Welding and heat treatment

Module_4

Industrial Technology

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Welding and heat treatment

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1.   WELDING

1.1.   WELDED JOINT

A welded joint is a non-detachable joint. Despite its many drawbacks, welded joints are widely used as a very versatile joining technology. It is used effectively in both component manufacturing and the construction of large structures.

From the point of view of the materials to be joined, we are now only concerned with the welding of metals and alloys, i.e. the welded joint is the metallic bond. To form a cohesive bond between the atoms of the particles, the atoms need to be brought closer together by a distance of a few lattice parameters. This can be done just by force or heat or a combination of heat and force. This is one of the criteria by which welding processes can be categorised.

1.2.   REQUIREMENTS FOR WELDED JOINTS

A welded joint creates metallic material continuity throughout the structure or a significant part of the structure. Therefore, not only their local properties are important, but also their influence on the whole construction. Local properties of a welded joint are: lack of cracks, strength, toughness, inclusivity and metallurgical structure. These qualities can be ensured by planning and adhering to the work procedure specification. Requirements for the impact on the construction are: safety against brittle fracture, fatigue and corrosion resistance of the structure. These requirements can be met by the right choice of materials and are closely related to the stresses on the structure.

1.3.   WELDABILITY

Weldability is a set of conditions under which the welded joint meets the requirements. The definition of weldability should be based on the requirements for the joint, taking into account the quality of the material to be welded and the technology used.
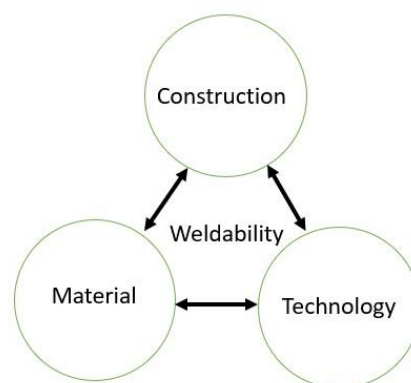
1. Figure Main factors affecting weldability

This also shows that there is no universal solution to this set of conditions, but that they must always be defined in a specific case. If a technology produces a welded joint that meets the requirements under normal conditions, it is called unconditional weldability. Of course, in this case, competence and workmanship cannot be ignored. For materials with poorer weldability properties, normal conditions do not ensure a good quality joint, but only some special conditions guarantee suitability, called conditional weldability. This condition can be preheating before welding, keeping the heat input within strict limits, or immediate post-weld heat treatment.

1.4. WELDING PROCESSES

Due to the limitations of the book, only the basic principles of these processes are described, without going into technological details.

1.4.1. SOLID-STATE WELDING PROCESSES

In solid state welding processes, the closing of the atoms to a grid parameter distance is achieved by mechanical work without melting the workpieces, and plastic deformation plays a crucial role in this. The mechanical stress must reach the flow stress (k_f), i.e. the flow criterion must be fulfilled.

$$\sigma_1 - \sigma_3 = k_f$$

where σ_1 – is the greatest principle stress
             σ_3 – is the smallest principle stress

The deformation brings the atoms closer together and the difference between the lattice orientations of the parts to be joined is eliminated.
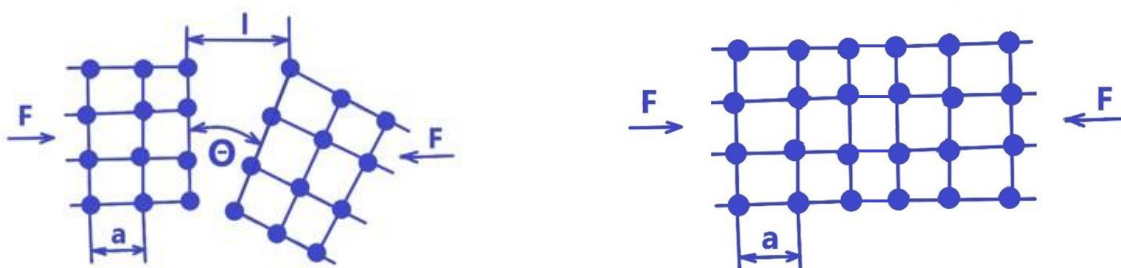

Figure 2. The principle of joint formation in solid-state welding at the crystal lattice level

A great advantage of this group of processes is that it is possible to weld metal combinations which, when fused, form brittle phases during the fusion process that make it impossible to create a weld with adequate mechanical properties. One such pairing is aluminium and copper

1.4.1.1. COLD WELDING

We call it a cold weld when the joint is created using a pressing tool below the recrystallisation temperature of the material. Only metals and alloys with high ductility can be welded cold, as a significant amount of ductile deformation is required to form a proper bond. Surface contamination, especially oxides, impairs the quality of the joint, so great care should be taken to clean the surfaces to be welded and the welding should be carried out as soon as possible after cleaning, before the surface oxide layer regenerates. At higher levels of ductile deformation, surface contaminants are removed by the resulting series of deformations, and the role of cleaning is negligible.
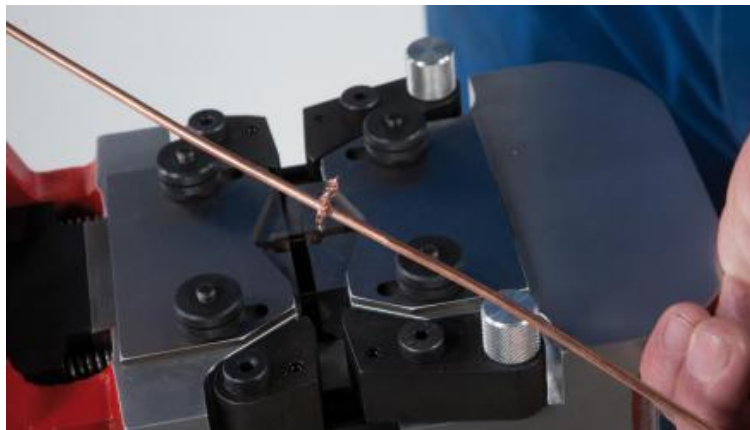
Figure 4. A cold welded joint and the pressing tool [2

Figure 5. Cross section of cold welded bead [2]

