

For the hard vacuum and soft vacuum EBW methods, the welding chamber used must be airtight and strong enough to prevent it from being crushed by atmospheric pressure. It must have openings so that the workpieces can be inserted and removed, and its size must be sufficient to hold the workpieces but not significantly larger, as larger chambers require more time to evacuate. The chamber must also be equipped with pumps capable of evacuating it to the desired pressure. For a hard vacuum, a diffusion pump is necessary, while soft vacuums can often be obtained by less costly equipment.

Electron beams can also be sent from their vacuum column through membrane or plasma window for a short distance into the air and this is used for production welding, for example welding the hard teeth of hacksaw blades onto a tougher backing steel. The plasma window is a relatively recent advance which has turned this kind of EBW into a far more practical tool. Previously the vacuum containment membranes were expensive and degraded quickly by the constant stream of high energy electrons.

# Friction welding

**Friction welding (FW)** is a class of solid-state welding processes that generates heat through mechanical friction between a moving workpiece and a stationary component, with the addition of a lateral force called "upset" to plastically displace and fuse the materials. Technically, because no melt occurs, friction welding is not actually a welding process in the traditional sense, but a forging technique. However, due to the similarities between these techniques and traditional welding, the term has become common. Friction welding is used with metals and thermoplastics in a wide variety of aviation and automotive applications.

## ***Benefits***

The combination of fast joining times of the order of a few seconds, and the direct heat input at the weld interface, gives rise to relatively small heat affected zones. Friction welding techniques are generally melt-free, which offers the advantage of avoiding grain growth in engineered materials such as high-strength heat-treated steels. Another advantage is that the motion tends to "clean" the surface between the materials being welded, which means they can be joined without as much prior preparation. During the welding process, depending on the method being used, small pieces of the "plastic" metal will be forced out of the working mass in rippled sheets of metal known as "flash". It is believed that the flash carries away debris and dirt.

Another advantage of friction welding is that it allows dissimilar materials to be joined. This is particularly useful in the aerospace field, where it is used to join lightweight aluminum stock to high-strength steels. Normally the wide difference in melting points of the two materials would make it impossible to weld using traditional techniques, and would require some sort of mechanical connection instead (bolts, etc.). Friction welding provides a "full strength" bond with no additional weight. Other common uses for these sorts of bi-metal joins is in the nuclear industry, where copper-steel joints are common in the reactor cooling systems; and in the transport of cryogenic fluids, where friction welding has been used to join aluminum alloys to stainless steels and high-nickel-alloy materials for cryogenic-fluids piping and containment vessels.

Friction welding is also used with thermoplastics, which act in a fashion analogous to metals under heat and pressure. The heats and pressures used on these materials are much lower than on metals, but the technique can be used to join metals to plastics with the metal interface being machined. For instance, the technique can be used to join eyeglass frames to the pins in their hinges. The lower energies and pressures used allows for a wider variety of techniques to be used.

## ***History***

Further patents were issued throughout Europe and the former Soviet Union. The US companies Caterpillar, Rockwell International, and American Manufacturing Foundry all

developed machines for this process. The most extensive historical records are kept with the American Welding Society.

## ***Metal techniques***

### **Spin welding**

Spin welding systems consist of two chucks for holding the materials to be welded, one of which is fixed and the other rotating. Before welding one of the work pieces is attached to the rotating chuck along with a flywheel of a given weight. The piece is then spun up to a high rate of rotation to store the required energy in the flywheel. Once spinning at the proper speed, the motor is removed and the pieces forced together under pressure. The force is kept on the pieces after the spinning stops to allow the weld to "set". This technique is also known as **inertia welding**, **rotational welding** or **inertial friction welding**.

### **Linear friction welding**

*Linear friction welding (LFW)* is similar to spin welding except that the moving chuck oscillates laterally instead of spinning. The speeds are much lower in general, which requires the pieces to be kept under pressure at all times. This also requires the parts to have a high shear strength. Linear friction welding requires more complex machinery than spin welding, but has the advantage that parts of any shape can be joined, as opposed to parts with a circular meeting point.

### **Friction surfacing**

*Friction surfacing* is a process derived from friction welding whereby a coating material is applied to a substrate. A rod composed of the coating material (called a mechtrode) is rotated under pressure, generating a plasticised layer in the rod at the interface with the substrate. By moving a substrate across the face of the rotating rod a plasticised layer is deposited between 0.2–2.5 millimetres (0.0079–0.098 in) thick depending on mechtrode diameter and coating material.

## ***Thermoplastic techniques***

### **Linear vibration welding**

In *linear vibration welding* the materials are placed in contact and put under pressure. An external vibration force is then applied to slip the pieces relative to each other, perpendicular to the pressure being applied. The parts are vibrated through a relatively small displacement known as the amplitude, typically between 1.0 and 1.8 mm, for a frequency of vibration of 200 Hz (high frequency), or 2–4 mm at 100 Hz (low frequency), in the plane of the joint. This technique is widely used in the automotive

industry, among others. A minor modification is *angular friction welding*, which vibrates the materials by torquing them through a small angle.

### **Orbital friction welding**

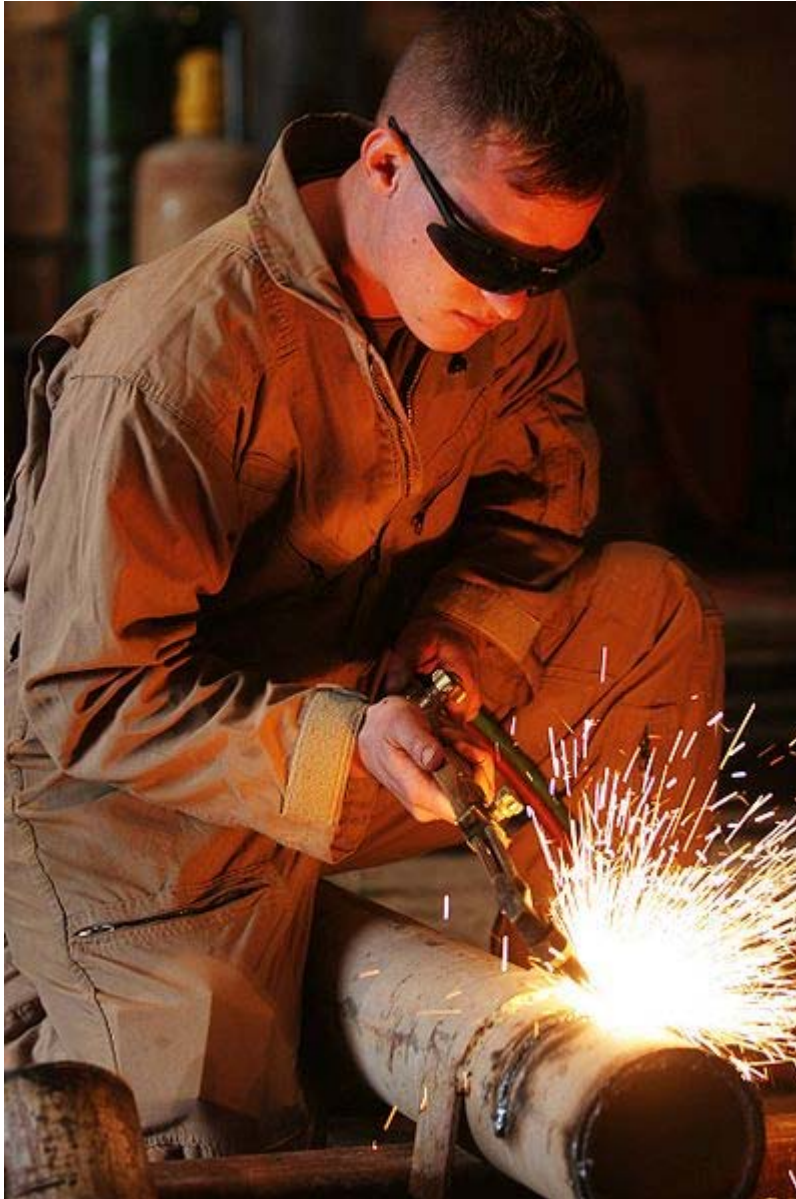
Orbital friction welding is similar to spin welding, but uses a more complex machine to produce an orbital motion in which the moving part rotates in a small circle, much smaller than the size of the joint as a whole.

## Chapter-13

# Oxy-Fuel Welding and Cutting



Side of metal, cut by oxygen - propane cutting torch



A cutting torch is used to cut a steel pipe.

**Oxy-fuel welding** (commonly called **oxyacetylene welding**, **oxy welding**, or **gas welding** in the U.S.) and **oxy-fuel cutting** are processes that use fuel gases and oxygen to weld and cut metals, respectively. French engineers Edmond Fouché and Charles Picard became the first to develop oxygen-acetylene welding in 1903. Pure oxygen, instead of air (20% oxygen/80% nitrogen), is used to increase the flame temperature to allow localized melting of the workpiece material (e.g. steel) in a room environment. A common propane/air flame burns at about 3,630 °F (2,000 °C), a propane/oxygen flame burns at about 4,530 °F (2,500 °C), and an acetylene/oxygen flame burns at about 6,330 °F (3,500 °C).

Oxy-fuel is one of the oldest welding processes, though in recent years it has become less popular in industrial applications. However, it is still widely used for welding pipes and tubes, as well as repair work. It is also frequently well-suited, and favored, for fabricating some types of metal-based artwork.

In **oxy-fuel welding**, a welding torch is used to weld metals. Welding metal results when two pieces are heated to a temperature that produces a shared pool of molten metal. The molten pool is generally supplied with additional metal called filler. Filler material depends upon the metals to be welded.

In **oxy-fuel cutting**, a cutting torch is used to heat metal to kindling temperature. A stream of oxygen is then trained on the metal, and metal burns in that oxygen and then flows out of the cut (kerf) as an oxide slag.

Torches that do not mix fuel with oxygen (combining, instead, atmospheric air) are not considered oxy-fuel torches and can typically be identified by a single tank (Oxy-fuel welding/cutting generally requires two tanks, fuel and oxygen). Most metals cannot be melted with a single-tank torch. As such, single-tank torches are typically used only for soldering and brazing, rather than welding.

## **Uses**

Oxy-gas torches are used for or have been used for:

- Welding metal
- Cutting metal
- Also, oxy-hydrogen flames are used:
  - In Stone Work for "flaming" where the stone is heated and a top layer crackles and breaks. A steel circular brush is attached to an angle grinder and used to remove the first layer leaving behind a bumpy surface similar to hammered bronze.
  - In the glass industry for "fire polishing".
  - In jewelry production for "water welding" using a *water torch*.
  - Formerly, to heat lumps of quicklime to obtain a bright white light called limelight, in theatres or optical ("magic") lanterns.
  - Formerly, in platinum works, as platinum is only fusible in the oxy-hydrogen flame and in an electric furnace.

In short, oxy-fuel equipment is quite versatile – not only because it is preferred for some sorts of iron or steel welding but also because it lends itself to brazing, braze-welding, metal heating (for annealing or tempering, bending or forming), the loosening of corroded nuts and bolts, and also is the ubiquitous means for oxy-fuel cutting of ferrous metals.

## **Apparatus**

The apparatus used in gas welding consists basically of an oxygen source and a fuel gas source (usually cylinders), two pressure regulators and two flexible hoses (one of each for each cylinder), and a torch. This sort of torch can also be used for soldering and brazing. The cylinders are often carried in a special wheeled trolley.

There have been examples of oxyhydrogen cutting sets with small (scuba-sized) gas cylinders worn on the user's back in a backpack harness, for rescue work and similar.

There are also examples of pressurized liquid fuel cutting torches, usually using gasoline. These are used for their increased portability.

## **Regulator**

The regulator is used to control pressure from the tanks to the required pressure in the hose. The flow rate is then adjusted by the operator using needle valves on the torch. Accurate flow control with a needle valve relies on a constant inlet pressure to it.

Most regulators have two stages: the first stage of the regulator is a fixed-pressure regulator whose function is to release the gas from the cylinder at a constant intermediate pressure, despite the pressure in the cylinder falling as the gas in the cylinder is used. This is similar to the first stage of a scuba-diving regulator. The adjustable second stage of the regulator controls the pressure reduction from the intermediate pressure to the low outlet pressure. The regulator has two pressure gauges, one indicating cylinder pressure, the other indicating hose pressure. The adjustment knob of the regulator is sometimes roughly calibrated for pressure, but an accurate setting requires observation of the gauge.

Some simpler or cheaper oxygen-fuel regulators have only a single stage regulator, or only a single gauge. A single-stage regulator will tend to reduce its outlet pressure as the cylinder is emptied, requiring manual readjustment. For low-volume users, this is an acceptable simplification. Welding regulators, unlike simpler LPG heating regulators, retain their outlet (hose) pressure gauge and do not rely on the calibration of the adjustment knob. The cheaper single-stage regulators may sometimes omit the cylinder contents gauge, or replace the accurate dial gauge with a cheaper and less precise "rising button" gauge.

## **Gas hoses**

The hoses are specifically designed for welding and cutting. The hose is usually a double-hose design, meaning that there are two hoses joined together. These hoses are colour-coded for visual identification and their threaded connectors are handed to avoid accidental mis-connection: oxygen is right-handed as normal, fuel gases use a left-handed thread. These left-handed threads also have an identifying groove cut into their nuts.

Colour coding of hoses varies between countries. In the USA, oxygen is green, and the fuel hose is red. In the UK, the oxygen hose is blue (black hoses may still be found on old equipment), and the acetylene fuel hose is red. Where LPG fuel, such as propane, is used, the fuel hose should be orange, indicating that it is compatible with LPG. LPG will damage an incompatible hose, including most acetylene hoses.

Connections between flexible hoses and rigid fittings are made by a crimped hose clip over a barbed spigot. The use of worm-drive or Jubilee clips is specifically forbidden in the UK. The hoses should also be clipped together at intervals approximately 3 feet apart.

### **Non-return valve**

Between the regulator and hose, and ideally between hose and torch on both oxygen and fuel lines, a flashback arrestor and/or non-return valve (check valve) should be installed to prevent flame or oxygen-fuel mixture being pushed back into either cylinder and damaging the equipment or making a cylinder explode.

European practice is to fit flashback arrestors at the regulator and check valves at the torch. US practice is to fit both at the regulator.

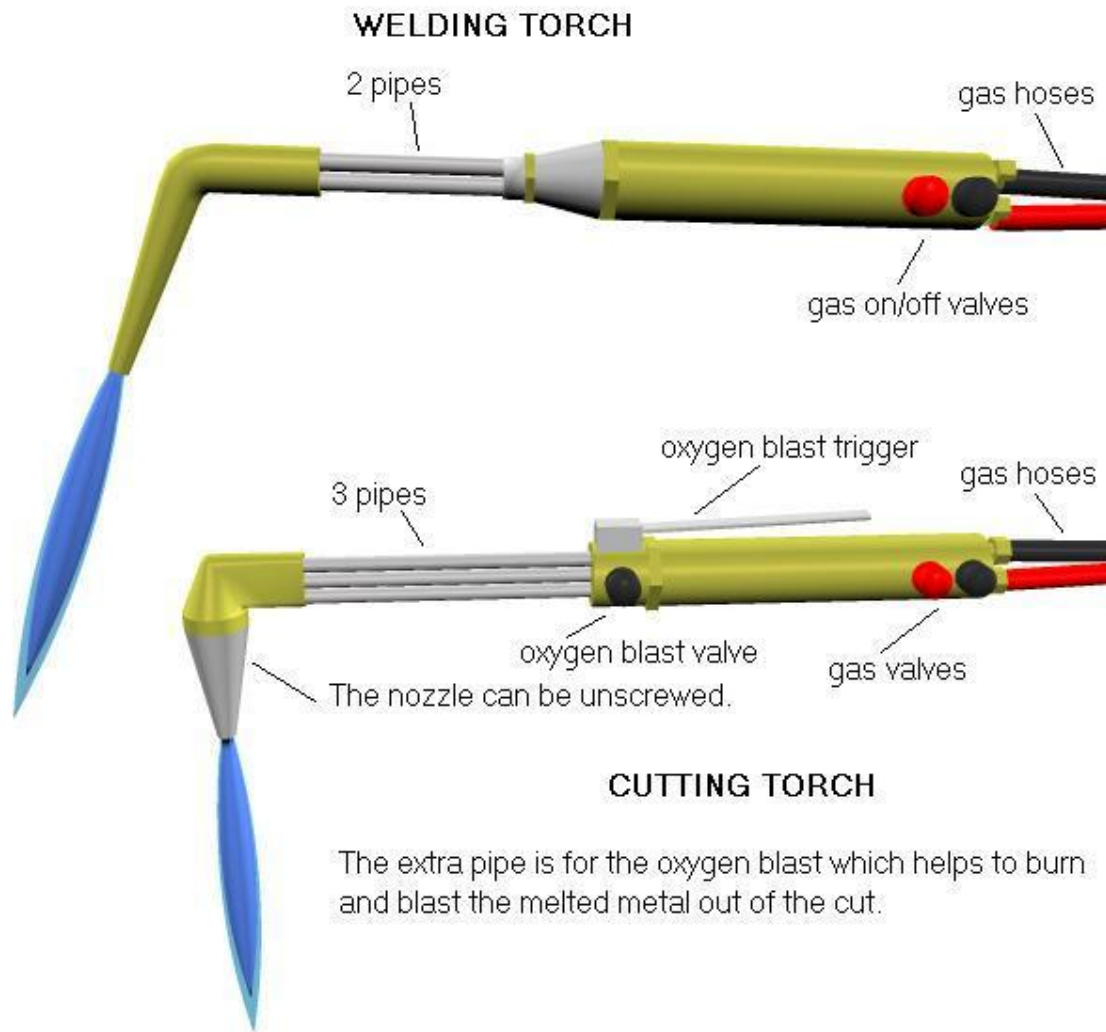
The flashback arrestor (not to be confused with a check valve) prevents the shock waves from downstream coming back up the hoses and entering the cylinder (possibly rupturing it), as there are quantities of fuel/oxygen mixtures inside parts of the equipment (specifically within the mixer and blowpipe/nozzle) that may explode if the equipment is incorrectly shut down; and acetylene decomposes at excessive pressures or temperatures. The flashback arrestor will remain switched off until someone resets it, in case the pressure wave created a leak downstream of the arrestor.