It is a variant of the cold welding process, when the mechanical work is provided by a shock wave generated by the release of chemical energy (explosion welding) or the energy of a magnetic field is used to form the joint (magnetic pulse welding). In both cases, the pieces to be welded slam into each other at high speed and the kinetic energy is converted into deformation work.
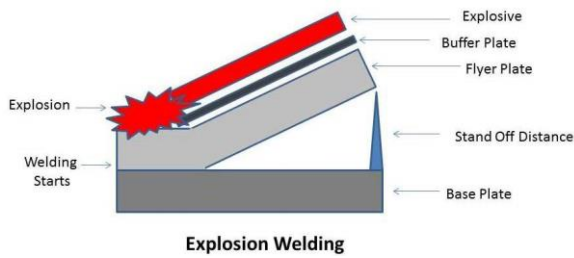
Figure 5. Principle of explosion welding [3]
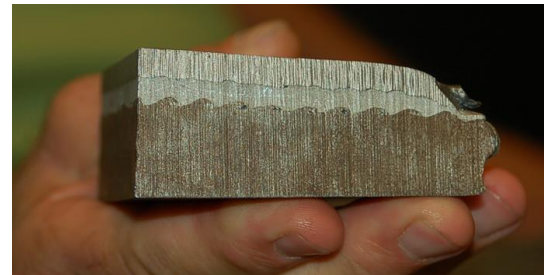
Figure 6. An explosion welded part [4]
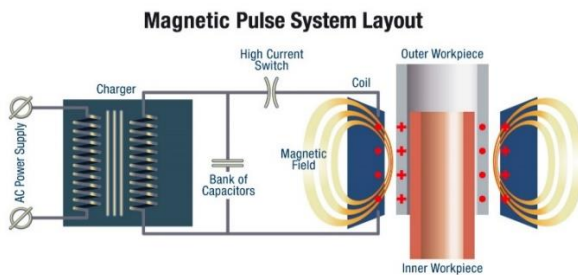
Figure 7. Principle of magnetic pulse welding [5]
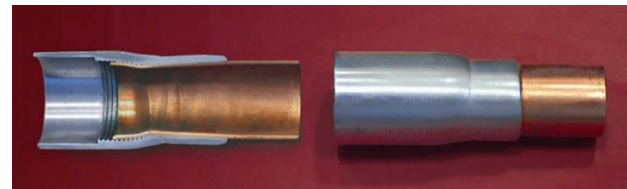
Figure 8. Magnetic pulse welded aluminium and copper tube [5]

1.4.1.2. WELDING PROCESSES USING THE FRICTION PRINCIPLE

In these welding processes, the frictional heat generated during relative displacement and the mechanical work together create the bond. The heat generated on frictional surfaces causes the temperature on the surfaces to rise and the plasticity of the material to increase, while the pressure mainly causes the surface to deform and form a flash, which carry surface contaminants away from the bonding zone. The last step in the process is to eliminate relative motion and increase the pressing force. In process variations where is significant heat generation, metals that are otherwise brittle in cold state can be welded.

Within this group of processes, friction welding is the most common. Relative motion typically means rotary motion, but for non-circular symmetrical pieces, linear oscillating motion can also be used.
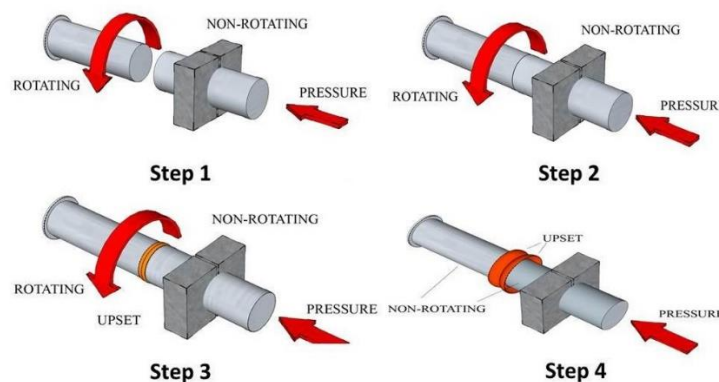
Figure 9. Stages of friction welding [6]
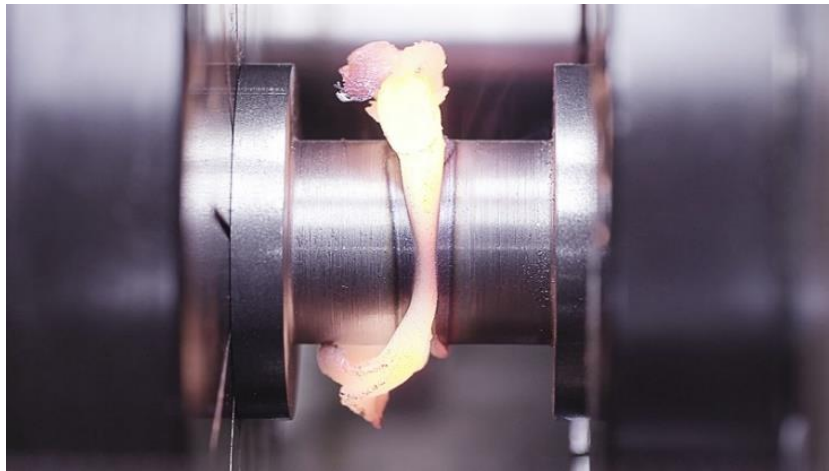
Figure 10. Friction welding with linear motion [7]

A relatively new variation of friction welding is friction stir welding. Here, the heat for welding is not generated by friction between the two workpieces, but it is generated by a rotating tool with pin that plunges the material. In addition to its rotary motion, the tool is given a feed motion to guide it along the line to be welded. The friction causes the heated pieces to become so plasticised that the tool mechanically mixes the two materials to create the welded joint.
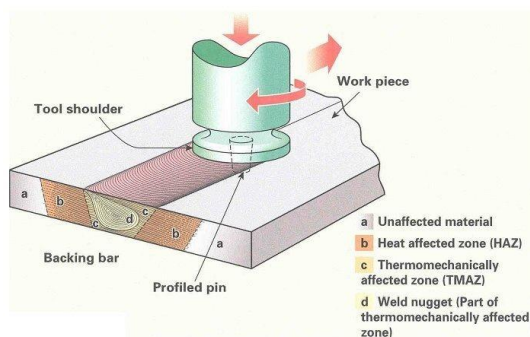
Figure 11. Principle of friction stir welding [8]

Figure 12. Tool during welding [9]

Another form of friction welding is ultrasonic welding. The main difference compared to the vibration version of friction welding is that the frequency of the vibration is higher and the amplitude is lower. During welding, the magnetostriction phenomenon is used to generate ultrasound. The idea is that ferromagnetic materials are deformed by a magnetic field. Rapidly changing magnetic fields can be used to vibrate these materials. The amplitude of the vibration can be increased by so-called acoustic transformers (or booster).
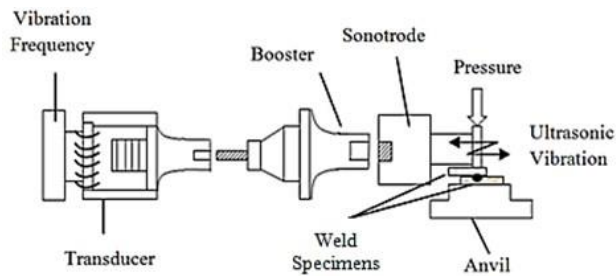
Figure 13. Main parts of ultrasonic welding equipment [10]
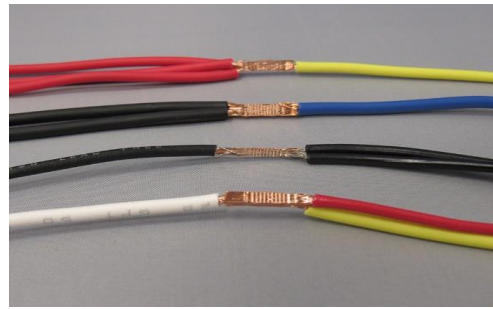
Figure 14. Ultrasonically welded cable connections [11]

In particular, ductile metals with high vibration damping can be welded well by ultrasonics. For more rigid materials, the high number of stresses during welding can cause fatigue problems. In the case of low damping, welding can result in damage to previously made joints. When ultrasonic welding, the workpiece in front of the sonotrode (or horn) must be lightweight or thin so that it can be easily vibrated. The direction of vibration is parallel to the surfaces to be welded when welding metals. Plastics can also be welded using ultrasound, in which case the amplitude of the vibration is perpendicular to the surface.

1.4.1.3. DIFFUSION WELDING

A rare and special type of solid-state welding is diffusion welding. The welded joint is formed by diffusion between the material parts to be welded. Special conditions must be created for diffusion to take place. In solids, diffusion is sufficiently fast when the temperature is close to solidus. Fast means at least multiple hours in this case, so a fairly long welding time is to be expected.
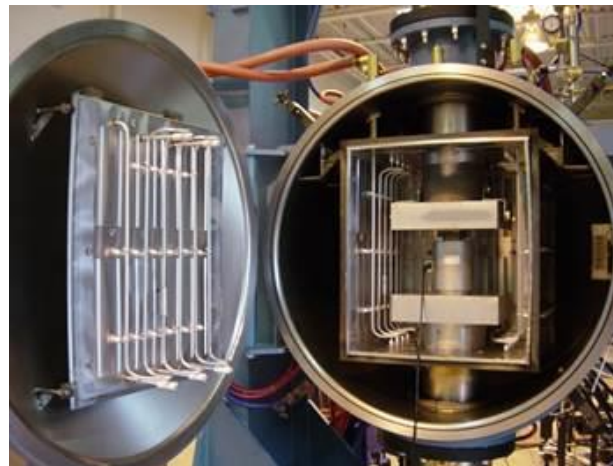
Figure 15. Vacuum furnace diffusion welding equipment [12]

Welding must be carried out in a shielded gas or vacuum chamber to protect the metal from the damaging effects of the air because of the high temperatures.
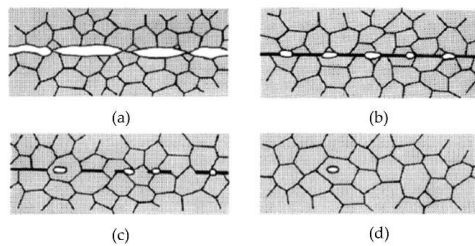
Figure 16. Stages of the diffusion welding process [13]

A perfect fit between the pieces to be welded must be ensured, as this is the only way to achieve the mutual diffusion of atoms. Fitting also requires that there are no foreign materials on the surface to prevent diffusion, so a high surface cleanness is required. Precise fitting can be ensured by using form-fit pieces and clamping force throughout the weld. The joint must be allowed to cool under pressure.

1.4.2. WELDING PROCESSES USING BOTH FUSION AND MECHANICAL STRESS

In these welding processes, the materials to be welded are melted, but it is also necessary to apply a clamping force to the pieces to achieve a good quality joint. As a heat source, the Joule heat generated by the resistance of an electric current or the heat of an electric arc is used.

1.4.2.1. RESISTANCE WELDING PROCESSES

The heat source for welding in this case is the Joule heat of the electric current.

$$Q = I^2 R t$$

Current can be conducted directly into the workpiece by electrodes - usually called resistance welding. Another solution is to induce eddy currents in the workpieces using a changing magnetic field - these processes are called induction welding.

1.4.2.1.1. DIRECT CURRENT RESISTANCE WELDS

In these procedures, the different resistance components are of great importance. At the start of the weld, the contact surfaces of the pieces to be welded develop a contact resistance, which is initially quite high, so this is where the heating will be the most intense. The deformation due to the clamping force on the electrodes and the melting of the roughness peaks improves the initial misalignment of the pieces, thus reducing the contact resistance. However, since the internal resistance of metals increases with temperature, it is still the part of the circuit with the highest resistance and the heat generation is concentrated here.
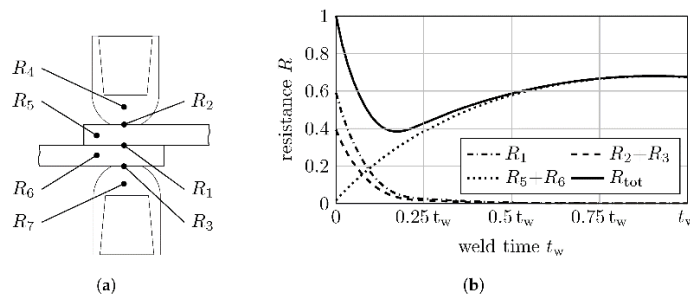
Figure 17. Changes in the different resistance components and total resistance as a function of time [14]