### **Check valve**

A check valve lets gas flow in one direction only. Not to be confused with a flashback arrestor, a check valve is not designed to block a shock wave. The pressure wave could occur while the ball is so far from the inlet that the pressure wave gets past before the ball reaches its off position. A check valve is usually a chamber containing a ball that is pressed against one end by a spring: gas flow one way pushes the ball out of the way, and no flow or flow the other way lets the spring push the ball into the inlet, blocking it.

### **Torches**

The torch is the part that the welder holds and manipulates to make the weld. It has a connection and valve for the fuel gas and a connection and valve for the oxygen, a handle for the welder to grasp, a mixing chamber (set at an angle) where the fuel gas and oxygen mix, with a tip where the flame forms.



The top torch is a welding torch and the bottom is a cutting torch

### **Welding torch**

A welding torch head is used to weld metals. It can be identified by having only one or two pipes running to the nozzle and no oxygen-blast trigger and two valve knobs at the bottom of the handle letting the operator adjust the oxygen flow and fuel flow.

### **Cutting torch**

A cutting torch head is used to cut materials. It is similar to a welding torch, but can be identified by the oxygen blow out trigger or lever.

The metal is first heated by the flame until it is cherry red. Once this temperature is attained, oxygen is supplied to the heated parts by pressing the "oxygen-blast trigger".

This oxygen reacts with the metal, forming iron oxide and producing heat. It is this heat which continues the cutting process. The cutting torch only heats the metal to start the process; further heat is provided by the burning metal.

The melting point of the iron oxide is around half of that of the metal; as the metal burns, it immediately turns to liquid iron oxide and flows away from the cutting zone. However, some of the iron oxide remains on the work piece, forming a hard "slag" which can be removed by gentle tapping, and/or a grinder.

### **Rose-bud torch**

A rose-bud torch is used to heat metals for bending, straightening, etc. where a large area needs to be heated. It is called as such because the flame at the end looks like a rose-bud. A welding torch can also be used to heat small area such as rusted nuts and bolts.

### **Injector torch**

A typical oxy-fuel torch, called an equal-pressure torch, merely mixes the two gases. In an injector torch, high pressure oxygen comes out of a small nozzle inside the torch head so that it drags the fuel gas along with it, via venturi effect.

### ***Fuels***

Oxy-fuel processes may use a variety of fuel gases, the most common being acetylene. Other gases that may be used are propylene, liquified petroleum gas (LPG), propane, natural gas, hydrogen, and MAPP gas. Many brands use different kinds of gases in their mixes.

## Acetylene



Acetylene generator as used in Bali by a reaction of calcium carbide with water. This is used where acetylene cylinders are not available. The term 'Las Karbit' means acetylene (carbide) welding in Indonesian.

Acetylene is the primary fuel for oxy-fuel welding and is the fuel of choice for repair work and general cutting and welding. Acetylene gas is shipped in special cylinders designed to keep the gas dissolved. The cylinders are packed with porous materials (e.g. kapok fibre, diatomaceous earth, or (formerly) asbestos), then filled to around 50% capacity with acetone, as acetylene is acetone soluble. This method is necessary because above 207 kPa (30 lbf/in<sup>2</sup>) (absolute pressure) acetylene is unstable and may explode.

There is about 1700 kPa (250 psi) pressure in the tank when full. Acetylene when combined with oxygen burns at a temperature of 3200 °C to 3500 °C (5800 °F to 6300 °F), highest among commonly used gaseous fuels. As a fuel acetylene's primary disadvantage, in comparison to other fuels, is high cost.

As acetylene is unstable at a pressure roughly equivalent to 33 feet/10 meters underwater, water submerged cutting and welding is reserved for hydrogen rather than acetylene.



Compressed gas cylinders containing oxygen and MAPP gas.

## Gasoline

Oxy-gasoline, also known as oxy-petrol, torches have been found to perform very well, especially where bottled gas fuel is not available or difficult to transport to the worksite.

Tests showed that an oxy-gasoline torch cut steel plate up to 0.5 in (13 mm) thick at the same rate as oxy-acetylene. In plate thicknesses greater than 0.5 inch the cutting rate was better than oxy-acetylene; at 4.5 in (110 mm) it was three times faster.

The gasoline is fed from a pressure tank whose pressure can be hand-pumped or fed from a gas cylinder. Another low cost approach commonly used by jewelry makers in Asia is using air bubbled through a gasoline container by a foot-operated air pump, and burning the fuel-air mixture in a specialized welding torch.

## Hydrogen

Hydrogen has a clean flame and is good for use on aluminium. It can be used at a higher pressure than acetylene and is therefore useful for underwater welding and cutting. It is a good type of flame to use when heating large amounts of material. The flame temperature is high, about 2,000 °C for hydrogen gas in air at atmospheric pressure, and up to 2800 °C when pre-mixed in a 2:1 ratio with pure oxygen (oxyhydrogen).

For some oxyhydrogen torches the oxygen and hydrogen are produced by electrolysis of water in an apparatus which is connected directly to the torch. Types of this sort of torch:

- The oxygen and the hydrogen are led off the electrolysis cell separately and are fed into the two gas connections of an ordinary oxy-gas torch. This happens in the water torch, which is sometimes used in small torches used in making jewelry and electronics.
- The mixed oxygen and hydrogen are drawn from the electrolysis cell and are led into a special torch designed to prevent flashback.

## MPS and MAPP gas

*Methylacetylene-propadiene* (MPS) gas and *MAPP* gas are similar fuels, because MAPP gas is liquefied petroleum gas mixed with MPS. It has the storage and shipping characteristics of LPG and has a heat value a little less than acetylene. Because it can be shipped in small containers for sale at retail stores, it is used by hobbyists and large industrial companies and shipyards because it does not polymerize at high pressures - above 15 psi or so (as acetylene does) and is therefore much less dangerous than acetylene. Further, more of it can be stored in a single place at one time, as the increased compressibility allows for more gas to be put into a tank. MAPP gas can be used at much higher pressures than acetylene, sometimes up to 40 or 50 psi in high-volume oxy-fuel cutting torches which can cut up to 12-inch-thick (300 mm) steel. Other welding gases that develop comparable temperatures need special procedures for safe shipping and handling. MPS and MAPP are recommended for cutting applications in particular, rather than welding applications.

## **Butane, propane and butane/propane mixes**

Butane, like propane, is a saturated hydrocarbon. Butane and propane do not react with each other and are regularly mixed together. Butane boils at 0.6 deg C. Propane is more volatile, with a boiling point of - 42 deg C. Vaporization is rapid at temperatures above the boiling points. The calorific (heat) values of both are almost equal. Both are thus mixed together to attain the vapor pressure that is required by the end user and depending on the ambient conditions. If the ambient temperature is very low propane is preferred to achieve higher vapor pressure at the given temperature.

Propane does not burn as hot as acetylene in its inner cone, and so it is rarely used for welding. Propane, however, has a very high number of BTUs per cubic foot in its outer cone, and so with the right torch (injector style) can make a faster and cleaner cut than acetylene, and is much more useful for heating and bending than acetylene.

Propane is cheaper than acetylene and easier to transport.

Like propylene, most propane tips are of a two-piece design. Propane often gets unfair criticism because it really needs changing the torch (from an equal pressure torch to an injector torch) and not just changing the tip to get the best performance. Most torches are equal pressure and designed for gases, such as acetylene, which are lighter than oxygen. Propane is a great deal heavier and runs much better through a low-pressure injector torch with a setting from a few ounces to about two pounds per square inch when cutting.

## **Propylene**

Propylene is used in production welding and cutting. It cuts similarly to propane. When propylene is used, the torch rarely needs tip cleaning. There is often a substantial advantage to cutting with an injector torch rather than an equal-pressure torch when using propylene.

## ***The role of oxygen***

Oxygen is not the fuel. It is what chemically combines with the fuel to produce the heat for welding. This is called 'oxidation', but the more specific and more commonly used term in this context is 'combustion'. In the case of hydrogen, the product of combustion is simply water. For the other hydrocarbon fuels, water and carbon dioxide are produced. The heat is released because the molecules of the products of combustion have a lower energy state than the molecules of the fuel and oxygen. In oxy-fuel cutting, oxidation of the metal being cut (typically iron) produces nearly all of the heat required to "burn" through the workpiece.

The word "oxygen" is often shortened to 'oxy', as in the term 'oxy-acetylene torch'.

Oxygen is usually produced elsewhere by distillation of liquified air and shipped to the welding site in high pressure vessels (commonly called "tanks" or "cylinders") at a

pressure of about 21,000 kPa (3,000 lbf/in<sup>2</sup> = 200 atmospheres). It is also shipped as a liquid in Dewar type vessels (like a large Thermos jar) to places that use large amounts of oxygen.

It is also possible to separate oxygen from air by passing the air, while under pressure, through a zeolite sieve which selectively absorbs the nitrogen and lets the oxygen (and argon) pass. This gives a purity of oxygen of about 93%. This works well for brazing.

## ***Types of flame***

The welder can adjust the oxy-acetylene flame to be carbonizing (aka reducing), neutral, or oxidizing. Adjustment is made by adding more or less oxygen to the acetylene flame. The neutral flame is the flame most generally used when welding or cutting. The welder uses the neutral flame as the starting point for all other flame adjustments because it is so easily defined. This flame is attained when welders, as they slowly open the oxygen valve on the torch body, first see only two flame zones. At that point, the acetylene is being completely burned in the welding oxygen and surrounding air. The flame is chemically neutral. The two parts of this flame are the light blue inner cone and the darker blue to colorless outer cone. The inner cone is where the acetylene and the oxygen combine. The tip of this inner cone is the hottest part of the flame. It is approximately 6,000 °F (3,300 °C) and provides enough heat to easily melt steel. In the inner cone the acetylene breaks down and partly burns to hydrogen and carbon monoxide, which in the outer cone combine with more oxygen from the surrounding air and burn.

An excess of acetylene creates a carbonizing flame. This flame is characterized by three flame zones; the hot inner cone, a white-hot "acetylene feather", and the blue-colored outer cone. This is the type of flame observed when oxygen is first added to the burning acetylene. The feather is adjusted and made ever smaller by adding increasing amounts of oxygen to the flame. A welding feather is measured as 2X or 3X, with X being the length of the inner flame cone. The unburned carbon insulates the flame and drops the temperature to approximately 5,000 °F (2,800 °C). The reducing flame is typically used for hardfacing operations or backhand pipe welding techniques. The feather is caused by incomplete combustion of the acetylene to cause an excess of carbon in the flame. Some of this carbon is dissolved by the molten metal to carbonize it. The carbonizing flame will tend to remove the oxygen from iron oxides which may be present, a fact which has caused the flame to be known as a "reducing flame".

The oxidizing flame is the third possible flame adjustment. It occurs when the ratio of oxygen to acetylene required for a neutral flame has been changed to give an excess of oxygen. This flame type is observed when welders add more oxygen to the neutral flame. This flame is hotter than the other two flames because the combustible gases will not have to search so far to find the necessary amount of oxygen, nor heat up as much thermally inert carbon. It is called an oxidizing flame because of its effect on metal. This flame adjustment is generally not preferred. The oxidizing flame creates undesirable oxides to the structural and mechanical detriment of most metals. In an oxidizing flame, the inner cone acquires a purplish tinge, gets pinched and smaller at the tip, and the sound

of the flame gets harsh. A slightly oxidizing flame is used in braze-welding and bronze-surfacing while a more strongly oxidizing flame is used in fusion welding certain brasses and bronzes

The size of the flame can be adjusted to a limited extent by the valves on the torch and by the regulator settings, but in the main it depends on the size of the orifice in the tip. In fact, the tip should be chosen first according to the job at hand, and then the regulators set accordingly.

## **Welding**

The flame is applied to the base metal and held until a small puddle of molten metal is formed. The puddle is moved along the path where the weld bead is desired. Usually, more metal is added to the puddle as it is moved along by means of dipping metal from a welding rod or filler rod into the molten metal puddle. The metal puddle will travel towards where the metal is the hottest. This is accomplished through torch manipulation by the welder.

The amount of heat applied to the metal is a function of the welding tip size, the speed of travel, and the welding position. The flame size is determined by the welding tip size. The proper tip size is determined by the metal thickness and the joint design.

Welding gas pressures using oxy-acetylene are set in accordance with the manufacturer's recommendations. The welder will modify the speed of welding travel to maintain a uniform bead width. Uniformity is a quality attribute indicating good workmanship. Trained welders are taught to keep the bead the same size at the beginning of the weld as at the end. If the bead gets too wide, the welder increases the speed of welding travel. If the bead gets too narrow or if the weld puddle is lost, the welder slows down the speed of travel. Welding in the vertical or overhead positions is typically slower than welding in the flat or horizontal positions.

The welder must add the filler rod to the molten puddle. The welder must also keep the filler metal in the hot outer flame zone when not adding it to the puddle to protect filler metal from oxidation. Do not let the welding flame burn off the filler metal. The metal will not wet into the base metal and will look like a series of cold dots on the base metal. There is very little strength in a cold weld. When the filler metal is properly added to the molten puddle, the resulting weld will be stronger than the original base metal.

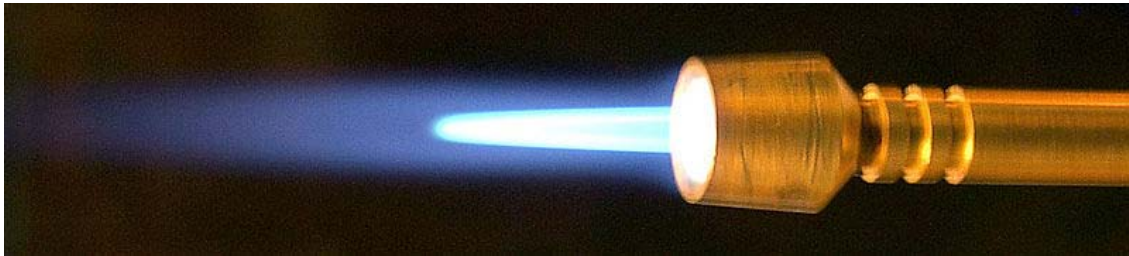
## **Cutting**

For cutting, the set-up is a little different. A cutting torch has a 60- or 90-degree angled head with orifices placed around a central jet. The outer jets are for preheat flames of oxygen and acetylene. The central jet carries only oxygen for cutting. The use of a number of preheating flames, rather than a single flame makes it possible to change the direction of the cut as desired without changing the position of the nozzle or the angle which the torch makes with the direction of the cut, as well as giving a better preheat

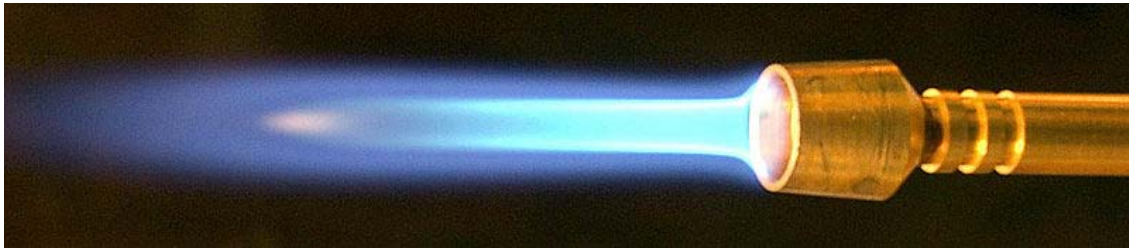
balance . Manufacturers have developed custom tips for Mapp, propane, and polypropylene gases to optimize the flames from these alternate fuel gases.

The flame is not intended to melt the metal, but to bring it to its ignition temperature.

The torch's trigger blows extra oxygen at higher pressures down the torch's third tube out of the central jet into the workpiece, causing the metal to burn and blowing the resulting molten oxide through to the other side. The ideal kerf is a narrow gap with a sharp edge on either side of the workpiece; overheating the workpiece and thus melting through it causes a rounded edge.



Oxygen Rich Butane Torch Flame



Fuel Rich Butane Torch Flame



Cutting a rail just before renewing the rails and the ballast.

Cutting is initiated by heating the edge or leading face (as in cutting shapes such as round rod) of the steel to the ignition temperature (approximately bright cherry red heat) using the pre-heat jets only, then using the separate cutting oxygen valve to release the oxygen from the central jet . The oxygen chemically combines with the iron in the ferrous material to instantly oxidize the iron into molten iron oxide, producing the cut. Initiating a cut in the middle of a workpiece is known as piercing.