Starting from the contacting surfaces, the workpieces begin to melt, forming a lens-shaped pool. In order to form a good quality bond, this pool must solidify under pressure.
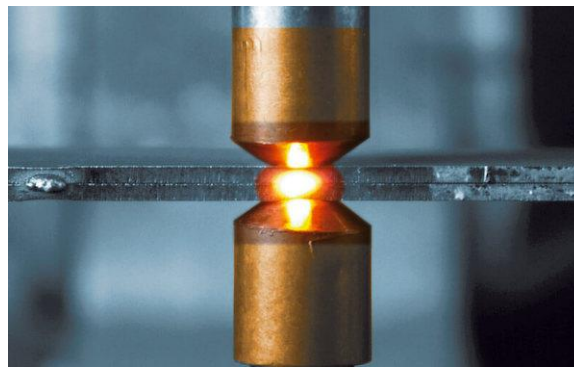
Figure 18. Formation of resistance spot welding [15]

1.4.2.1.1.1.   RESISTANCE SPOT WLDING

In resistance spot welding, the electrodes ensure that the current is concentrated and the pieces are clamped together during welding. For a given plate thickness, there is an optimal spot diameter. This requires synchronising the welding current and time during the welding process. Lobe diagrams are plots of welding current and time. They indicate the current-time combinations to achieve acceptable welds.
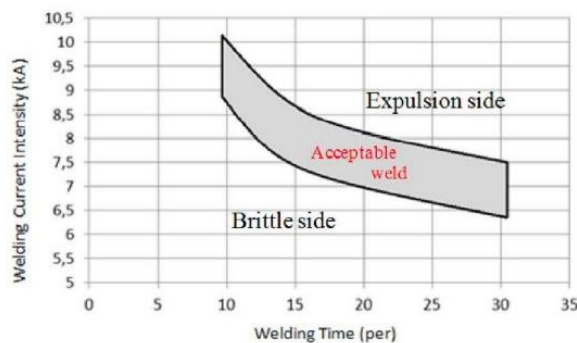
Figure 19. Weld lobe curve [16]

There will be an expulsion above and an underwelded seam below. A more complex work sequence gives the possibility to preheat the workpiece before welding or to heat treat it after welding. Seam qualification is relatively easy to perform using various destructive tests. The good nuggets are unbuttoned, i.e. it is not the nugget that is damaged, but one of the plates around the nugget is pulled out.

Figure 20. Pulled out resistance spot welded seam

1.4.2.1.1.2.   RESISTANCE SEAM WELDING

The principle of joint design is identical to resistance spot welding, the main difference being the shape of the electrodes. In seam welding, rolling electrodes are used. In this case, the welding is not done with a continuous current, but with pulses of current to weld a series of points.
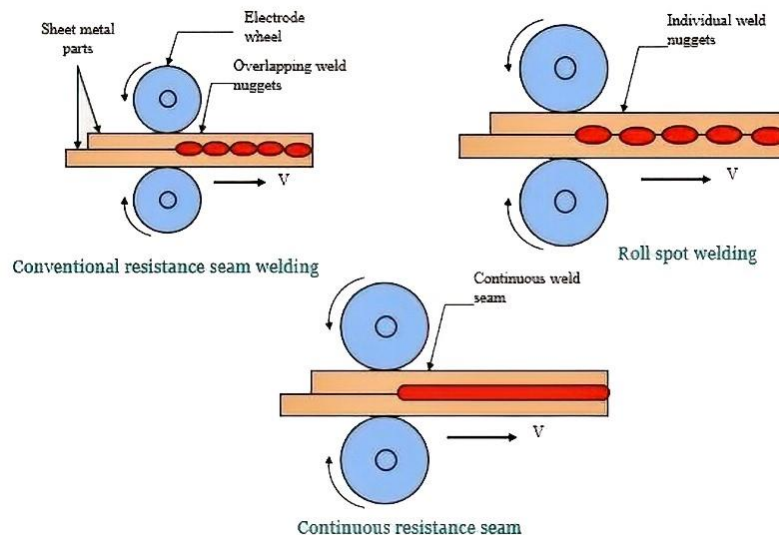
Figure 21. Resistance seam welding variants [17]

The interval between pulses and the circumferential speed of the rollers determine how far apart the seam points are. There can be overlap between the individual welded spots, in which case a continuous weld is obtained, but it is also possible to weld a series of spots at a given distance from each other.

1.4.2.1.1.3.   RESISTANCE PROJECTION WELDING

In resistance projection welding, the current is not concentrated by the electrodes but by the shape of the workpiece. We speak of a natural projection when the original shape of the workpieces to be welded is such that there is little surface contact between them. Such a crossed joint of two cylindrical pieces. The projection can also be formed by plastic shaping or machining, called an artificial projection.
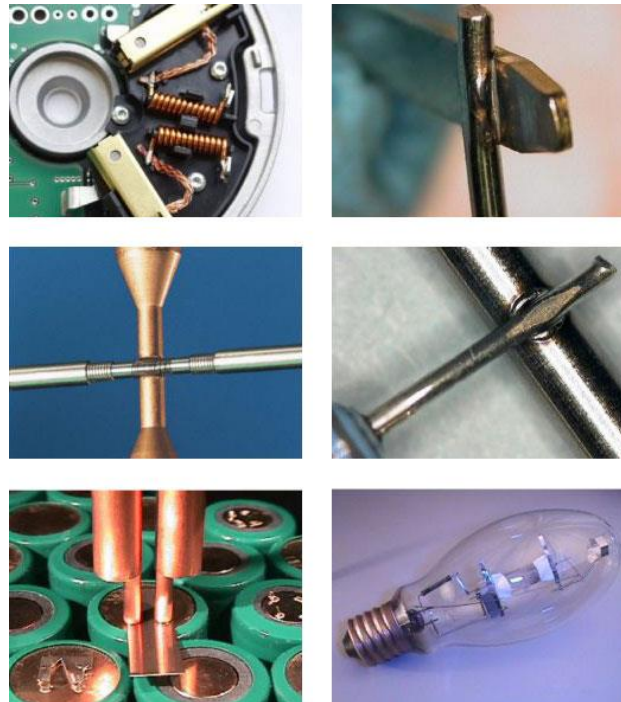
Figure 22. Resistance projection welded pieces [18]

1.4.2.1.1.4.   FOIL SEAM WELDING

In foil seam welding the plates to be welded don't create a lap joint but meet at the edge. A foil of 0.2 mm thick and 4-5 mm wide is placed between the welding rollers and the workpieces. The plates are gripped with clamping jaws close to the weld line, and the pressure required for welding is provided by the prevented thermal expansion of the plates. When welding, the foil does not disappear completely, leaving a small step on the surface of the welded piece.
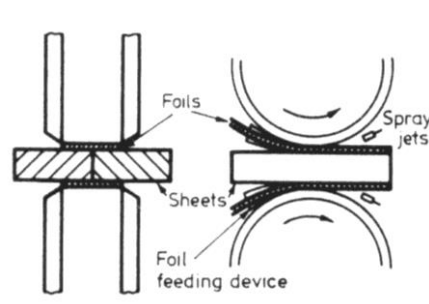
Figure 23. Foil seam resistance welding layout sketch [19]

1.4.2.1.2.   INDUCTION WELDING

In induction welding, a so-called inductor is used to create a changing magnetic field, which generates an eddy current in the workpiece to be welded. The energy input is non-contact. Joule heat from the eddy current heats the edges to be welded. The Joule heat of the eddy current provides the energy to weld the workpieces. Eddy currents create a magnetic field of their own that forces the electrons towards the surface of the conducting material, called the skin effect. The heating depth can be controlled by the frequency of change of the magnetic field.