It is worth noting several things at this point:

- The oxygen flowrate is critical — too little will make a slow ragged cut; too much will waste oxygen and produce a wide concave cut. Oxygen Lances and other custom made torches do not have a separate pressure control for the cutting oxygen, so the cutting oxygen pressure must be controlled using the oxygen regulator. The oxygen cutting pressure should match the cutting tip oxygen orifice. Consult the tip manufacturer's equipment data for the proper cutting oxygen pressures for the specific cutting tip .
- The oxidation of iron by this method is highly exothermic. Once started, steel can be cut at a surprising rate, far faster than if it was merely melted through. At this point, the pre-heat jets are there purely for assistance. The rise in temperature will be obvious by the intense glare from the ejected material, even through proper

- goggles. (A thermic lance is a tool which also uses rapid oxidation of iron to cut through almost any material.)*
- Since the melted metal flows out of the workpiece, there must be room on the opposite side of the workpiece for the spray to exit. When possible, pieces of metal are cut on a grate that lets the melted metal fall freely to the ground. The same equipment can be used for oxyacetylene blowtorches and welding torches, by exchanging the part of the torch in front of the torch valves.

For a basic oxy-acetylene rig, the cutting speed in light steel section will usually be nearly twice as fast as a petrol-driven cut-off grinder. The advantages when cutting large sections are obvious - an oxy-fuel torch is light, small and quiet and needs very little effort to use, whereas a cut-off grinder is heavy and noisy and needs considerable operator exertion and may vibrate severely, leading to stiff hands and possible long-term repetitive strain injury. Oxy-acetylene torches can easily cut through ferrous materials in excess of 50 mm (2 inches). Oxygen Lances are used in scrapping operations and cut sections thicker than 200 mm (8 inches). Cut-off grinders are useless for these kinds of application.

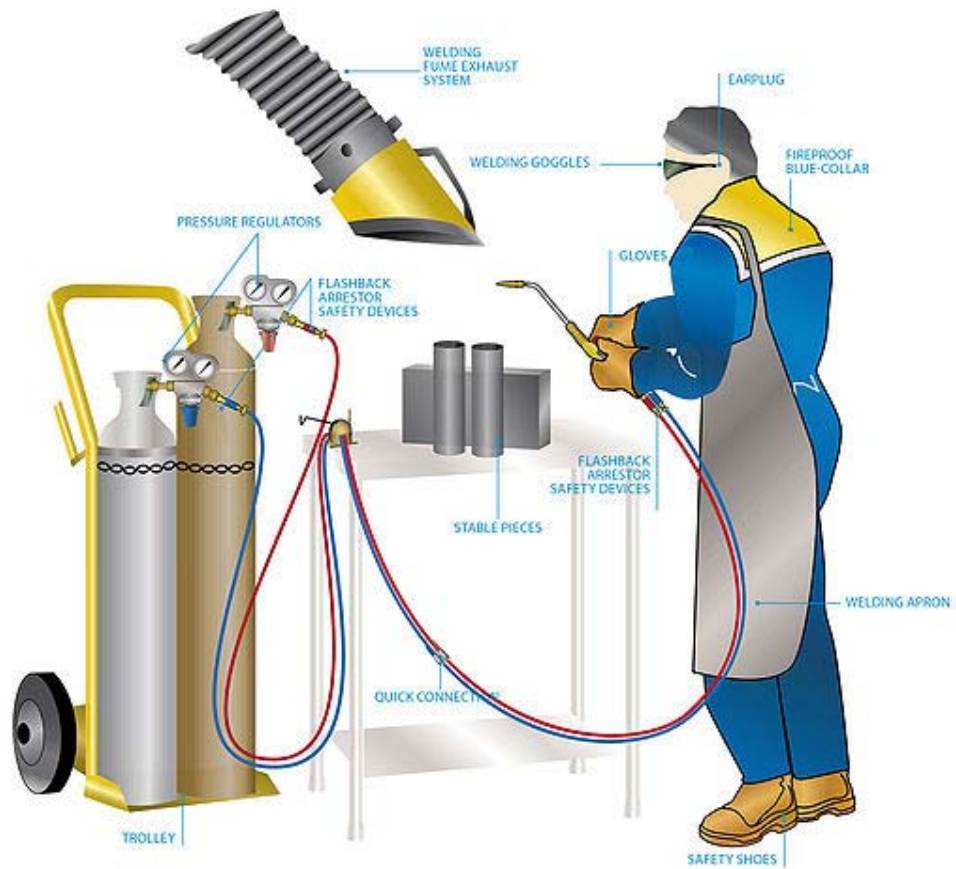
Robotic oxy-fuel cutters sometimes use a high-speed divergent nozzle. This uses an oxygen jet that opens slightly along its passage. This allows the compressed oxygen to expand as it leaves, forming a high-velocity jet that spreads less than a parallel-bore nozzle, allowing a cleaner cut. These are not used for cutting by hand since they need very accurate positioning above the work. Their ability to produce almost any shape from large steel plates gives them a secure future in shipbuilding and in many other industries.

Oxy-propane torches are usually used for cutting up scrap to save money, as LPG is far cheaper joule-for-joule than acetylene, although propane does not produce acetylene's very neat cut profile. Propane also finds a place in production, for cutting very large sections.

Oxy-acetylene can only cut low to medium carbon steels and wrought iron. High carbon steels cannot be cut because the melting point is very close to the temperature of the flame, and so the slag from the cutting action does not eject as sparks, but rather mixes with the clean melt near the cut. This keeps the oxygen from reaching the clean metal and burning it. In the case of cast iron, graphite between the grains and the shape of the grains themselves interfere with cutting action of torch.

## Safety

### Correct and safe oxygas welding station



Oxygas welding station (keep cylinders and hoses away from the flame)

**This type of goggles is NOT adequate eye protection for arc welding.**



This model has clear fixed lenses and flip-up dark lenses. It can be worn over ordinary spectacles.



Gas welding/cutting goggles and safety helmet

Oxyacetylene welding/cutting is not difficult, but there are a good number of subtle safety points that should be learned such as:

- More than 1/7 the capacity of the cylinder should not be used per hour. This causes the acetone inside the acetylene cylinder to come out of the cylinder and contaminate the hose and possibly the torch.
- Acetylene is dangerous above 15 psi pressure. It is unstable and explosively decomposes.
- Proper ventilation when welding will help to avoid large chemical exposure.

## **The importance of eye protection**

Proper protection such as welding goggles should be worn at all times, including to protect the eyes against glare and flying sparks. Special safety eyewear must be used—both to protect the welder and to provide a clear view through the yellow-orange flare given off by the incandescing flux. In the 1940s cobalt melters' glasses were borrowed from steel foundries and were still available until the 1980s. However, the lack of protection from impact, ultra-violet, infrared and blue light caused severe eyestrain and eye damage. Didymium eyewear, developed for glassblowers in the 1960s, was also borrowed—until many complained of eye problems from excessive infrared, blue light, and insufficient shading. Today very good eye protection can be found designed especially for gas-welding aluminum that cuts the sodium orange flare completely and provides the necessary protection from ultraviolet, infrared, blue light and impact, according to ANSI Z87-1989 safety standards for a Special Purpose Lens.

## **Fuel leakage**

Fuel gases that are denser than air (Propane, Propylene, MAPP, Butane, etc...), may collect in low areas if allowed to escape. To avoid an ignition hazard, special care should be taken when using these gases over areas such as basements, sinks, storm drains, etc. In addition, leaking fittings may catch fire during use and pose a risk to personnel as well as property.

## **Safety with cylinders**

When using fuel and oxygen tanks they should be fastened securely upright to a wall or a post or a portable cart. An oxygen tank is especially dangerous for the reason that the oxygen is at a pressure of 21 MPa ( $3000 \text{ lbf/in}^2 = 200 \text{ atmospheres}$ ) when full, and if the tank falls over and its valve strikes something and is knocked off, the tank will effectively become an extremely deadly flying missile propelled by the compressed oxygen, capable of even breaking through a brick wall. For this reason, never move an oxygen tank around without its valve cap screwed in place.

On an oxyacetylene torch system there will be three types of valves, the tank valve, the regulator valve, and the torch valve. There will be a set of these three valves for each gas. The gas in the tanks or cylinders is at high pressure. Oxygen cylinders are generally filled to approximately 2200 psi. The regulator converts the high pressure gas to a low pressure stream suitable for welding. Never attempt to directly use high-pressure gas.

## **Chemical exposure**

A less obvious hazard of welding is exposure to harmful chemicals. Exposure to certain metals, metal oxides, or carbon monoxide can often lead to severe medical conditions. Damaging chemicals can be produced from the fuel, from the work-piece, or from a protective coating on the work-piece. By increasing ventilation around the welding

environment, the welders will have much less exposure to harmful chemicals from any source.

The most common fuel used in welding is acetylene, which has a two-stage reaction. The primary chemical reaction involves the acetylene disassociating in the presence of oxygen to produce heat, carbon monoxide, and hydrogen gas:  $C_2H_2 + O_2 \rightarrow 2CO + H_2$ . A secondary reaction follows where the carbon monoxide and hydrogen combine with more oxygen to produce carbon dioxide and water vapor. When the secondary reaction does not burn all of the reactants from the primary reaction, the welding processes produces large amounts of carbon monoxide, and it often does. Carbon monoxide is also the byproduct of many other incomplete fuel reactions.

Almost every piece of metal is an alloy of one type or another. Copper, aluminium, and other base metals are occasionally alloyed with beryllium, which is a highly toxic metal. When a metal like this is welded or cut, high concentrations of toxic beryllium fumes are released. Long-term exposure to beryllium may result in shortness of breath, chronic cough, and significant weight loss, accompanied by fatigue and general weakness. Other alloying elements such as arsenic, manganese, silver, and aluminium can cause sickness to those who are exposed.

More common are the anti-rust coatings on many manufactured metal components. Zinc, cadmium, and fluorides are often used to protect irons and steels from oxidizing. Galvanized metals have a very heavy zinc coating. Exposure to zinc oxide fumes can lead to a sickness named "metal fume fever". This condition rarely lasts longer than 24 hours, but is still unpleasant. Not unlike common influenza, fevers, chills, nausea, cough, and fatigue are common effects of high zinc oxide exposure.

## **Flashback**

*Flashback* is the condition of the flame propagating down the hoses of an oxy-fuel welding and cutting system. To prevent such a situation a flashback arrestor is usually employed. The flame burns backwards into the hose, causing a popping or squealing noise. It can cause an explosion in the hose with the potential to injure or kill the operator. Using a lower pressure than recommended can cause a flashback.

## Chapter-14

# Electric Resistance Welding

**Electric resistance welding (ERW)** refers to a group of welding processes such as spot and seam welding that produce coalescence of faying surfaces where heat to form the weld is generated by the electrical resistance of material vs the time and the force used to hold the materials together during welding. Some factors influencing heat or welding temperatures are the proportions of the workpieces, the coating or the lack of coating, the electrode materials, electrode geometry, electrode pressing force, weld current and weld time. Small pools of molten metal are formed at the point of most electrical resistance (the connecting surfaces) as a high current (100–100,000 A) is passed through the metal. In general, resistance welding methods are efficient and cause little pollution, but their applications are limited to relatively thin materials and the equipment cost can be high (although in production situations the cost per weld may be as low as \$0.04 USD per weld depending on application and manufacturing rate).

### *Spot welding*



Spot welder

Spot welding is a resistance welding method used to join two to three overlapping metal sheets, studs, projections, electrical wiring hangers, some heat exchanger fins, and some tubing. Usually power sources and welding equipment are sized, to the specific thickness and material being welded together. Thickness are limited to the output of the welding power source and equipment range due to the high current required for the application . Care is taken to eliminate, contaminates between the faying surfaces. Usually, Two copper electrodes are simultaneously used to clamp the metal sheets together and to pass current through the sheets. When the current is passed through the electrodes to the sheets, heat is generated due to the higher electrical resistance where the surfaces contact each other. As the electrical resistance of the material causes an heat buildup in the work between the copper electrodes, the rising temperature causes a rising resistance, and results in a molten pool contained most of the time between the electrodes. The water cooled copper electrodes remove the surface heat quickly, speeding solidification of the weld, since copper is an excellent conductor. As the heat dissipates throughout the workpiece in less than a second(controls are based in AC cycles, or microseconds) the molten, or at least plastic, state grows to meet the welding tips. When the current is stopped the copper tips cool the spot weld, causing the metal to solidify under pressure. Some of the different currents used are Direct Current, Alternating Current, and Medium Frequency Half wave Direct Current, as well as high frequency half wave Direct current.

If excessive heat is applied, or applied too quickly,or the force between the base materials is too low, or the coating too thick, or too conductive, the molten area may extend to the outside, and with its high pressure (typically 30,000 psi) will escape the containment force of the tips with a burst of molten metal called expulsion. When this occurs, the metal will be thinner and have less strength than a weld with no expulsion. The common method of checking a weld is a peel test. A alternative test is the restrained tensile test, which is much more difficult to perform, and requires calibrated equipment. Ultrasonic Evaluation has been tried and is still in a "unapproved" state for many OEMs.

The advantages of the method include efficient energy use, limited workpiece deformation, high production rates, easy automation, and no required filler materials. When high strength in shear is needed, spot welding is used in preference to more costly mechanical fastening, such as riveting. While the shear strength of each weld is high, the fact that the weld spots do not form a continuous seam means that the overall strength is often significantly lower than with other welding methods, limiting the usefulness of the process. It is used extensively in the automotive industry— cars can have several thousand spot welds. A specialized process, called shot welding, can be used to spot weld stainless steel.

There are three basic types of resistance welding bonds: solid state, fusion, and reflow braze. In a *solid state bond*, also called a thermo-compression bond, dissimilar materials with dissimilar grain structure, e.g. molybdenum to tungsten, are joined using a very short heating time, high weld energy, and high force. There is little melting and minimum grain growth, but a definite bond and grain interface. Thus the materials actually bond while still in the solid state. The bonded materials typically exhibit excellent shear and tensile strength, but poor peel strength. In a *fusion bond*, either similar or dissimilar

materials with similar grain structures are heated to the melting point (liquid state) of both. The subsequent cooling and combination of the materials forms a “nugget” alloy of the two materials with larger grain growth. Typically, high weld energies at either short or long weld times, depending on physical characteristics, are used to produce fusion bonds. The bonded materials usually exhibit excellent tensile, peel and shear strengths. In a *reflow braze bond*, a resistance heating of a low temperature brazing material, such as gold or solder, is used to join either dissimilar materials or widely varied thick/thin material combinations. The brazing material must “wet” to each part and possess a lower melting point than the two workpieces. The resultant bond has definite interfaces with minimum grain growth. Typically the process requires a longer (2 to 100 ms) heating time at low weld energy. The resultant bond exhibits excellent tensile strength, but poor peel and shear strength.

### ***Seam welding***

Resistance seam welding is a process that produces a weld at the faying surfaces of two similar metals. The seam may be a butt joint or an overlap joint and is usually an automated process. It differs from butt welding in that butt welding typically welds the entire joint at once and seam welding forms the weld progressively, starting at one end. Like spot welding, seam welding relies on two electrodes, usually made from copper, to apply pressure and current. The electrodes are disc shaped and rotate as the material passes between them. This allows the electrodes to stay in constant contact with the material to make long continuous welds. The electrodes may also move or assist the movement of the material.

A transformer supplies energy to the weld joint in the form of low voltage, high current AC power. The joint of the work piece has high electrical resistance relative to the rest of the circuit and is heated to its melting point by the current. The semi-molten surfaces are pressed together by the welding pressure that creates a fusion bond, resulting in a uniformly welded structure. Most seam welders use water cooling through the electrode, transformer and controller assemblies due to the heat generated. Seam welding produces an extremely durable weld because the joint is forged due to the heat and pressure applied. A properly welded joint formed by resistance welding is typically stronger than the material from which it is formed.

A common use of seam welding is during the manufacture of round or rectangular steel tubing. Seam welding has been used to manufacture steel beverage cans but is no longer used for this as modern beverage cans are seamless aluminum.

### ***Other methods***

Other ERW methods include flash welding, resistance projection welding, and upset welding.

## Chapter-15

# Arc Welding



Gas metal arc welding

**Arc welding** is a type of welding that uses a welding power supply to create an electric arc between an electrode and the base material to melt the metals at the welding point. They can use either direct (DC) or alternating (AC) current, and consumable or non-consumable electrodes. The welding region is sometimes protected by some type of inert or semi-inert gas, known as a shielding gas, and/or an evaporating filler material. The process of arc welding is widely used because of its low capital and running costs. Getting the arc started is called striking the arc. An arc may be struck by either lightly tapping the electrode against the metal or scratching the electrode against the metal at high speed.

## Development

While examples of forge welding go back to the Bronze Age and the Iron Age, arc welding did not come into practice until much later. In 1802, Vasily Petrov discovered the continuous electric arc and subsequently proposed its possible practical applications, including welding. The French electrical inventor Auguste de Méritens produced the first carbon arc torch, patented in 1881, which was successfully used for welding lead in the manufacture of lead-acid batteries. In 1881-1882 a Russian inventor Nikolai Bernardos created the an electric arc welding method for steel known as carbon arc welding, using carbon electrodes. The advances in arc welding continued with the invention of metal electrodes in the late 19th century by a Russian, Nikolai Slavyanov (1888), and an American, C. L. Coffin. Around 1900, A. P. Strohmenger released in Britain a coated metal electrode which gave a more stable arc. In 1905 Russian scientist Vladimir Mitkevich proposed the usage of three-phase electric arc for welding. In 1919, alternating current welding was invented by C.J. Holslag but did not become popular for another decade.