Inductor construction can be coil or line inductor.
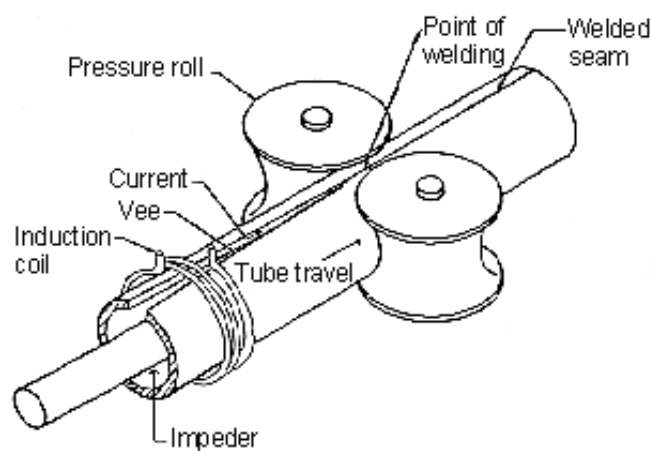
Figure 24. Continuous pipe production by induction welding [20]

The most important application of induction welding is the production of longitudinally welded pipes and hollow sections. It can also be used for butt-welding of hollow sections. Another welding related application is the localised, intermittent stress relief heat treatment of welds in large welded structures.

Figure 25. Butt welding with induction welding [21]

1.4.2.2. PRESSURE ARC WELDS

In the case of pressure arc welding, the surfaces to be welded are melted by the arc after arc ignition, and the melted surfaces are then pressed together.

1.4.2.2.1. ROTATING ARC WELDING

This process is used for butt welding of pipes. The electric arc was ignited by removing the tubes after they touched. A magnetic field is created around the tube so that a tangential force is produced on the electrons moving in the arc. This force induces the arc to rotate around the circumference of the tube and results in a uniform melting of the front surfaces. At the end of the process, the pipes are pressed together to form the welded joint.
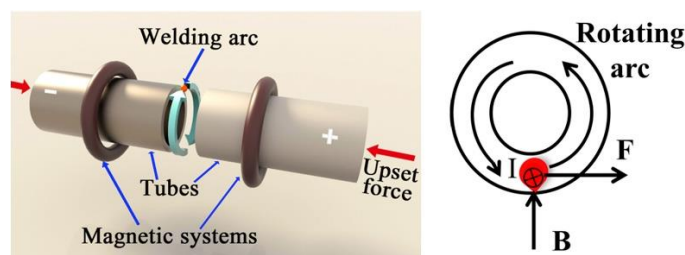
Figure 26. Schematic and force figure of rotating arc welding [22]

1.4.2.2.2. STUD ARC WELDING

The process is used for productive and reliable quality welding of studs of different sizes and lengths. The power source can be either a transformer or a capacitor bank. With capacitor power sources, higher currents can be achieved, so less welding time is sufficient to make the joint.
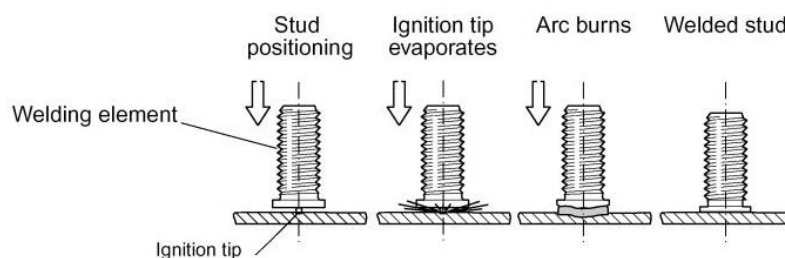
Figure 27. Stages of tip-ignition stud arc welding [23]

Arc ignition can be done by arc pulling, where the pin is pulled away from the workpiece after a short-circuit. Another solution is to use an ignition tip at the end of the stud to be welded. A very high current density then develops in the small cross-section ignition tip, causing it to explode and ignite the arc. The arc melts the front surface in a thin layer, and when the pin is pressed in, the melt is extruded and the welded joint is formed with a small amount of plastic deformation. For smaller stud sizes and shorter welding times, there is no need to protect the weld. In the case of larger studs, a protective gas, welding flux or ceramic ring is used to protect the weld.

Figure 28. Welding gun and welded studs with ceramic rings [24]

Figure 29. Welded studs on boiler tubes [25]

For arc stud welding, the two ground cable clamps shall be positioned so that they are symmetrical with respect to the weld location. This is because the high current and the short welding time result in a strong magnetic field, which in the asymmetric case can deflect the arc, causing the weld to shift relative to the stud. The qualification of the welds on the test plate is simple, the studs must not break when bent down the stud to the plane of the plate. The welding process is automated, ensuring consistent weld quality

1.4.3. FUSION WELDING PROCESSES

Fusion welding processes use chemical energy, Joule heat of electricity, electric arc, plasma, laser beam and electron beam as heat sources.