Competing welding processes such as resistance welding and oxyfuel welding were developed during this time as well; but both, especially the latter, faced stiff competition from arc welding especially after metal coverings (known as flux) for the electrode, to stabilize the arc and shield the base material from impurities, continued to be developed.

During World War I welding started to be used in shipbuilding in Great Britain in place of riveted steel plates. The Americans also became more accepting of the new technology when the process allowed them to repair their ships quickly after a German attack in the New York Harbor at the beginning of the war. Arc welding was first applied to aircraft during the war as well, and some German airplane fuselages were constructed using this process. In 1919, the British shipbuilder Cammell Laird started construction of merchant ship, the *Fullagar*, with an entirely welded hull; she was launched in 1921.

During the 1920s, major advances were made in welding technology, including the 1920 introduction of automatic welding in which electrode wire was continuously fed. Shielding gas became a subject receiving much attention as scientists attempted to protect welds from the effects of oxygen and nitrogen in the atmosphere. Porosity and brittleness were the primary problems and the solutions that developed included the use of hydrogen, argon, and helium as welding atmospheres. During the following decade,

further advances allowed for the welding of reactive metals such as aluminum and magnesium. This, in conjunction with developments in automatic welding, alternating current, and fluxes fed a major expansion of arc welding during the 1930s and then during World War II.

During the middle of the century, many new welding methods were invented. Submerged arc welding was invented in 1930 and continues to be popular today. In 1932 a Russian, Konstantin Khrenov successfully implemented the first underwater electric arc welding. Gas tungsten arc welding, after decades of development, was finally perfected in 1941 and gas metal arc welding followed in 1948, allowing for fast welding of non-ferrous materials but requiring expensive shielding gases. Using a consumable electrode and a carbon dioxide atmosphere as a shielding gas, it quickly became the most popular metal arc welding process. In 1957, the flux-cored arc welding process debuted in which the self-shielded wire electrode could be used with automatic equipment, resulting in greatly increased welding speeds. In that same year, plasma arc welding was invented. Electroslag welding was released in 1958 and was followed by its cousin, electrogas welding, in 1961.

## Power supplies



A diesel powered welding generator (the electric generator is on the left) as used in Indonesia.



Engine driven welder capable of AC/DC welding

To supply the electrical energy necessary for arc welding processes, a number of different power supplies can be used. The most common classification is constant current power supplies and constant voltage power supplies. In arc welding, the voltage is directly related to the length of the arc, and the current is related to the amount of heat input. Typical currents are 50 to 500 amps, depending on the size of weld required; 100 amps is typical for manual welders. Voltage output is typically 20 to 50 volts during welding, though some power supplies also include a small high voltage source to aid in initially striking the arc. Constant current power supplies are most often used for manual welding processes such as gas tungsten arc welding and shielded metal arc welding, because they maintain a relatively constant current even as the voltage varies. This is important because in manual welding, it can be difficult to hold the electrode perfectly steady, and as a result, the arc length and thus voltage tend to fluctuate. Constant voltage power supplies hold the voltage constant and vary the current, and as a result, are most often used for automated welding processes such as gas metal arc welding, flux cored arc welding, and submerged arc welding. In these processes, arc length is kept constant, since any fluctuation in the distance between the wire and the base material is quickly rectified

by a large change in current. For example, if the wire and the base material get too close, the current will rapidly increase, which in turn causes the heat to increase and the tip of the wire to melt, returning it to its original separation distance.

The direction of current used in arc welding also plays an important role in welding. Consumable electrode processes such as shielded metal arc welding and gas metal arc welding generally use direct current, but the electrode can be charged either positively or negatively. In welding, the positively charged anode will have a greater heat concentration and, as a result, changing the polarity of the electrode has an impact on weld properties. If the electrode is positively charged, it will melt more quickly, increasing weld penetration and welding speed. Alternatively, a negatively charged electrode results in more shallow welds. Non-consumable electrode processes, such as gas tungsten arc welding, can use either type of direct current (DC), as well as alternating current (AC). With direct current however, because the electrode only creates the arc and does not provide filler material, a positively charged electrode causes shallow welds, while a negatively charged electrode makes deeper welds. Alternating current rapidly moves between these two, resulting in medium-penetration welds. One disadvantage of AC, the fact that the arc must be re-ignited after every zero crossing, has been addressed with the invention of special power units that produce a square wave pattern instead of the normal sine wave, eliminating low-voltage time after the zero crossings and minimizing the effects of the problem.

## Consumable electrode methods



Shielded metal arc welding

One of the most common types of arc welding is shielded metal arc welding (SMAW), which is also known as manual metal arc welding (MMA) or stick welding. An electric current is used to strike an arc between the base material and a consumable electrode rod or 'stick'. The electrode rod is made of a material that is compatible with the base material being welded and is covered with a flux that protects the weld area from oxidation and contamination by producing CO<sub>2</sub> gas during the welding process. The electrode core itself acts as filler material, making a separate filler unnecessary. The process is very versatile, requiring little operator training and inexpensive equipment. However, weld times are rather slow, since the consumable electrodes must be frequently replaced and because slag, the residue from the flux, must be chipped away after welding. Furthermore, the process is generally limited to welding ferrous materials, though specialty electrodes have made possible the welding of cast iron, nickel, aluminium, copper and other metals. The versatility of the method makes it popular in a number of applications including repair work and construction.

Gas metal arc welding (GMAW), commonly called MIG (Metal Inert Gas), is a semi-automatic or automatic welding process with a continuously fed consumable wire acting as both electrode and filler metal, along with an inert or semi-inert shielding gas flowed around the wire to prevent the weld site from contamination. Constant voltage, direct current power source is most commonly used with GMAW, but constant current alternating current are used as well. With continuously fed filler electrodes, GMAW offers relatively high welding speeds, however the more complicated equipment reduces convenience and versatility in comparison to the SMAW process. Originally developed for welding aluminium and other non-ferrous materials in the 1940s, GMAW was soon economically applied to steels. Today, GMAW is commonly used in industries such as the automobile industry for its quality, versatility and speed. Because of the need to maintain a stable shroud of shielding gas around the weld site, it can be problematic to use the GMAW process in areas of high air movement such as outdoors.

Flux-cored arc welding (FCAW) is a variation of the GMAW technique. FCAW wire is actually a fine metal tube filled with powdered flux materials. Flux cored wire generates an effective gas shield precisely at the weld site, permitting application involving more windy conditions or contaminated materials, however the flux cored wire leaves a slag residue and is more expensive than solid wire.

Submerged arc welding (SAW) is a high-productivity automatic welding method in which the arc is struck beneath a covering layer of flux. This increases arc quality, since contaminants in the atmosphere are blocked by the flux. The slag that forms on the weld generally comes off by itself and, combined with the use of a continuous wire feed, the weld deposition rate is high. Working conditions are much improved over other arc welding processes since the flux hides the arc and no smoke is produced. The process is commonly used in industry, especially for large products. As the arc is not visible, it requires full automatization. In-position welding is not possible with SAW.

## **Non-consumable electrode methods**

Gas tungsten arc welding (GTAW), or tungsten inert gas (TIG) welding, is a manual welding process that uses a non-consumable electrode made of tungsten, an inert or semi-inert gas mixture, and a separate filler material. Especially useful for welding thin materials, this method is characterized by a stable arc and high quality welds, but it requires significant operator skill and can only be accomplished at relatively low speeds. It can be used on nearly all weldable metals, though it is most often applied to stainless steel and light metals. It is often used when quality welds are extremely important, such as in bicycle, aircraft and naval applications. A related process, plasma arc welding, also uses a tungsten electrode but uses plasma gas to make the arc. The arc is more concentrated than the GTAW arc, making transverse control more critical and thus generally restricting the technique to a mechanized process. Because of its stable current, the method can be used on a wider range of material thicknesses than can the GTAW process and is much faster. It can be applied to all of the same materials as GTAW except magnesium; automated welding of stainless steel is one important application of the process. A variation of the process is plasma cutting, an efficient steel cutting process.

Other arc welding processes include atomic hydrogen welding, carbon arc welding, electroslag welding, electrogas welding, and stud arc welding.

## **Corrosion issues**

Some materials, notably high-strength steels, aluminium, and titanium alloys, are susceptible to hydrogen embrittlement. If the electrodes used for welding contain traces of moisture, the water decomposes in the heat of the arc and the liberated hydrogen enters the lattice of the material, causing its brittleness. Electrodes for such materials, with special low-hydrogen coating, are delivered in sealed moisture-proof packaging. New electrodes can be used straight from the can, but when moisture absorption may be suspected, they have to be dried by baking (usually at 800 to 1000 °F (425 to 550 °C)) in a drying oven. Flux used has to be kept dry as well.





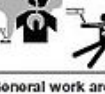





Some austenitic stainless steels and nickel-based alloys are prone to intergranular corrosion. When subjected to temperatures around 700 °C (1,300 °F) for too long time, chromium reacts with carbon in the material, forming chromium carbide and depleting the crystal edges of chromium, impairing their corrosion resistance in a process called sensitization. Such sensitized steel undergoes corrosion in the areas near the welds where the temperature-time was favorable for forming the carbide. This kind of corrosion is often termed weld decay.

Knifeline attack (KLA) is another kind of corrosion affecting welds, impacting steels stabilized by niobium. Niobium and niobium carbide dissolves in steel at very high temperatures. At some cooling regimes, niobium carbide does not precipitate, and the steel then behaves like unstabilized steel, forming chromium carbide instead. This affects only a thin zone several millimeters wide in the very vicinity of the weld, making it

difficult to spot and increasing the corrosion speed. Structures made of such steels have to be heated in a whole to about 1,950 °F (1,070 °C), when the chromium carbide dissolves and niobium carbide forms. The cooling rate after this treatment is not important.

Filler metal (electrode material) improperly chosen for the environmental conditions can make them corrosion-sensitive as well. There are also issues of galvanic corrosion if the electrode composition is sufficiently dissimilar to the materials welded, or the materials are dissimilar themselves. Even between different grades of nickel-based stainless steels, corrosion of welded joints can be severe, despite that they rarely undergo galvanic corrosion when mechanically joined.

## Safety issues

WELDING SAFETY CHECKLIST		
HAZARD	FACTORS TO CONSIDER	PRECAUTION SUMMARY
 <p>Electric shock can kill</p>	<ul style="list-style-type: none"> <li>Wetness</li> <li>Welder in or on workpiece</li> <li>Confined space</li> <li>Electrode holder and cable insulation</li> </ul>	<ul style="list-style-type: none"> <li>Insulate welder from workpiece and ground using <i>dry</i> insulation. Rubber mat or dry wood.</li> <li>Wear <i>dry, hole-free</i> gloves. (Change as necessary to keep dry.)</li> <li>Do not touch electrically "hot" parts or electrode with bare skin or wet clothing.</li> <li>If wet area and welder cannot be insulated from workpiece with dry insulation, use a semiautomatic, constant-voltage welder or stick welder with voltage reducing device.</li> <li>Keep electrode holder and cable insulation in good condition. Do not use if insulation damaged or missing.</li> </ul>
 <p>Fumes and gases can be dangerous</p>	<ul style="list-style-type: none"> <li>Confined area</li> <li>Positioning of welder's head</li> <li>Lack of general ventilation</li> <li>Electrode types, i.e., manganese, chromium, etc. See MSDS</li> <li>Base metal coatings, galvanize, paint</li> </ul>	<ul style="list-style-type: none"> <li>Use ventilation or exhaust to keep air breathing zone clear, comfortable.</li> <li>Use helmet and positioning of head to minimize fume in breathing zone.</li> <li>Read warnings on electrode container and material safety data sheet (MSDS) for electrode.</li> <li>Provide additional ventilation/exhaust where special ventilation requirements exist.</li> <li>Use special care when welding in a confined area.</li> <li>Do not weld unless ventilation is adequate.</li> </ul>
 <p>Welding sparks can cause fire or explosion</p>	<ul style="list-style-type: none"> <li>Containers which have held combustibles</li> <li>Flammable materials</li> </ul>	<ul style="list-style-type: none"> <li>Do not weld on containers which have held combustible materials (unless strict AWS F4.1 procedures are followed). Check before welding.</li> <li>Remove flammable materials from welding area or shield from sparks, heat.</li> <li>Keep a fire watch in area during and after welding.</li> <li>Keep a fire extinguisher in the welding area.</li> <li>Wear fire retardant clothing and hat. Use earplugs when welding overhead.</li> </ul>
 <p>Arc rays can burn eyes and skin</p>	<ul style="list-style-type: none"> <li>Process: gas-shielded arc most severe</li> </ul>	<ul style="list-style-type: none"> <li>Select a filter lens which is comfortable for you while welding.</li> <li>Always use helmet when welding.</li> <li>Provide non-flammable shielding to protect others.</li> <li>Wear clothing which protects skin while welding.</li> </ul>
 <p>Confined space</p>	<ul style="list-style-type: none"> <li>Metal enclosure</li> <li>Wetness</li> <li>Restricted entry</li> <li>Heavier than air gas</li> <li>Welder inside or on workpiece</li> </ul>	<ul style="list-style-type: none"> <li>Carefully evaluate adequacy of ventilation especially where electrode requires special ventilation or where gas may displace breathing air.</li> <li>If basic electric shock precautions cannot be followed to insulate welder from work and electrode, use semiautomatic, constant-voltage equipment with cold electrode or stick welder with voltage reducing device.</li> <li>Provide welder helper and method of welder retrieval from outside enclosure.</li> </ul>
 <p>General work area hazards</p>	<ul style="list-style-type: none"> <li>Cluttered area</li> </ul>	<ul style="list-style-type: none"> <li>Keep cables, materials, tools neatly organized.</li> </ul>
	<ul style="list-style-type: none"> <li>Indirect work (welding ground) connection</li> </ul>	<ul style="list-style-type: none"> <li>Connect work cable as close as possible to area where welding is being performed. Do <i>not</i> allow alternate circuits through scaffold cables, hoist chains, ground leads.</li> </ul>
	<ul style="list-style-type: none"> <li>Electrical equipment</li> </ul>	<ul style="list-style-type: none"> <li>Use only double insulated or properly grounded equipment.</li> <li>Always disconnect power to equipment before servicing.</li> </ul>
	<ul style="list-style-type: none"> <li>Engine-driven equipment</li> </ul>	<ul style="list-style-type: none"> <li>Use in only open, well ventilated areas.</li> <li>Keep enclosure complete and guards in place.</li> <li>See Lincoln service shop if guards are missing.</li> <li>Refuel with engine off.</li> <li>If using auxiliary power, OSHA may require GFI protection or assured grounding program (or isolated windings if less than 5KW).</li> </ul>
	<ul style="list-style-type: none"> <li>Gas cylinders</li> </ul>	<ul style="list-style-type: none"> <li>Never touch cylinder with the electrode.</li> <li>Never lift a machine with cylinder attached.</li> <li>Keep cylinder upright and chained to support.</li> </ul>

Welding Safety Checklist

Welding can be a dangerous and unhealthy practice without the proper precautions; however, with the use of new technology and proper protection the risks of injury or death associated with welding can be greatly reduced.

### **Heat and sparks**

Because many common welding procedures involve an open electric arc or flame, the risk of burns from heat and sparks is significant. To prevent them, welders wear protective clothing in the form of heavy leather gloves and protective long sleeve jackets to avoid exposure to extreme heat, flames, and sparks.

### **Eye damage**



Auto Darkening Welding hood with 90x110 mm cartridge and 3.78 in. x 1.85 in. viewing area

The brightness of the weld area leads to a condition called arc eye in which ultraviolet light causes inflammation of the cornea and can burn the retinas of the eyes. Welding goggles and helmets with dark face plates are worn to prevent this exposure and, in recent years, new helmet models have been produced featuring a face plate that self-darkens upon exposure to high amounts of UV light. To protect bystanders, transparent welding curtains often surround the welding area. These curtains, made of a polyvinyl chloride plastic film, shield nearby workers from exposure to the UV light from the electric arc, but should not be used to replace the filter glass used in helmets.

Those dark face plates must be much darker than those in sunglasses or blowtorching goggles. Sunglasses and blowtorching goggles are *not* adequate for arc welding protection.

In 1970, a Swedish doctor, Åke Sandén, developed a new type of welding goggles that used a multilayer interference filter to block most of the light from the arc. He had observed that most welders could not see well enough, with the mask on, to strike the arc, so they would flip the mask up, then flip it down again once the arc was going: this exposed their naked eyes to the intense light for a while. By coincidence, the spectrum of an electric arc has a notch in it, which coincides with the yellow sodium line. Thus, a welding shop could be lit by sodium vapor lamps or daylight, and the welder could see well to strike the arc. The Swedish government required these masks to be used for arc welding, but they were not used in the United States. They may have disappeared.