1.4.3.1. GAS WELDING

The most important heat-producing chemical process is burning. There are many flammable gases, of which the burning of acetylene in oxygen is the most efficient in terms of both flame temperature and flame power. With an optimal mixing ratio, a flame temperature of 3160 °C can be achieved.
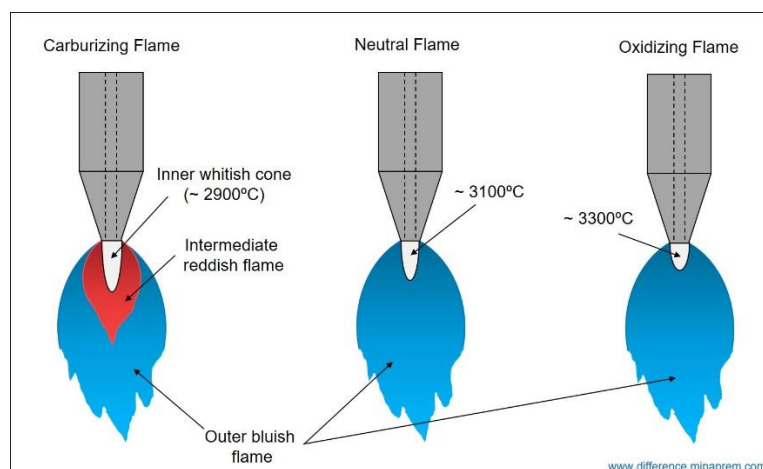
Figure 30. Flame types [26]

Acetylene is an unstable compound, explosive on its own, and its mixtures with air and oxygen form an explosive mixture over a wide range. Therefore, its handling and use is allowed under very strict safety rules. It should also be noted that during the combustion process, the flame not only uses the oxygen in the cylinder, but also burns some of the oxygen in the ambient air, which can result in the formation of carbon monoxide as the oxygen concentration decreases. It is therefore very important to ensure proper ventilation during flame welding.

Its use has been steadily declining due to the dangers listed and its low productivity. For a long time it was used because of its independence from the electricity grid.

Figure 31. Gas welding process [27]

A two-handed welding process, with one hand guiding the welding torch and the welder using the other hand to feed the filler material. Welding to the left is when the filler rod moves to the front and the flame follows it. This technology is used for welding thin sheets. When welding on the right, the flame is in front and the stick follows it. This version is used for welding thicker plates.

1.4.3.2. THERMITE WELDING

Chemical energy is also the heat source for this welding process. Oxides of iron are reduced by aluminium according to the following equations:

$$3FeO + 2Al = 3Fe + Al_2O_3 + Q$$
$$Fe_2O_3 + 2Al = 2Fe + Al_2O_3 + Q$$
$$3Fe_3O_4 + 8Al = 9Fe + 4Al_2O_3 + Q$$
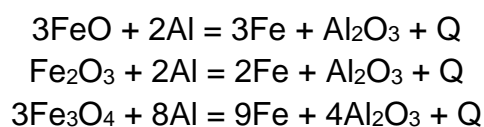
- where Q [kJ/mol] is the heat generated by chemical reaction.

The reaction is initiated with a thermite igniter or an acetylene-oxygen flame. The starting temperature must exceed 2000 °C. Tiny explosions occur in the iron oxide, which cracks the high melting point oxide layer on the surface of the aluminium grains. The intense reaction

produces so-called thermite iron and a large amount of heat. Thermite iron can reach temperatures of up to 2500-3000 °C and must be cooled. Steel pieces are also added to the thermite mixture for cooling purposes, which also increases the amount of iron. Since we want to obtain steel of the right quality as a weld material, coke is added to adjust the C content, Manganese and Silicon for deoxidation, and Titanium and Vanadium for grain refining.

Figure 32. Railway track thermite welding [28]

The reaction takes place in a so-called thermite crucible, at the end of which molten steel collects at the bottom of the crucible and is fed through a tapping hole to the welding location. The process is a cast welding process, so a mould must be formed around the weld seam using refractory materials.

It is mainly used for field joint welding of railway rails. Before welding, the rail ends must be preheated, otherwise the thermite iron will freeze onto the rail end without melting it. After welding, remove the mould and cut off the excess, then machine the rail tread to the correct geometry and surface quality.

1.4.3.3. ELECTROSLAG WELDING

Electroslag welding is a fully mechanised process, the energy source being the Joule heat of the current flowing through the molten slag. The welding process starts as an arc welding on a cut-off plate, the heat of the arc melts the covering welding flux for slag formation. Since the resistance of the molten slag is less than the resistance of the arc, the slag takes over the current conduction and the arc goes out.
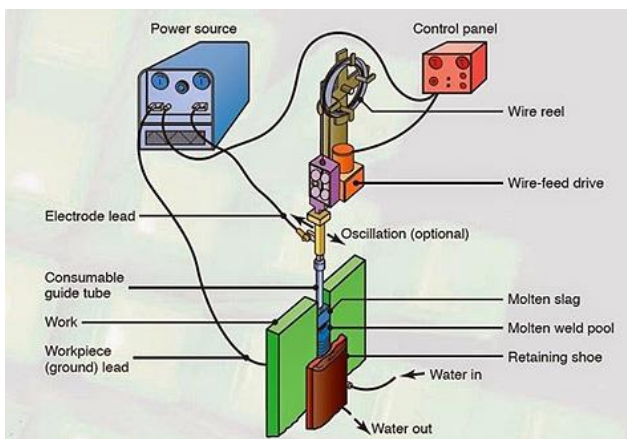
Figure 33. Schematic of the Electroslag welding process [29]

Figure 34. ESW welds [29]

It is used for butt welding in the vertical position for thick plates. Either a cavity closed on four sides is formed with the plates to be welded, or, in the case of two plates, the molten slag and metal bath is supported on the open side by water-cooled copper retaining shoes, which rises with the level of the slag and metal bath. For cladding welding, it is used with a strip electrode in the horizontal position. Protection of the metal pool is provided by the molten slag from the granulated flux.

Figure 35. Electroslag cladding [30]

1.4.3.4. SUBMERGED ARC WELDING

Submerged arc welding is a high power, fully automated process. It is economical to use in places where long seams have to be made on thick plates. One such area is ship and tank manufacturing. The heat source is the electrical arc burning between the consumable wire electrode and the workpiece. The welding flux is fed from the flux hopper on the welding head through a funnel to the surface of the workpiece, and behind the welding head a vacuum cleaner sucks back the unmelted flux particles, which can be reused.
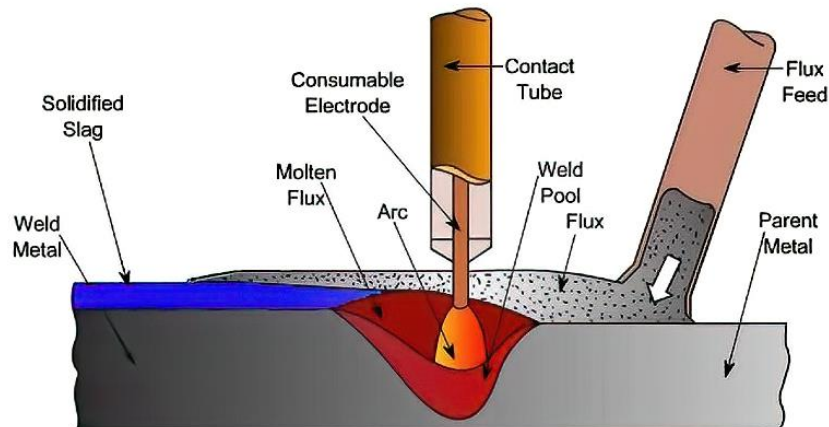
Figure 36. The principle of submerged arc welding [31]

Due to the characteristics of the granulated flux, the process can only be used in a horizontal position. With a sufficiently thick layer of flux, arc light is not visible and any drafts or wind will not damage the seam. The optimal thickness of the flux layer is approximately ten times the wire diameter.