### **Inhaled matter**

Welders are also often exposed to dangerous gases and particulate matter. Processes like flux-cored arc welding and shielded metal arc welding produce smoke containing particles of various types of oxides. The size of the particles in question tends to influence the toxicity of the fumes, with smaller particles presenting a greater danger. Additionally, many processes produce various gases (most commonly carbon dioxide and ozone, but others as well) that can prove dangerous if ventilation is inadequate. Furthermore, the use of compressed gases and flames in many welding processes pose an explosion and fire risk; some common precautions include limiting the amount of oxygen in the air and keeping combustible materials away from the workplace.

### **Interference with pacemakers**

Certain welding machines which use a high frequency AC current component have been found to affect pacemaker operation when within 2 meters of the power unit and 1 meter of the weld site.

## Chapter-16

# Plastic Welding

**Plastic welding** or **heat sealing** is the process of welding plastic workpieces together. It is one of the primary processes of joining or welding plastics.

There are several techniques with which this can be accomplished:

### ***Hot gas welding***

Hot gas welding, also known as *hot air welding*, is a plastic welding technique which is analogous to gas welding metals, though the specific techniques are different. A specially designed heat gun, called a *hot air welder*, produces a jet of hot air that softens both the parts to be joined and a plastic filler rod, all of which must be of the same or a very similar plastic. Welding PVC to acrylic is an exception to this rule.

Hot air/gas welding is a common fabrication technique for manufacturing smaller items such as chemical tanks, water tanks, heat exchangers, and plumbing fittings.

In the case of webs and films a filler rod may not be used. Two sheets of plastic are heated via a hot gas (or a heating element) and then rolled together. This is a quick welding process and can be performed continuously.

### **Freehand welding**

With freehand welding, the jet of hot air (or inert gas) from the welder is played on the weld area and the tip of the weld rod at the same time. As the rod softens, it is pushed into the joint and fuses to the parts. This process is slower than most others, but it can be used in almost any situation.

### ***Speed tip welding***

With speed welding, the plastic welder, similar to a soldering iron in appearance and wattage, is fitted with a feed tube for the plastic weld rod. The speed tip heats the rod and the substrate, while at the same time it presses the molten weld rod into position. A bead

of softened plastic is laid into the joint, and the parts and weld rod fuse. With some types of plastic such as polypropylene, the melted welding rod must be "mixed" with the semi-melted base material being fabricated or repaired. These welding techniques have been perfected over time and have been utilised for over 50 years by professional plastic fabricators and repairers internationally. Speed tip welding method is a much faster welding technique and with practice can be used in tight corners.

### ***Extrusion welding***

Extrusion welding allows the application of bigger welds in a single weld pass. It is the preferred technique for joining material over 6 mm thick. Welding rod is drawn into a miniature hand held plastic extruder, plasticized, and forced out of the extruder against the parts being joined, which are softened with a jet of hot air to allow bonding to take place.

### ***Contact welding***

This is the same as spot welding except that heat is supplied with conduction of the pincher tips instead of electrical conduction. Two plastic parts are brought together where heated tips pinch them, melting and joining the parts in the process.

### ***Hot plate welding***

Related to contact welding, this technique is used to weld larger parts, or parts that have a complex weld joint geometry. The two parts to be welded are placed in the tooling attached to the two opposing platens of a press. A hot plate, with a shape that matches the weld joint geometry of the parts to be welded, is moved in position between the two parts. The two opposing platens move the parts into contact with the hot plate until the heat softens the interfaces to the melting point of the plastic. When this condition is achieved the hot plate is removed, and the parts are pressed together and held until the weld joint cools and re-solidifies to create a permanent bond.

The most common form of this welding is butt heat fusion welding which welds two circular tubes end to end.

### ***High frequency welding***

Certain plastics with chemical dipoles, such as PVC, polyamides (PA) and acetates can be heated with high frequency electromagnetic waves. High frequency welding uses this property to soften the plastics for joining. The heating can be localized, and the process can be continuous. Also known as Dielectric Sealing, R.F. (Radio Frequency) Heat Sealing.

In a ferromagnetic work piece, plastics can be induction-welded by formulating them with metallic or ferromagnetic compounds, called susceptors. These susceptors absorb

electromagnetic energy from an induction coil, become hot, and lose their heat energy to the surrounding material by thermal conduction.

Radio frequency welding is a very mature technology that has been around since the 1940s. Two pieces of material are placed on a table press that applies pressure to both surface areas. Dies are used to direct the welding process. When the press comes together, high frequency waves (usually 27.12 MHz) are passed through the small area between the die and the table where the weld takes place. This high frequency (radio frequency) field causes the molecules in certain materials to move and get hot, and the combination of this heat under pressure causes the weld to take the shape of the die. RF welding is fast. This type of welding is used to connect polymer films used in a variety of industries where a strong consistent leak-proof seal is required. In the fabrics industry, RF is most often used to weld PVC and polyurethane (PU) coated fabrics. This is a very consistent method of welding.

The most common materials used in RF welding are PVC and polyurethane. It is also possible to weld other polymers such as nylon, PET, EVA and some ABS plastics.

### ***Ultrasonic welding***

In ultrasonic welding, high frequency (15 kHz to 40 kHz) low amplitude vibration is used to create heat by way of friction between the materials to be joined. The interface of the two parts is specially designed to concentrate the energy for the maximum weld strength. Ultrasonic can be used on almost all plastic material. It is the fastest heat sealing technology available.

### ***Friction welding***

In friction welding, the two parts to be assembled are rubbed together at a lower frequency (typically 100–300 Hz) and higher amplitude (typically 1 to 2 mm (0.039 to 0.079 in)) than ultrasonic welding. The friction caused by the motion combined with the clamping pressure between the two parts creates the heat which begins to melt the contact areas between the two parts. At this point, the plasticized materials begin to form layers that intertwine with one another, which therefore results in a strong weld. At the completion of the vibration motion, the parts remain held together until the weld joint cools and the melted plastic re-solidifies. The friction movement can be linear or orbital, and the joint design of the two parts has to allow this movement.

### ***Spin welding***

Spin welding is another form of frictional welding. With this process, one part is held stationary, while the other one is rotated at high velocity. The rotating part is then pressed against the fixed part with significant force.

## ***Laser welding***

This technique requires one part to be transmissive to a laser beam and either the other part absorptive or a coating at the interface to be absorptive to the beam. The two parts are put under pressure while the laser beam moves along the joining line. The beam passes through the first part and is absorbed by the other one or the coating to generate enough heat to soften the interface creating a permanent weld.

Semiconductor diode lasers are typically used in plastic welding. Wavelengths in the range of 808 nm to 980 nm can be used to join various plastic material combinations. Power levels from less than 1W to 100W are needed depending on the materials, thickness and desired process speed.

Diode laser systems have the following advantages in joining of plastic materials:

- Cleaner than adhesive bonding
- No micro-nozzles to get clogged
- No liquid or fumes to affect surface finish
- No consumables
- Higher throughput
- Can access work-piece in challenging geometry
- High level of process control

Requirements for high strength joints include:

- Adequate transmission through upper layer
- Absorption by lower layer
- Material compatibility – wetting
- Good joint design – clamping pressure, joint area
- Lower power density

Materials that can be joined include:

- Polypropylene
- Polycarbonate
- Acrylic
- Nylon
- ABS

Specific applications include sealing / welding / joining of: catheter bags, medical containers, automobile remote control keys, heart pacemaker casings, syringe tamper evident joints, headlight or tail-light assemblies, pump housings, and cellular phone parts.

## ***Solvent welding***

In solvent welding, a solvent is applied which can temporarily dissolve the polymer at room temperature. When this occurs, the polymer chains are free to move in the liquid and can mingle with other similarly dissolved chains in the other component. Given sufficient time, the solvent will permeate through the polymer and out into the environment, so that the chains lose their mobility. This leaves a solid mass of entangled polymer chains which constitutes a solvent weld.

This technique is commonly used for connecting PVC and ABS pipe, as in household plumbing. The "gluing" together of plastic (polycarbonate, polystyrene or ABS) models is also a solvent welding process.

Dichloromethane (methylene chloride), which is obtainable in paint stripper, can solvent weld polycarbonate and polymethylmethacrylate. Dichloromethane chemically welds certain plastics; for example, it is used to seal the casing of electric meters. It is also a component - along with tetrahydrofuran - of the solvent used to weld plumbing.

## ***Welding rod***

A plastic welding rod, also known as a *thermoplastic welding rod*, is a rod with circular or triangular cross-section used to bind two pieces of plastic together. They are available in a wide range of colors to match the base material's color.

An important aspect of plastic welding rod design and manufacture is the porosity of the material. A high porosity will lead to air bubbles (known as *voids*) in the rods, which decrease the quality of the welding. The highest quality of plastic welding rods are therefore those with zero porosity, which are called *voidless*.

## Chapter-17

# Nondestructive Testing

**Nondestructive testing** or **Non-destructive testing (NDT)** is a wide group of analysis techniques used in science and industry to evaluate the properties of a material, component or system without causing damage. The terms **Nondestructive examination (NDE)**, **Nondestructive inspection (NDI)**, and **Nondestructive evaluation (NDE)** are also commonly used to describe this technology. Because NDT does not permanently alter the article being inspected, it is a highly-valuable technique that can save both money and time in product evaluation, troubleshooting, and research. Common NDT methods include ultrasonic, magnetic-particle, liquid penetrant, radiographic, remote visual inspection (RVI), eddy-current testing, and low coherence interferometry . NDT is a commonly-used tool in forensic engineering, mechanical engineering, electrical engineering, civil engineering, systems engineering, aeronautical engineering, medicine, and art.

### **Methods**

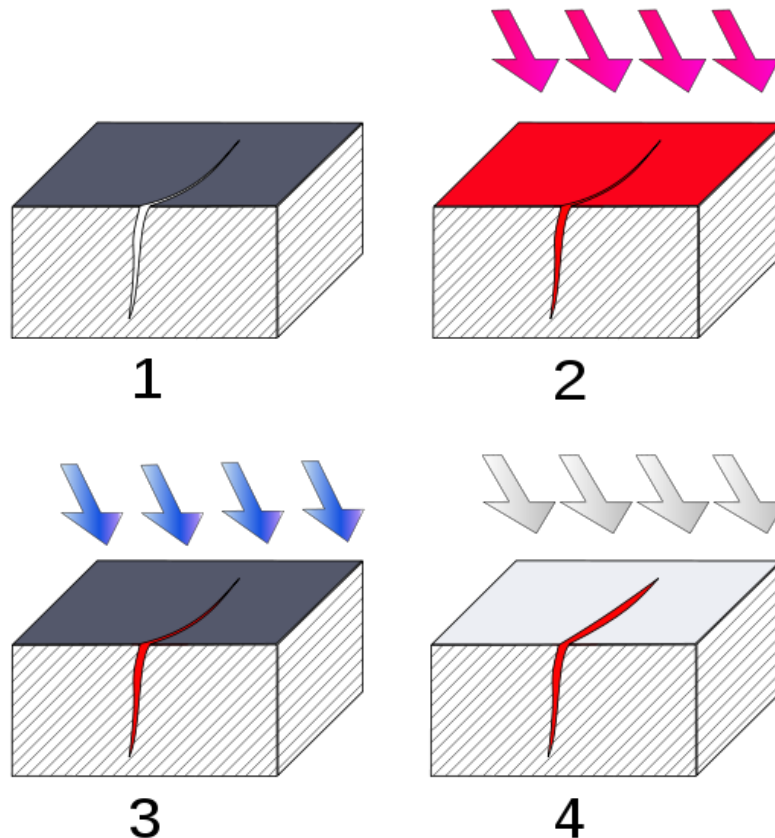
NDT methods may rely upon use of electromagnetic radiation, sound, and inherent properties of materials to examine samples. This includes some kinds of microscopy to examine external surfaces in detail, although sample preparation techniques for metallography, optical microscopy and electron microscopy are generally destructive as the surfaces must be made smooth through polishing or the sample must be electron transparent in thickness. The inside of a sample can be examined with penetrating electromagnetic radiation, such as X-rays or 3D X-rays for volumetric inspection. Sound waves are utilized in the case of ultrasonic testing. Contrast between a defect and the bulk of the sample may be enhanced for visual examination by the unaided eye by using liquids to penetrate fatigue cracks. One method (liquid penetrant testing) involves using dyes, fluorescent or non-fluorescing, in fluids for non-magnetic materials, usually metals. Another commonly used method for magnetic materials involves using a liquid suspension of fine iron particles applied to a part while it is in an externally applied magnetic field (magnetic-particle testing). Thermoelectric effect (or use of the Seebeck effect) uses thermal properties of an alloy to quickly and easily characterize many alloys. The chemical test, or chemical spot test method, utilizes application of sensitive chemicals that can indicate the presence of individual alloying elements.

## Training

Non-Destructive Testing (NDT) training is provided for people working in many industries. It is generally necessary that the student successfully completes a theoretical training program (usually 40 hours of classroom training), as well as have performed several hundred hours of practical application of the particular method they wish to be trained in. At this point, they can apply to write a certifying exam with one of the few governing bodies. Getting certified to inspect steels is quite a complex, and difficult process. Further, NDT Training has recently become available online. WorldSpec.org is one of the innovative companies that helped pioneer this new "era" in NDT Training.

## Examples

### Weld verification



1. Section of material with a surface-breaking crack that is not visible to the naked eye.
2. Penetrant is applied to the surface.
3. Excess penetrant is removed.
4. Developer is applied, rendering the crack visible.

In manufacturing, welds are commonly used to join two or more metal surfaces. Because these connections may encounter loads and fatigue during product lifetime, there is a chance that they may fail if not created to proper specification. For example, the base metal must reach a certain temperature during the welding process, must cool at a specific rate, and must be welded with compatible materials or the joint may not be strong enough to hold the surfaces together, or cracks may form in the weld causing it to fail. The typical welding defects, lack of fusion of the weld to the base metal, cracks or porosity inside the weld, and variations in weld density, could cause a structure to break or a pipeline to rupture.

Welds may be tested using NDT techniques such as industrial radiography using X-rays or gamma rays, ultrasonic testing, liquid penetrant testing or via eddy current. In a proper weld, these tests would indicate a lack of cracks in the radiograph, show clear passage of sound through the weld and back, or indicate a clear surface without penetrant captured in cracks.

Welding techniques may also be actively monitored with acoustic emission techniques before production to design the best set of parameters to use to properly join two materials.

## **Structural mechanics**

Structures can be complex systems that undergo different loads during their lifetime. Some complex structures, such as the turbomachinery in a liquid-fuel rocket, can also cost millions of dollars. Engineers will commonly model these structures as coupled second-order systems, approximating dynamic structure components with springs, masses, and dampers. These sets of differential equations can be used to derive a transfer function that models the behavior of the system.

In NDT, the structure undergoes a dynamic input, such as the tap of a hammer or a controlled impulse. Key properties, such as displacement or acceleration at different points of the structure, are measured as the corresponding output. This output is recorded and compared to the corresponding output given by the transfer function and the known input. Differences may indicate an inappropriate model (which may alert engineers to unpredicted instabilities or performance outside of tolerances), failed components, or an inadequate control system.

## ***Notable events in early industrial NDT***

- 1854 Hartford, Connecticut: a boiler at the Fales and Gray Car works explodes, killing 21 people and seriously injuring 50. Within a decade, the State of Connecticut passes a law requiring annual inspection (in this case visual) of boilers.
- 1895 Wilhelm Conrad Röntgen discovers what are now known as X-rays. In his first paper he discusses the possibility of flaw detection.

- 1880 - 1920 The "Oil and Whiting" method of crack detection is used in the railroad industry to find cracks in heavy steel parts. (A part is soaked in thinned oil, then painted with a white coating that dries to a powder. Oil seeping out from cracks turns the white powder brown, allowing the cracks to be detected.) This was the precursor to modern liquid penetrant tests.
- 1920 Dr. H. H. Lester begins development of industrial radiography for metals.
- 1924 — Lester uses radiography to examine castings to be installed in a Boston Edison Company steam pressure power plant .
- 1926 The first electromagnetic eddy current instrument is available to measure material thicknesses.
- 1927 - 1928 Magnetic induction system to detect flaws in railroad track developed by Dr. Elmer Sperry and H.C. Drake.
- 1929 Magnetic particle methods and equipment pioneered (A.V. DeForest and F.B. Doane.)
- 1930s Robert F. Mehl demonstrates radiographic imaging using gamma radiation from Radium, which can examine thicker components than the low-energy X-ray machines available at the time.
- 1935 - 1940 Liquid penetrant tests developed (Betz, Doane, and DeForest)
- 1935 - 1940s Eddy current instruments developed (H.C. Knerr, C. Farrow, Theo Zuschlag, and Fr. F. Foerster).
- 1940 - 1944 Ultrasonic test method developed in USA by Dr. Floyd Firestone.
- 1950 The Schmidt Hammer (also known as "Swiss Hammer") is invented. The instrument uses the world's first patented non-destructive testing method for concrete.
- 1950 J. Kaiser introduces acoustic emission as an NDT method.

## ***Applications***

NDT is used in a variety of settings that covers a wide range of industrial activity.