Figure 37. Welding of a rotating vessel with submerged arc [31]

The power sources used have a drooping characteristic and can withstand a sustained short circuit. So-called external regulation is used to control the arc length. The wire feed rate is not constant. The change in arc length causes a significant change in arc voltage and this signal is fed back to the feed motor. An increase in arc length causes an increase in voltage, this signal increases the speed of the feed motor and thus restores the working arc length. The control also works when the arc length is reduced, slowing down the feed rate. Flux plays a very important role in the welding process. It stabilises the arc, protects and shapes the seam by slag formation and has an important metallurgical role. The constituents of welding fluxes can be grouped according to their nature: basic, neutral and acidic. The ratio of basic to acidic components is expressed by the basicity index. The more basic the welding flux, the lower the dissolved oxygen content of the seam will be and thus the better its toughness. Main constituents: MnO, SiO_2, CaO, ZrO_2, Al_2O_3, CaF_2. The process is characterised by very good mechanical properties of the weld. However, there is a risk of hot cracking due to the high heat input.

1.4.3.5. MANUAL METAL ARC (MMA) WELDING WITH COATED ELECTRODE

This is the earliest arc welding process. Arc welding between a coated metal consumable electrode and the workpiece with an arc formed under the protection of the materials formed by the electrode coating. It is widely used because of its simplicity and low cost. There are electrodes suitable for welding virtually every metal and alloy used in industry. The process does not require a huge investment. Disadvantages are low deposition rate and human factors affecting quality.

Figure 38. Manual metal arc welding [32]

The current source has a drooping characteristic, providing a nearly constant current regardless of the arc length. It can also withstand prolonged short-circuits during arc ignition without damage. In more modern current sources, electrode sticking is prevented by limiting the short-circuit current. Arc ignition is achieved by pulling the arc after the short circuit created by the electrode core wire.
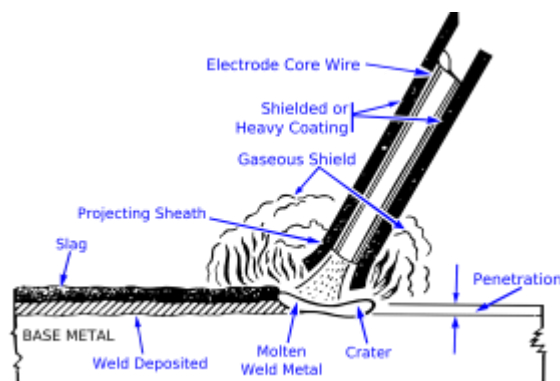
Figure 39. Principle of manual metal arc welding [32]

The main flux coating types are rutile, basic, acidic and cellulose. The applicable current and polarity is determined by the coating type, which is always specified by the electrode manufacturers. The gas formed from the flux coating by the arc forces air out of the arc space, and the resulting slag forms a layer on the surface of the seam. The complex metallurgical processes that take place between the molten slag and the metal bath ensure the correct composition and mechanical properties of the weld. The solidifying slag shapes the seam and slows down its cooling.

The current as a function of the electrode diameter can be calculated using the following equation:

$$I = (30 - 60)d_e \quad [A]$$

The arc voltage can be estimated using the following formula:

$$U = 0.04 \cdot I + 20 \quad [V]$$

1.4.3.6. GAS METAL ARC WELDING

Nowadays, the most commonly used welding processes are various versions of gas metal arc welding, thanks to their high productivity and ease of automation. The heat source of the process is the burning arc between the mechanically fed consumable wire electrode and the workpiece.
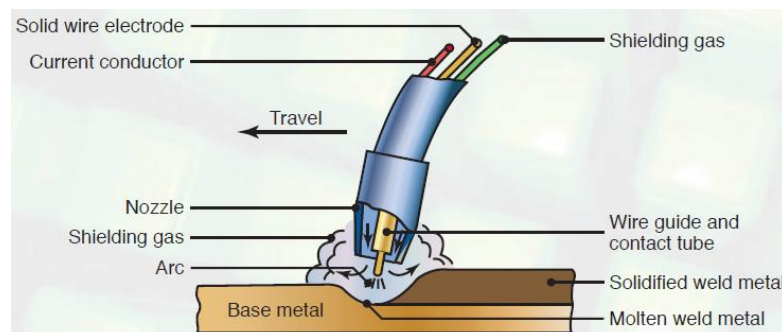
Figure 40. Principle of gas metal arc welding [33]

The protection of the seam, the wire and the detaching droplets is ensured by a protective gas flowing through a nozzle concentric with the wire. Its other role is to stabilise the arc and cool the welding gun. Inadequate gas protection can result in gas porosity in the weld and the burning out of certain alloying elements from the weld material, for a number of reasons. Too much shielding gas results in turbulent flow, and too little shielding gas cannot force the air out of the arc. The spattering that sticks to the inner surface of the gas nozzle and narrows it also causes a turbulent gas flow. Over-tilted welding guns, high nozzle distance and drafts can also cause the gas protection to fail. The amount of shielding gas should be chosen according to the nozzle diameter. The protective gas used can be either inert or active. Argon, helium and their mixtures are used as inert shielding gases. The inert gases do not chemically react with the weld pool, and achieve their protective effect by forcing air out of the arc

atmosphere. The active shielding gases contain components that react chemically with the weld pool, such as oxygen, carbon dioxide, hydrogen and nitrogen.