- Automotive
  - Engine parts
  - Frame
- Aviation / Aerospace
  - Airframes
    - Spaceframes
  - Powerplants
    - Propellers
    - Reciprocating Engines
    - Gas turbine engines
  - Rocketry
- Construction
  - Structures
  - Bridges
  - Cover Meter
- Maintenance, repair and operations

- Bridges
- Manufacturing
  - Machine parts
  - Castings and Forgings
- Industrial plants such as Nuclear, Petrochemical, Power, Refineries, Pulp and Paper, Fabrication shops, Mine processing and their Risk Based Inspection programmes.
  - Pressure vessels
  - Storage tanks
  - Welds
  - Boilers
  - Heat exchangers
  - Turbine bores
  - In-plant Piping
- Miscellaneous
  - Pipelines
    - In-line Inspection using "pigs"
    - Pipeline integrity management
    - Leak Detection
  - Railways
    - Rail Inspection
    - Wheel Inspection
  - Tubular NDT, for Tubing material
  - Corrosion Under Insulation (CUI)
  - Amusement park rides
  - Submarines and other Naval warships
  - Medical imaging applications

## ***Methods and techniques***



An example of a 3D replicating technique. The flexible high-resolution replicas allow surfaces to be examined and measured under laboratory conditions. A replica can be taken from all solid materials.

NDT is divided into various *methods* of nondestructive testing, each based on a particular scientific principle. These methods may be further subdivided into various *techniques*. The various methods and techniques, due to their particular natures, may lend themselves especially well to certain applications and be of little or no value at all in other applications. Therefore choosing the right method and technique is an important part of the performance of NDT.

- Acoustic emission testing (AE or AT)
- Blue Etch Anodize (BEA)

- Dye penetrant inspection Liquid penetrant testing (PT or LPI)
- Electromagnetic testing (ET)
  - Alternating current field measurement (ACFM)
  - Alternating current potential drop measurement (ACPD)
  - Barkhausen testing
  - Direct current potential drop measurement (DCPD)
  - Eddy-current testing (ECT)
  - Magnetic flux leakage testing (MFL) for pipelines, tank floors, and wire rope
  - Magnetic-particle inspection (MT or MPI)
  - Remote field testing (RFT)
- Ellipsometry
- Guided wave testing (GWT)
- Hardness testing
- Impulse excitation technique (IET)
- Infrared and thermal testing (IR)
  - Thermographic inspection
- Laser testing
  - Electronic speckle pattern interferometry
  - Holographic interferometry
  - Low coherence interferometry
  - Profilometry
  - Shearography
- Leak testing (LT) or Leak detection
  - Absolute pressure leak testing (pressure change)
  - Bubble testing
  - Halogen diode leak testing
  - Hydrogen leak testing
  - Mass spectrometer leak testing
  - Tracer-gas leak testing method Helium, Hydrogen and refrigerant gases
- Magnetic resonance imaging (MRI) and NMR spectroscopy
- Optical microscopy
- Positive Material Identification (PMI)
- Radiographic testing (RT)
  - Computed radiography
  - Digital radiography (real-time)
  - Neutron radiographic testing (NR)
  - SCAR (Small Controlled Area Radiography)
  - X-ray computed tomography (CT)
- Scanning electron microscopy
- Surface Temper Etch (Nital Etch)
- Ultrasonic testing (UT)
  - ART (Acoustic Resonance Technology)
  - Electro Magnetic Acoustic Transducer (EMAT) (non-contact)
  - Laser ultrasonics (LUT)
  - Internal rotary inspection system (IRIS) ultrasonics for tubes

- Phased array ultrasonics
  - Time of flight diffraction ultrasonics (TOFD)
  - Time of Flight Ultrasonic Determination of 3D Elastic Constants (TOF)
- Visual inspection (VT)
  - Pipeline video inspection
- Corroscan/C-scan
- IRIS - Internal Rotary Inspection System
- 3D Tomography
- Heat Exchanger Life Assessment System
- RTJ Flange Special Ultrasonic Testing

## ***Personnel qualification and certification***

Succesful and consistent application of nondestructive testing techniques depends heavily on personnel training and experience. Personnel involved in application of industrial NDT methods and interpretation of results should be certified, and in some industrial sectors certification is enforced by law or by the applied codes and standards.

### **Definitions**

The following definitions for *qualification* and *certification* are given in ISO 9712 and EN 473:

- **Certification:** "Procedure, used by the certification body to confirm that the qualification requirements for a method, level and sector have been fulfilled, leading to the issuing of a certificate".
- **Qualification:** "Demonstration of physical attributes, knowledge, skill, training and experience required to properly perform NDT tasks".

In US standards and codes, while a very similar definition of qualification is included in ASNT SNT-TC-1A, certification is simply defined as: "Written testimony of qualification".

### **Certification schemes**

There are two approaches in personnel certification:

1. **Employer Based Certification:** Under this system the employer compiles their own *Written Practice*. The written practice defines the responsibilities of each level of certification, as implemented by the company, and describes the training, experience and examination requirements for each level of certification. In industrial sectors the written practices are usually based on recommended practice SNT-TC-1A of the American Society for Nondestructive Testing. ANSI standard CP-189 outlines requirements for any written practice that conforms to the standard.

2. **Personal Central Certification:** The concept of central certification is that an NDT operator can obtain certification from a central certification authority, that is recognised by most employers, third parties and/or government authorities. Industrial standards for central certification schemes are ISO 9712 and EN 473. Certification under these standards involves training, work experience under supervision and passing a written and practical examination set up by the independent certification authority.

In the United States employer based schemes are the norm, however central certification schemes exist as well. The most notable is *ASNT Level III* (established in 1976-1977), which is organized by the American Society for Nondestructive Testing for Level 3 NDT personnel.

*NAVSEA 250-1500* is another US central certification scheme, specifically developed for use in the naval nuclear program.

Central certification is more widely used in the European Union, where certifications are issued by accredited bodies (independent organizations conforming to ISO 17024 and accredited by a national accreditation authority like UKAS). The Pressure Equipment Directive (97/23/EEC) actually enforces personnel certification to EN 473 for the initial testing of steam boilers and some categories of pressure vessels and piping. Certifications issued by a national NDT society which is a member of the European Federation of NDT (EFNDT) are mutually acceptable by the other member societies under a multilateral recognition agreement.

Canada also implements an ISO 9712 central certification scheme, which is administered by Natural Resources Canada, a government department.

The aerospace sector worldwide sticks to employer based schemes. In America it is based mostly on AIA-NAS-410 and in the European Union on the equivalent and very similar standard EN 4179

## **Levels of certification**

Most NDT personnel certification schemes listed above specify three "levels" of qualification and/or certification, usually designated as *Level 1*, *Level 2* and *Level 3* (although some codes specify roman numerals, like *Level II*). The roles and responsibilities of personnel in each level are generally as follows (there are slight differences or variations between different codes and standards):

- **Level 1** are technicians qualified to perform only specific calibrations and tests under close supervision and direction by higher level personnel. They can only report test results. Normally they work following specific work instructions for testing procedures and rejection criteria.

- **Level 2** are engineers or experienced technicians who are able to set up and calibrate testing equipment, conduct the inspection according to codes and standards (instead of following work instructions) and compile work instructions for Level 1 technicians. They are also authorized to report, interpret, evaluate and document testing results. They can also supervise and train Level 1 technicians. In addition to testing methods, they must be familiar with applicable codes and standards and have some knowledge of the manufacture and service of tested products.
- **Level 3** are usually specialized engineers or very experienced technicians. They can establish NDT techniques and procedures and interpret codes and standards. They also direct NDT laboratories and have central role in personnel certification. They are expected to have wider knowledge covering materials, fabrication and product technology.

## **Terminology**

### Indication

The response or evidence from an examination, such as a blip on the screen of an instrument. Indications are classified as *true* or *false*. *False indications* are those caused by factors not related to the principles of the testing method or by improper implementation of the method, like film damage in radiography, electrical interference in ultrasonic testing etc. *True indications* are further classified as *relevant* and *non relevant*. *Relevant indications* are those caused by flaws. *Non relevant indications* are those caused by known features of the tested object, like gaps, threads, case hardening etc.

### Interpretation

Determining if an indication is of a type to be investigated. For example, in electromagnetic testing, indications from metal loss are considered flaws because they should usually be investigated, but indications due to variations in the material properties may be harmless and nonrelevant.

### Flaw

A type of discontinuity that must be investigated to see if it is rejectable. For example, porosity in a weld or metal loss.

### Evaluation

Determining if a flaw is rejectable. For example, is porosity in a weld larger than acceptable by code?

### Defect

A flaw that is rejectable — i.e. does not meet acceptance criteria. Defects are generally removed or repaired.

### Penetrant testing

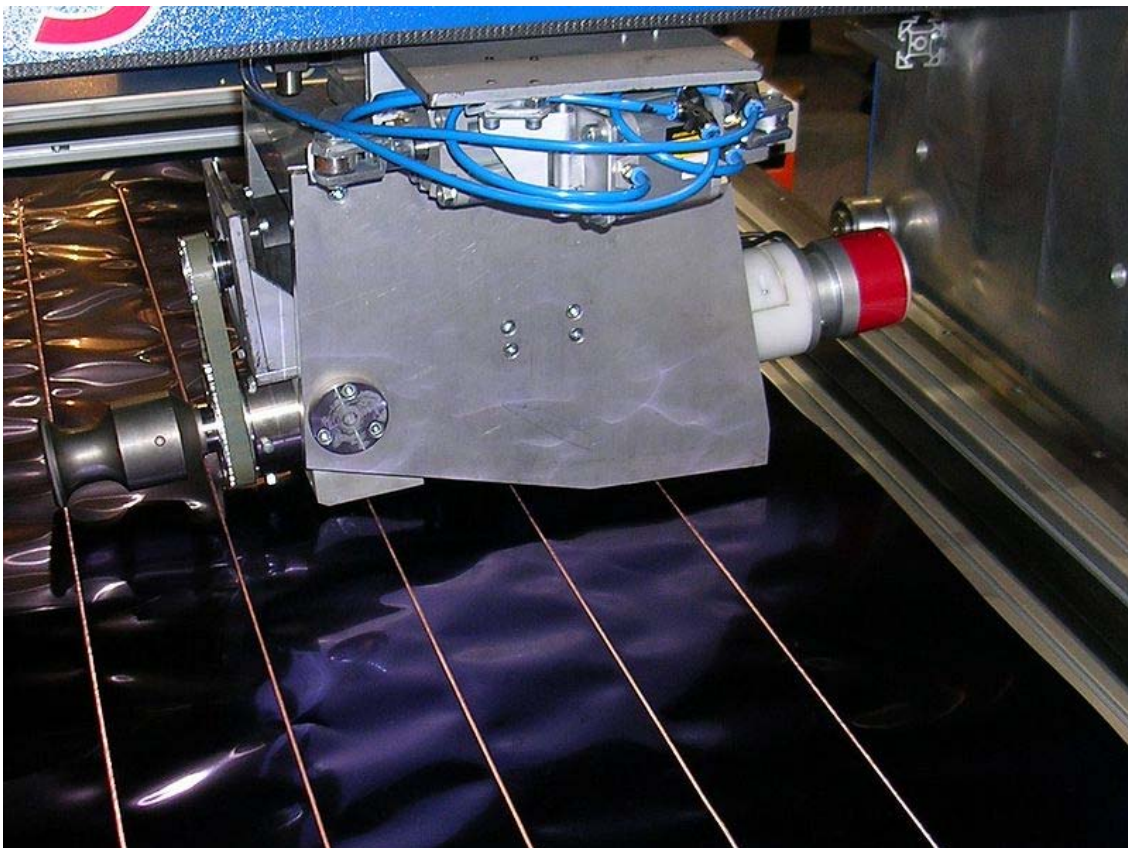
Non-destructive test typically comprising a penetrant, a method of excess removal and a developer to produce a visible indication of surface-breaking discontinuities.

## ***Reliability and statistics***

Defect detection tests are among the more commonly employed of non-destructive tests. The evaluation of NDT reliability commonly contains two statistical errors. First, most tests fail to define the objects that are called "sampling units" in statistics; it follows that the reliability of the tests cannot be established. Second, the literature usually misuses statistical terms in such a way as to make it sound as though sampling units *are* defined. These two errors may lead to incorrect estimates of probability of detection.

## Chapter-18

# Ultrasonic Welding



Ultrasonic welding of thin metallic foils. The sonotrode is rotated along the weld seam.

**Ultrasonic welding** is an industrial technique whereby high-frequency ultrasonic acoustic vibrations are locally applied to workpieces being held together under pressure to create a solid-state weld. It is commonly used for plastics, and especially for joining dissimilar materials. In ultrasonic welding, there are no connective bolts, nails, soldering materials, or adhesives necessary to bind the materials together.

## ***History***

In 1960 Sonobond Ultrasonics, originally known as Aeroprojects, Incorporated, developed the first metal ultrasonic welding machine to be awarded a United States Patent.

## ***Process***

For joining complex injection molded thermoplastic parts, ultrasonic welding equipment can be easily customized to fit the exact specifications of the parts being welded. The parts are sandwiched between a fixed shaped nest (anvil) and a sonotrode (horn) connected to a transducer, and a ~20 kHz low-amplitude acoustic vibration is emitted. (Note: Common frequencies used in ultrasonic welding of thermoplastics are 15 kHz, 20 kHz, 30 kHz, 35 kHz, 40 kHz and 70 kHz). When welding plastics, the interface of the two parts is specially designed to concentrate the melting process. One of the materials usually has a spiked energy director which contacts the second plastic part. The ultrasonic energy melts the point contact between the parts, creating a joint. This process is a good automated alternative to glue, screws or snap-fit designs. It is typically used with small parts (e.g. cell phones, consumer electronics, disposable medical tools, toys, etc.) but it can be used on parts as large as a small automotive instrument cluster. Ultrasonics can also be used to weld metals, but are typically limited to small welds of thin, malleable metals, e.g. aluminum, copper, nickel. Ultrasonics would not be used in welding the chassis of an automobile or in welding pieces of a bicycle together, due to the power levels required.

Ultrasonic welding of thermoplastics causes local melting of the plastic due to absorption of vibration energy. The vibrations are introduced across the joint to be welded. In metals, Ultrasonic welding occurs due to high-pressure dispersion of surface oxides and local motion of the materials. Although there is heating, it is not enough to melt the base materials. Vibrations are introduced along the joint being welded.

Practical application of ultrasonic welding for rigid plastics was completed in the 1960s. At this point only hard plastics could be welded. The patent for the ultrasonic method for welding rigid thermoplastic parts was awarded to Robert Soloff and Seymour Linsley in 1965. Soloff, the founder of Sonics & Materials Inc., was a lab manager at Branson Instruments where thin plastic films were welded into bags and tubes using ultrasonic probes. He unintentionally moved the probe close to a plastic tape dispenser and the halves of the dispenser welded together. He realized that the probe did not need to be manually moved around the part but that the ultrasonic energy could travel through and around rigid plastics and weld an entire joint. He went on to develop the first ultrasonic press. The first application of this new technology was in the toy industry.

The first car made entirely out of plastic was assembled using ultrasonic welding in 1969. Even though plastic cars did not catch on ultrasonic welding did. The automotive industry has used it regularly since the 1980s. It is now used for a multitude of applications.

Ultrasonic welding can be used for both hard and soft plastics, such as semicrystalline plastics, and metals. Ultrasonic welding machines also have much more power now. The understanding of ultrasonic welding has increased with research and testing. The invention of more sophisticated and inexpensive equipment and increased demand for plastic and electronic components has led to a growing knowledge of the fundamental process. However, many aspects of ultrasonic welding still require more study, such as relating weld quality to process parameters. Ultrasonic welding continues to be a rapidly developing field.

Benefits of Ultrasonic welding are that it is much faster than conventional adhesives or solvents. Drying time is very quick, the pieces do not need to remain in a jig for long periods of time waiting for the joint to dry or cure. The welding can easily be automated also, making clean and precise joints. Site of the weld is also very clean not needing any touch up to material and bond.

## ***Components***

All ultrasonic welding systems are composed of the same basic elements:

- A press to put the 2 parts to be assembled under pressure
- A nest or anvil where the parts are placed and allowing the high frequency vibration to be directed to the interfaces
- An ultrasonic stack composed of a converter or piezoelectric transducer, an optional booster and a sonotrode (US: Horn). All three elements of the stack are specifically tuned to resonate at the same exact ultrasonic frequency (Typically 20, 30, 35 or 40 kHz)
  - Converter: Converts the electrical signal into a mechanical vibration
  - Booster: Modifies the amplitude of the vibration. It is also used in standard systems to clamp the stack in the press.
  - Sonotrode: Applies the mechanical vibration to the parts to be welded.
- An electronic ultrasonic generator (US: Power supply) delivering a high power AC signal with frequency matching the resonance frequency of the stack.
- A controller controlling the movement of the press and the delivery of the ultrasonic energy.

## ***Applications***

The applications of ultrasonic welding are extensive and are found in many industries including electrical and computer, automotive and aerospace, medical, and packaging. Whether two items can be ultrasonically welded is determined by their thickness. If they are too thick this process will not join them. This is the main obstacle in the welding of metals. However, wires, microcircuit connections, sheet metal, foils, ribbons and meshes are often joined using ultrasonic welding. Ultrasonic welding is a very popular technique for bonding thermoplastics. It is fast and easily automated with weld times often below one second and there is no ventilation system required to remove heat or exhaust. This

type of welding is often used to build assemblies that are too small, too complex, or too delicate for more common welding techniques.

### **Computer and electrical industries**

In the electrical and computer industry ultrasonic welding is often used to join wired connections and to create connections in small, delicate circuits. Junctions of wire harnesses are often joined using ultrasonic welding. Wire harnesses are large groupings of wires used to distribute electrical signals and power. Electric motors, field coils, transformers and capacitors may also be assembled with ultrasonic welding. It is also often preferred in the assembly of storage media such as flash drives and computer disks because of the high volumes required. Ultrasonic welding of computer disks has been found to have cycle times of less than 300 ms.

One of the areas in which ultrasonic welding is most used and where new research and experimentation is centered is microcircuits. This process is ideal for microcircuits since it creates reliable bonds without introducing impurities or thermal distortion into components. Semiconductor devices, transistors and diodes are often connected by thin aluminum and gold wires using ultrasonic welding. It is also used for bonding wiring and ribbons as well as entire chips to microcircuits. An example of where microcircuits are used is in medical sensors used to monitor the human heart in bypass patients.

One difference between ultrasonic welding and traditional welding is the ability of ultrasonic welding to join dissimilar materials. The assembly of battery components is a good example of where this ability is utilized. When creating battery and fuel cell components, thin gauge copper, nickel and aluminum connections, foil layers and metal meshes are often ultrasonically welded together. Multiple layers of foil or mesh can often be applied in a single weld eliminating steps and cost.

### **Aerospace and automotive industries**

For automobiles, ultrasonic welding tends to be utilized in the assembly of large plastic components and electrical components such as instrument panels, door panels, lamps, air ducts, steering wheels, upholstery and engine components. As plastics have continued to replace other materials in the design and manufacture of automobiles, the assembly and joining of plastic components has increasingly become a critical issue. Some of the advantages for ultrasonic welding are low cycle times, automation, low capital costs, and flexibility. Also, ultrasonic welding does not damage surface finish, which is a crucial consideration for many car manufacturers, because the high-frequency vibrations prevent marks from being generated.

Ultrasonic welding is generally utilized in the aerospace industry when joining thin sheet gauge metals and other lightweight materials. Aluminum is a difficult metal to weld using traditional techniques because of its high thermal conductivity. However, it is one of the easier materials to weld using ultrasonic welding because it is a softer alloy metal and thus a solid-state weld is simple to achieve. Since aluminum is so widely used in the

aerospace industry, it follows that ultrasonic welding is an important manufacturing process. Also, with the advent of new composite materials, ultrasonic welding is becoming even more prevalent. It has been used in the bonding of the popular composite material carbon fiber. Numerous studies have been done to find the optimum parameters that will produce quality welds for this material.

### **Medical industry**

In the medical industry ultrasonic welding is often used because it does not introduce contaminants or degradation into the weld and the machines can be specialized for use in clean rooms. The process can also be highly automated, provides strict control over dimensional tolerances and does not interfere with the biocompatibility of parts. Therefore, it increases part quality and decreases production costs. Items such as arterial filters, anesthesia filters, blood filters, IV catheters, dialysis tubes, pipettes, cardiometry reservoirs, blood/gas filters, face masks and IV spike/filters can all be made using ultrasonic welding. Another important application in the medical industry for ultrasonic welding is textiles. Items like hospital gowns, sterile garments, masks, transdermal patches and textiles for clean rooms can be sealed and sewn using ultrasonic welding. This prevents contamination and dust production and reduces the risk of infection.

### **Packaging industry**



Butane lighter

Packaging is perhaps the application in which ultrasonic welding is most often used. Many everyday items are either created or packaged using ultrasonic welding techniques. Sealing containers, tubes and blister packs are some common applications.

Ultrasonic welding is also applied in the packaging of dangerous materials such as explosives, fireworks and other reactive chemicals. These items tend to require hermetic sealing but cannot be subjected to high temperatures. One simple example of this application is the container for a butane lighter. This container weld must be able to withstand high pressure and stress and must be airtight to contain the butane. Another example is the packaging of ammunition and propellants. These packages must be able to withstand high pressure and stresses in order to protect the consumer from the contents. When sealing hazardous materials, safety is a primary concern.

The food industry finds ultrasonic welding preferable to traditional joining techniques because it is fast, sanitary and can produce hermetic seals. Milk and juice containers are examples of some products that are often sealed using ultrasonic welding. The paper parts to be sealed are coated with plastic, generally polypropylene or polyethylene, and then welded together to create an airtight seal. The main obstacle to overcome in this process is the setting of the parameters. For example, if over-welding occurs then the concentration of plastic in the weld zone may be too low and cause the seal to break. If it is under-welded the seal is incomplete. Variations in the thicknesses of materials can cause variations in weld quality. Some other food items that are sealed using ultrasonic welding include candy bar wrappers, frozen food packages and beverage containers.

The electrical and computer, automotive, aerospace, medical, and packaging industries are some of the industries which utilize ultrasonic welding. This process is used to assemble everything from microcircuits to milk cartons. It is increasing in popularity throughout many of these industries because of low cycle times, automation, low capital costs, flexibility, cleanliness, dimensional reliability and the bonding of dissimilar materials. Some of the drawbacks of ultrasonic welding are that its use is limited by the thickness of the materials, it may require expensive specialized tooling and it may generate noise.

## **Safety**

Ultrasonic welding machines, like most industrial equipment, pose the risk of some hazards. These include exposure to high heat levels and voltages. This equipment should always be operated using the safety guidelines provided by the manufacturer in order to avoid injury. For instance, operators must never place hands or arms near the welding tip when the machine is activated. Also, operators should be provided with hearing protection and safety glasses. Operators should be informed of the OSHA regulations for the ultrasonic welding equipment and these regulations should be enforced.

Ultrasonic welding machines must receive routine maintenance and inspection. Panel doors, housing covers and protective guards may need to be removed for maintenance.

This should be done when the power to the equipment is off and only by the trained professional who is servicing the machine.

Since this is an ultrasonic process it would seem that sound would not be an issue. However, sub-harmonic vibrations, which can create annoying audible noise, may be caused in larger parts near the machine due to the ultrasonic welding frequency. This noise can be dampened by clamping these large parts at one or more locations. Also, high-powered welders with frequencies of 15 kHz and 20 kHz typically emit a potentially damaging high-pitched squeal in the range of human hearing. Shielding this radiating sound can be done using an acoustic enclosure. In short, there are hearing and safety concerns with ultrasonic welding that are important to consider, but generally they are comparable to those of other welding techniques.

## Chapter-19

# Welding Defect

A **welding defect** is any flaw that compromises the usefulness of the finished weldment.

According to the American Society of Mechanical Engineers (ASME) welding defect causes are broken down into the following percentages: 41% poor process conditions, 32% operator error, 12% wrong technique, 10% incorrect consumables, and 5% bad weld grooves.

### **Major causes**

#### **Residual stresses**

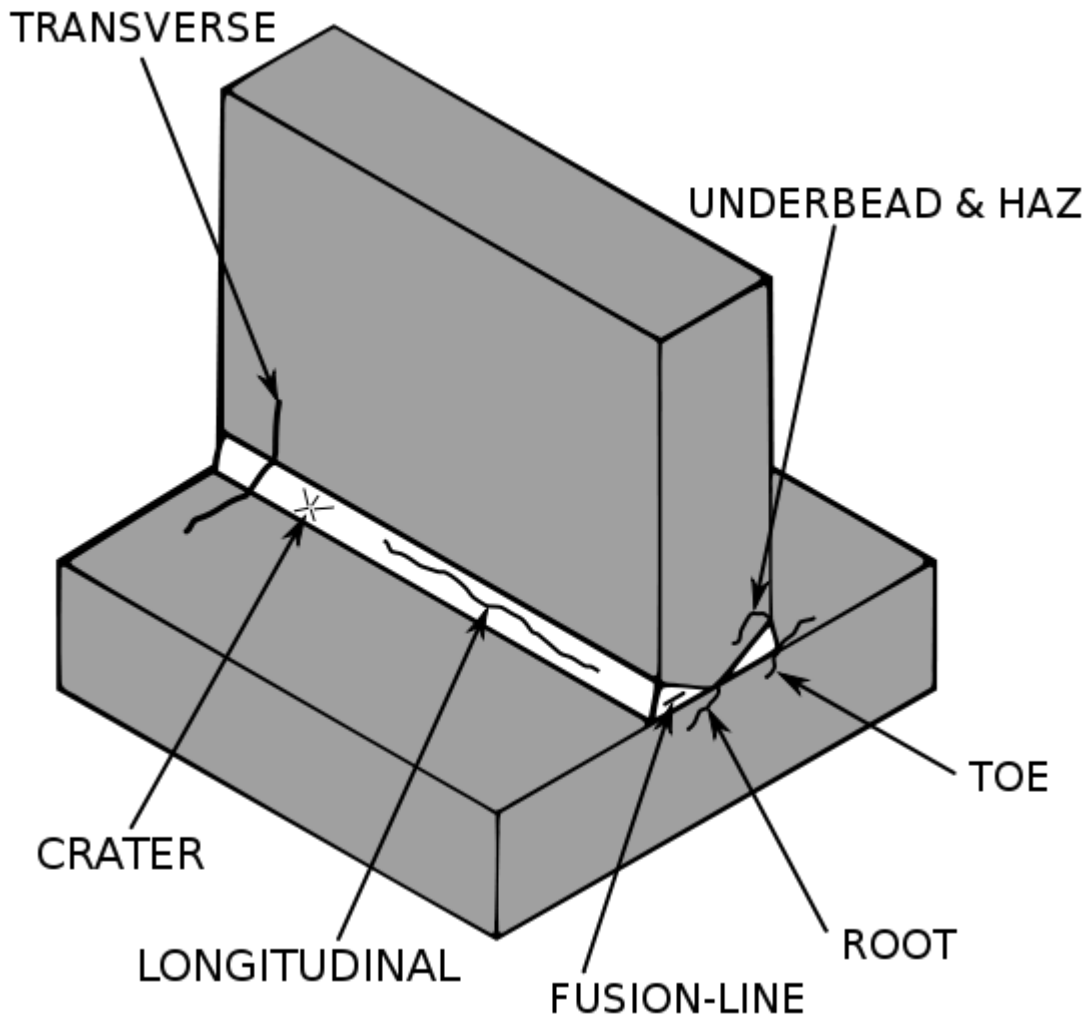
The magnitude of stress that can be formed from welding can be roughly calculated using:

$$E\alpha\Delta T$$

Where E is Young's modulus,  $\alpha$  is the coefficient of thermal expansion, and  $\Delta T$  is the temperature change. For steel this calculates out to be approximately 3.5 GPa (510,000 psi).

## Types

### Cracks



Defects related to fracture.

### Arc strike cracking

Arc strike cracking occurs when the arc is struck but the spot is not welded. This occurs because the spot is heated above the materials upper critical temperature and then essentially quenched. This forms martensite, which is brittle, and micro-cracks. Usually the arc is struck in the weld groove so this type of crack does not occur, but if the arc is struck outside of the weld groove then it must be welded over to prevent the cracking. If this is not an option then the arc spot can be postheated, *i.e.*, the area is heated with an oxy-acetylene torch, and then allowed to cool slowly.

## **Cold cracking**

Residual stresses can reduce the strength of the base material, and can lead to catastrophic failure through cold cracking, as in the case of several of the Liberty ships. Cold cracking is limited to steels, and is associated with the formation of martensite as the weld cools. The cracking occurs in the heat-affected zone of the base material. To reduce the amount of distortion and residual stresses, the amount of heat input should be limited, and the welding sequence used should not be from one end directly to the other, but rather in segments.

Cold cracking only occurs when all the following preconditions are met:

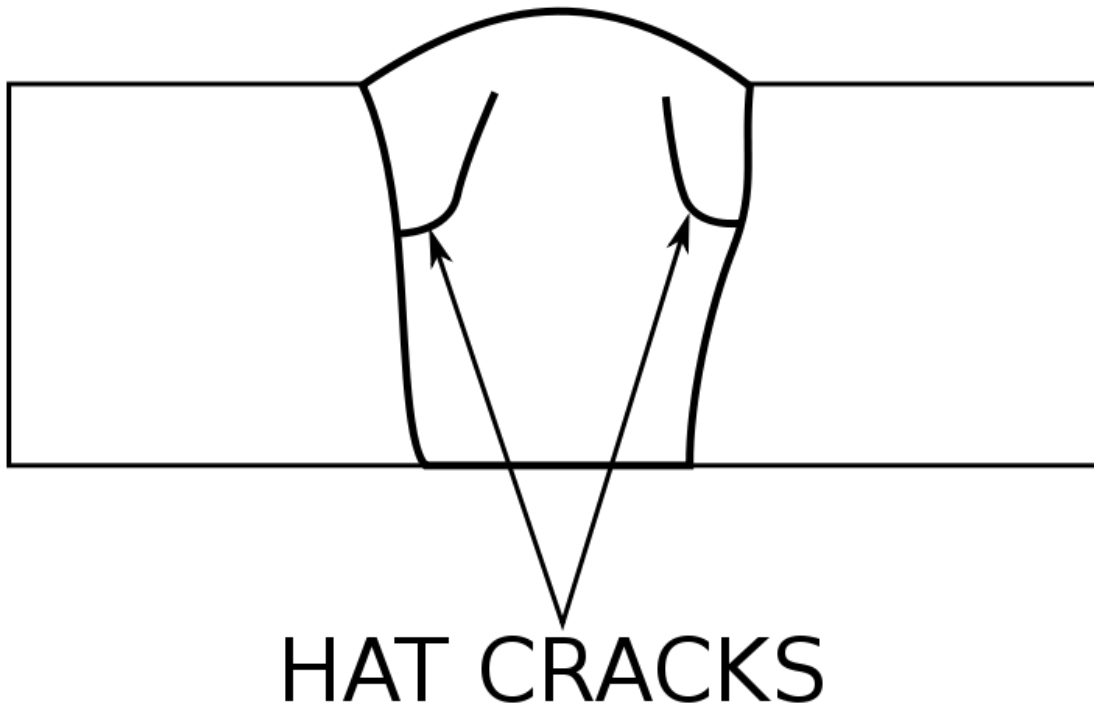
- susceptible microstructure (*e.g.* martensite)
- hydrogen present in the microstructure (hydrogen embrittlement)
- service temperature environment (normal atmospheric pressure): -100 to +100 °F
- high restraint

Eliminating any one of these will eliminate this condition.

## **Crater crack**

Crater cracks occur when a crater is not filled before the arc is broken. This causes the outer edges of the crater to cool more quickly than the crater, which creates sufficient stresses to form a crack. It may form a longitudinal or transverse crack or form multiple radial cracks.

## Hat crack



Hat cracks get their name from the shape of the cross-section of the weld, because the weld flares out at the face of the weld. The crack starts at the fusion line and extends up through the weld. They are usually caused by too much voltage or not enough speed.

## Hot cracking

Hot cracking, also known as solidification cracking, can occur with all metals, and happens in the fusion zone of a weld. To diminish the probability of this type of cracking, excess material restraint should be avoided, and a proper filler material should be utilized. Other causes include too high welding current, poor joint design that does not diffuse heat, impurities (such as sulfur and phosphorus), preheating, speed is too fast, and long arcs.

## Underbead crack

An underbead crack, also known as a heat-affected zone (HAZ) crack, is a crack that forms a short distance away from the fusion line; it occurs in low alloy and high alloy steel. The exact causes of this type of crack are not completely understood, but it is known that dissolved hydrogen must be present. The other factor that affects this type of crack is internal stresses resulting from: unequal contraction between the base metal and the weld metal, restraint of the base metal, stresses from the formation of martensite, and stresses from the precipitation of hydrogen out of the metal.

## Longitudinal crack

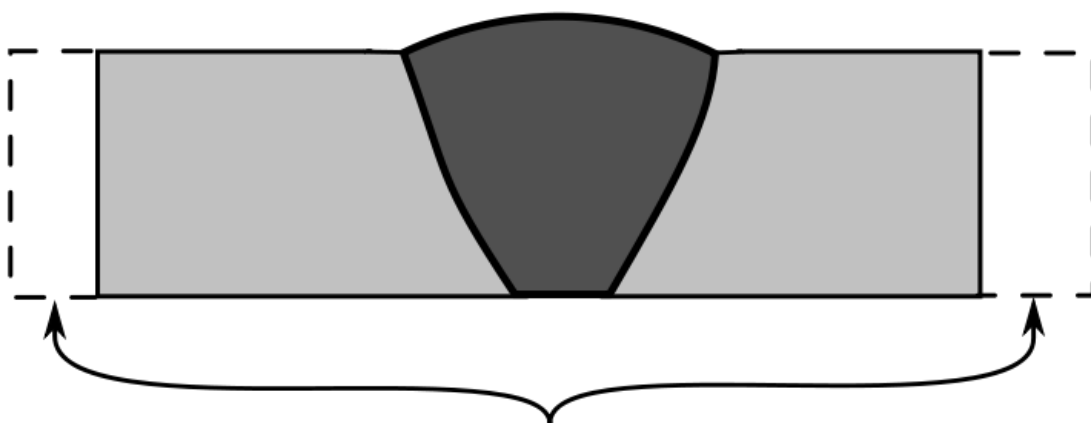
Longitudinal cracks run along the length of a weld bead. There are three types: *check cracks*, *root cracks*, and *full centerline cracks*. Check cracks are visible from the surface and extend partially into weld. They are usually caused by high shrinkage stresses, especially on final passes, or by a hot cracking mechanism. Root cracks start at the root and extend part way into the weld. They are the most common type of longitudinal crack because of the small size of the first weld bead. If this type of crack is not addressed then it will usually propagate into subsequent weld passes, which is how full centerline cracks (a crack from the root to the surface) usually form.

## Reheat cracking

Reheat cracking is a type of cracking that occurs in HSLA steels, particularly chromium, molybdenum and vanadium steels, during postheating. It is caused by the poor creep ductility of the heat affected zone. Any existing defects or notches aggravate crack formation. Things that help prevent reheat cracking include heat treating first with a low temperature soak and then with a rapid heating to high temperatures, grinding or peening the weld toes, and using a two layer welding technique to refine the HAZ grain structure.

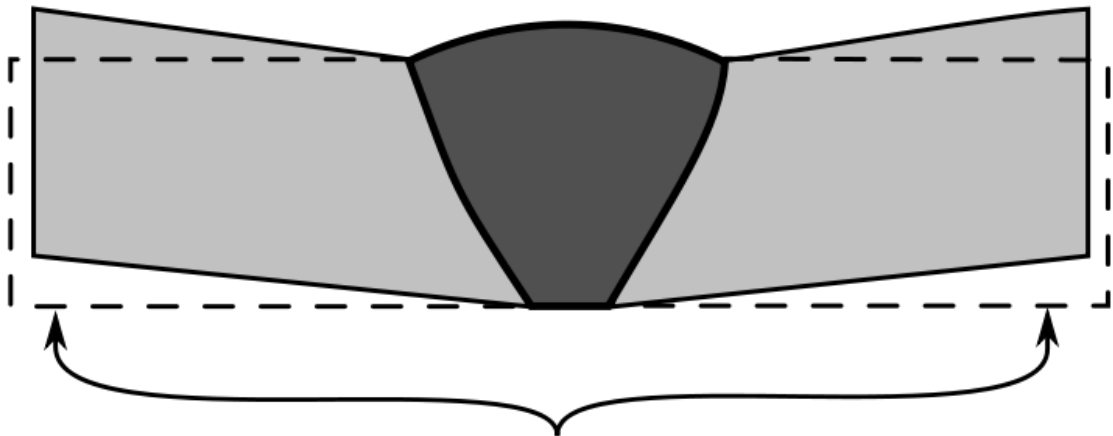
## Distortion

Welding methods that involve the melting of metal at the site of the joint necessarily are prone to shrinkage as the heated metal cools. Shrinkage then introduces residual stresses and distortion. Distortion can pose a major problem, since the final product is not the desired shape. To alleviate certain types of distortion the workpieces can be offset so that after welding the product is the correct shape. The following pictures describe various types of welding distortion:



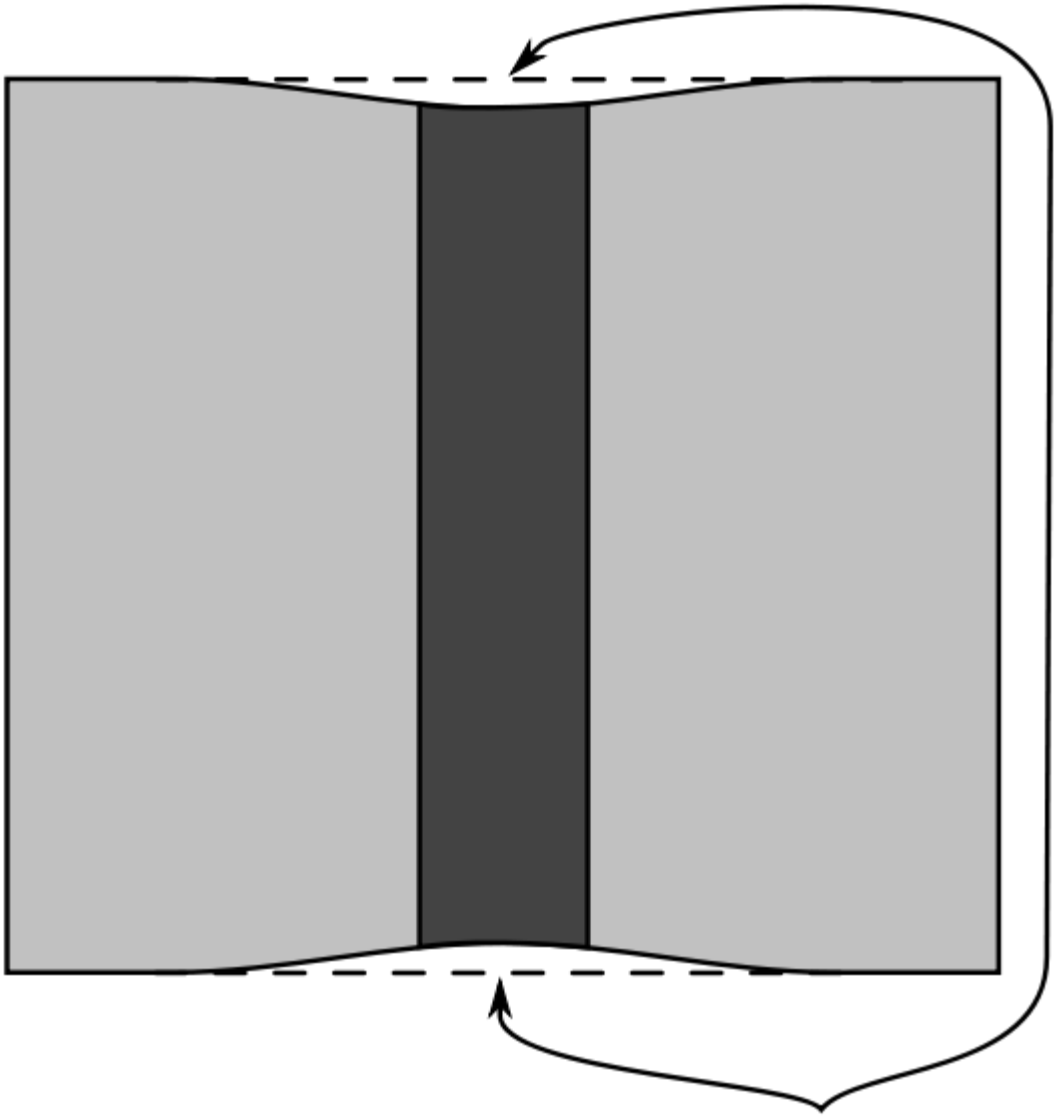
**ORIGINAL SIZE**

Transverse shrinkage



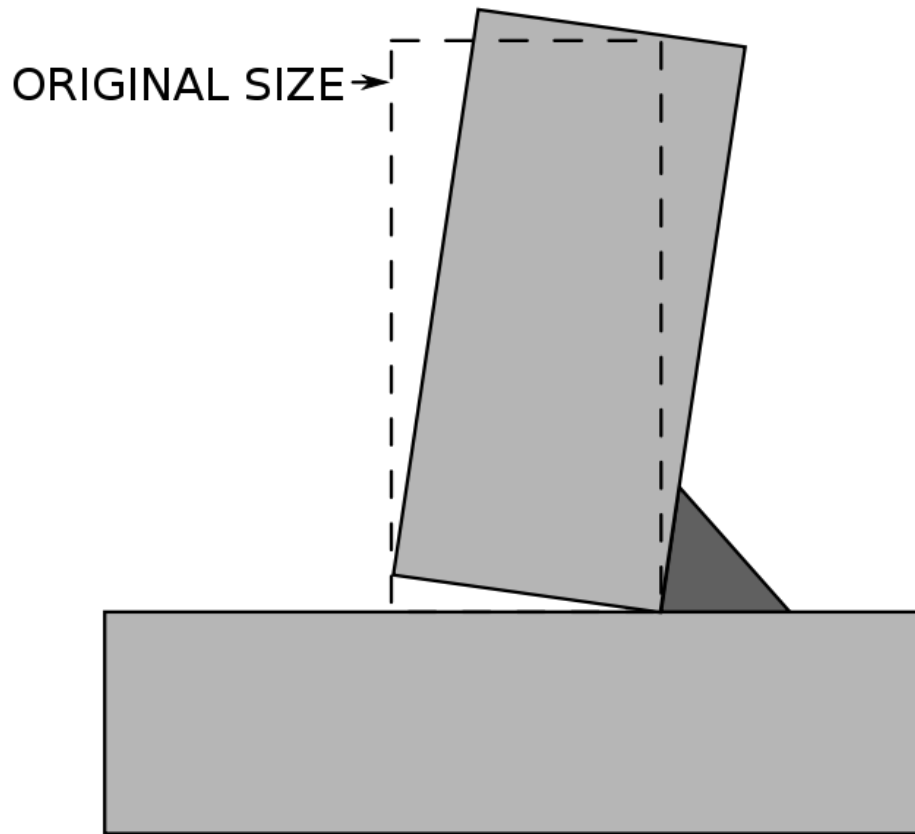
**ORIGINAL SIZE**

Angular distortion

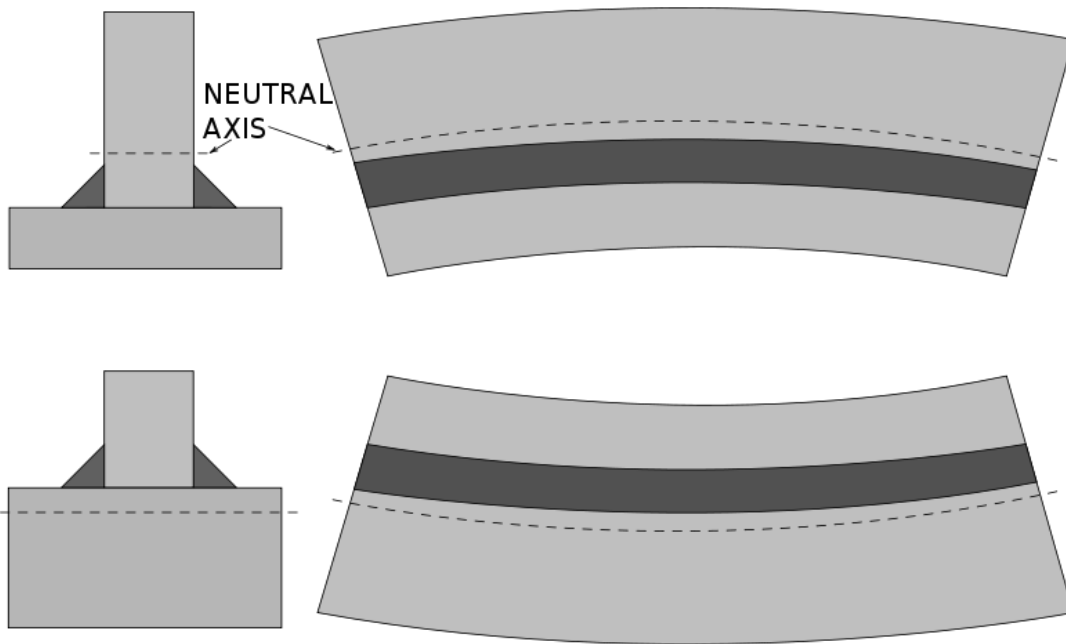


**ORIGINAL SIZE**

Longitudinal shrinkage



Fillet distortion



Neutral axis distortion

## **Gas inclusion**

Gas inclusions is a wide variety of defects that includes *porosity*, *blow holes*, and *pipes* (or *wormholes*). The underlying cause for gas inclusions is the entrapment of gas within the solidified weld. Gas formation can be from any of the following causes: high sulfur content in the workpiece or electrode, excessive moisture from the electrode or workpiece, too short of an arc, or wrong welding current or polarity.

## **Inclusions**

There are two types of inclusions: *linear inclusions* and *isolated inclusions*. Linear inclusions occur when there is slag or flux in the weld. Slag forms from the use of a flux, which is why this type of defect usually occurs in welding processes that use flux, such as shielded metal arc welding, flux-cored arc welding, and submerged arc welding, but it can also occur in gas metal arc welding. This defect usually occurs in welds that require multiple passes and there is poor overlap between the welds. The poor overlap does not allow the slag from the previous weld to melt out and rise to the top of the new weld bead. It can also occur if the previous weld left and undercut or an uneven surface profile. To prevent slag inclusions the slag should be cleaned from the weld bead between passes via grinding, wire brushing, or chipping.

Isolated inclusions occur when rust or mill scale is present on the base metal.

## **Lack of fusion and incomplete penetration**

Lack of fusion is the poor adhesion of the weld bead to the base metal; incomplete penetration is a weld bead that does not start at the root of the weld groove. Incomplete penetration forms channels and crevices in the root of the weld which can cause serious issues in pipes because corrosive substances can settle in these areas. These types of defects occur when the welding procedures are not adhered to; possible causes include the current setting, arc length, electrode angle, and electrode manipulation.

## **Lamellar tearing**

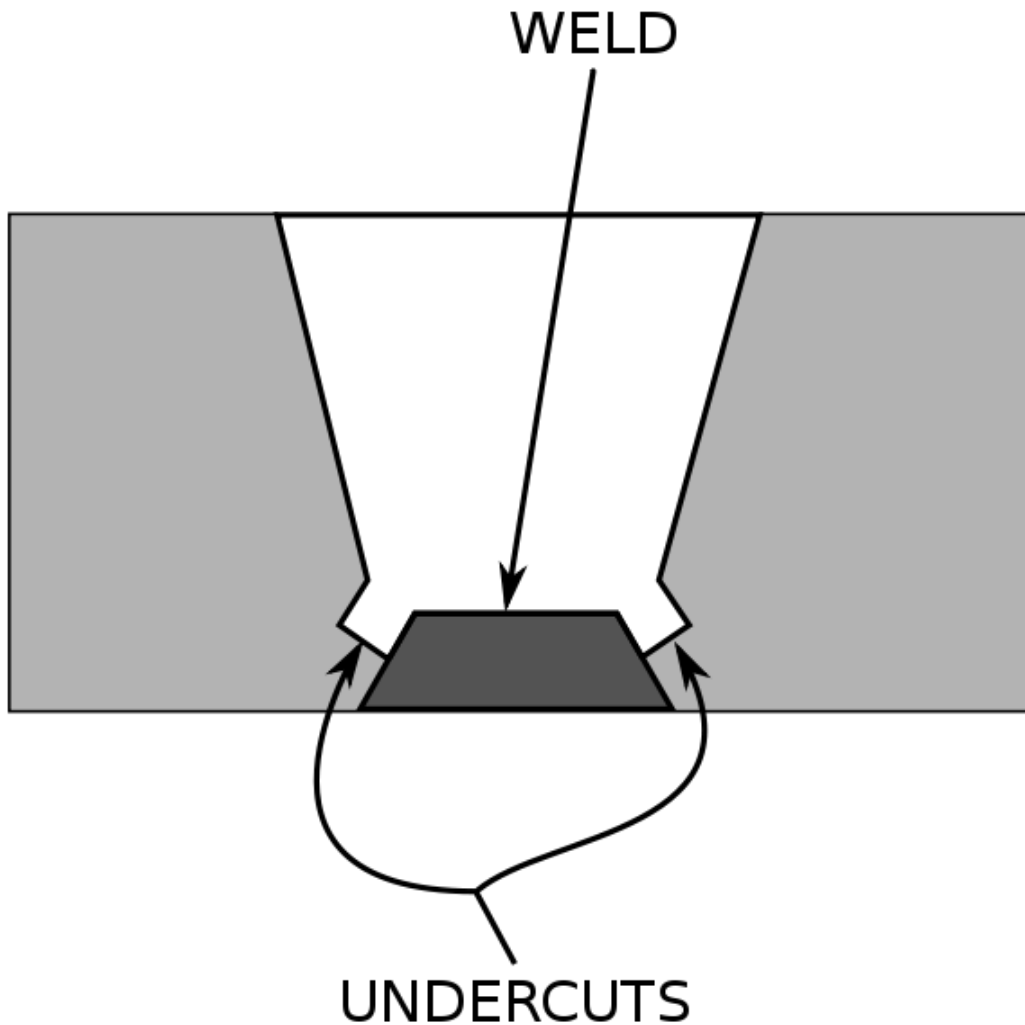
Lamellar tearing is a type of welding defect that occurs in rolled steel plates. It has rarely been an issue since the 1970s because steel produced since then has less sulfur.

There is a combination of causes: non-metallic inclusions, too much hydrogen in the material, and shrinkage forces perpendicular to the face of the plates. The main factor among these reasons is the non-metal inclusions, of which the sulfur is the main problem. Lamellar tearing is no longer a problem anymore because sulfur levels are typically kept below 0.005%.

Some things that are done to overcome lamellar tearing are: reducing amount of sulfur in the material or adding alloying elements that control the shape of sulfide inclusions, such as rare earth elements, zirconium, or calcium. A more drastic option is change the

workpieces to castings or forgings because this type of defect does not occur in those workpieces.

## Undercut



Undercutting is when the weld reduces the cross-sectional thickness of the base metal, which reduces the strength of the weld and workpieces. One reason for this type of defect is excessive current, causing the edges of the joint to melt and drain into the weld; this leaves a drain-like impression along the length of the weld. Another reason is if a poor technique is used that does not deposit enough filler metal along the edges of the weld. A third reason is using an incorrect filler metal, because it will create greater temperature gradients between the center of the weld and the edges. Other causes include too small of an electrode angle, a dampened electrode, excessive arc length, and slow speed.