The choice of shielding gas is based on the material to be welded and the type of material transfer to be used. When welding steels, a certain amount of oxidising component is required in the shielding gas, as the oxide film formed on the surface of the molten bath reduces its surface tension. The molten metal has the effect of wetting the base material more, resulting in a smoother seam to base material transition. For carbon steels, pure CO_2 and a mixture of Ar/CO_2 82/18% is used. The former is cheaper, the latter results in a more attractive seam with less spatter and higher productivity. When pulse arc welding carbon steels, the amount of CO_2 in the mixture should be reduced below 15%. For stainless steels, to maintain corrosion resistance, even fewer oxidizing components are added to the shielding gas mixture, with 2-5% CO_2 or 1-3% O_2 mixed with argon. For duplex steels, the austenite/ferrite ratio of the weld can be controlled by adding an appropriate amount of austenite-forming nitrogen component. Neutral shielding gas is used for welding aluminium, copper, titanium, nickel and their alloys.

The static characteristic curve of the current sources used in this method is nearly flat. The power can be controlled by adjusting the open-circuit voltage, and the current can be adjusted by changing the wire feed. The welding process is stable when the wire feed rate is equal to the wire melting rate. The welding machine is then working at a stable operating point. The stable operating points are located in a so-called working line. Around the working line there is a working range where it is possible to weld at all. In gas metal arc welding, there is a self-regulating mechanism which ensures a nearly constant arc length. This means that the system reacts to a change in arc length by returning the arc length and current to a value close to the stable working point (M_1). The wire feed rate is a preset constant value and the wire melting rate is proportional to the current. If the welder holds the welding gun further away and the arc length increases as a result, the welding current at the new working point (M_3) is reduced. This reduces the melting rate, so the feeder feeds the wire faster than it melts. This causes the arc length to start decreasing until the original working point (M_1) is restored.
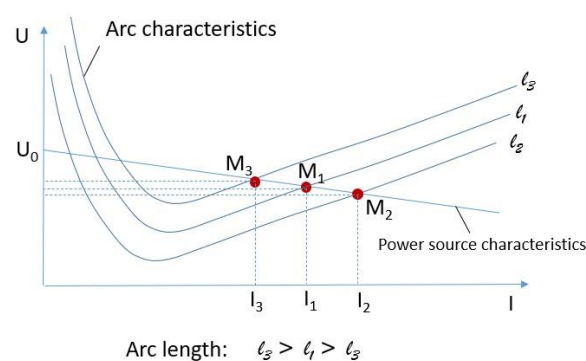
Figure 41. How self-adjusting of the arc works.

As arc length decreases, the current increases, so the melting rate will now be greater than the feed rate, and the arc length increases until the stable working point is restored. Adding to the completeness is the fact that the length of the wire through which the welding current flows will change, so the resistance of the circuit will also change. This resistance change will affect the working point and the welding current. If the welder keeps a shorter distance, the current will increase, and if the distance is longer, the welding current will decrease. These findings apply to welding machines that do not have any control electronics. Modern welding machine controls intervene in these processes, resulting in an even more stable welding process.

An essential part of the welding process is how the filler material passes from the wire into the weld pool. The process is affected by the shielding gas used, the magnitude and type of welding current, the material and diameter of the wire electrode. Based on the mode of weld metal transfer, we distinguish between short-circuit, spray arc, rotary arc, pulse arc and mixed modes.
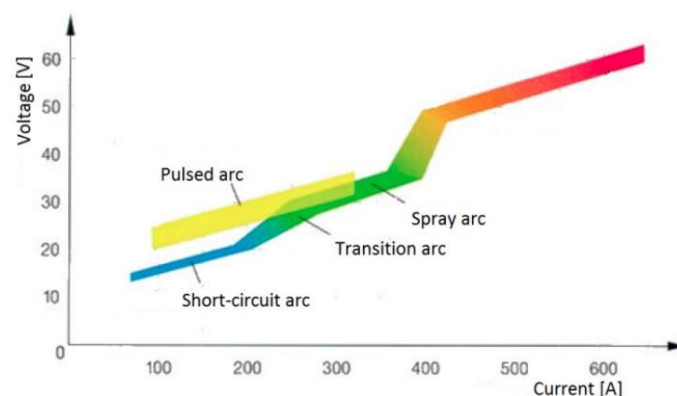
Figure 42. Stable arc range of the gas metal arc welding process
in the case of 1.2 mm solid wire diameter with M21 shielding gas [34]

Short-circuit (or dip) transfer mode is characterised by low current and voltage. The droplets formed at the end of the wire are short-circuited and the magnetic effect of the current (pinch effect), which increases the current in the short-circuit, pulls the droplet off the end of the wire. The arc re-ignites and the next droplet begins to form. The process is repeated at a frequency of 30-200 Hz. Due to the small arc power, a small pool is formed, which the surface tension can hold in the gravitational field. Therefore, it is suitable for position welding, root welding without support or welding of thin plates and tubes.
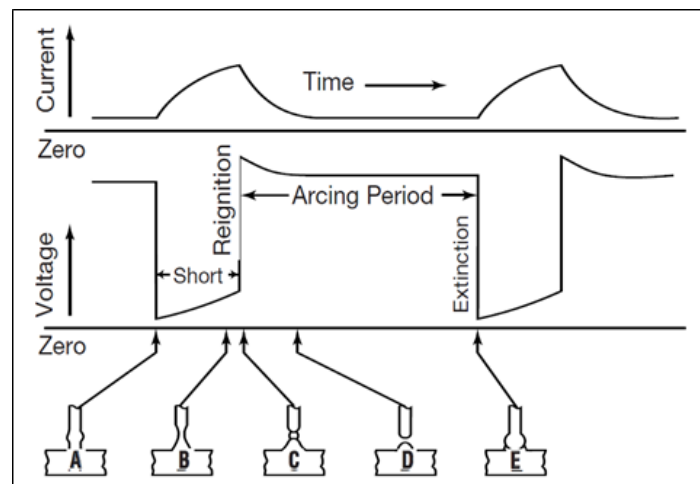
Figure 43. Current and voltage fluctuations during the dip-transfer mode [35]

A spray arc is formed when the current exceeds a critical value depending on the shielding gas and wire size. As the current is increased, the end of the wire becomes sharper and the droplets of the material are smaller and smaller, the droplets can no longer bridge the distance between the end of the wire and the weld pool, and the material transition becomes short-circuit-free. This mode of mass transfer does not occur in pure CO_2 and only occurs in a mixed protective gas with up to 25% CO_2. Due to its higher power, the weld pool is larger and more liquid and can therefore only be used in a horizontal position. It can be used for welding filling and covering rows of multilayer seams in thicker plates. It is characterized by high productivity, deep penetration and low spattering.
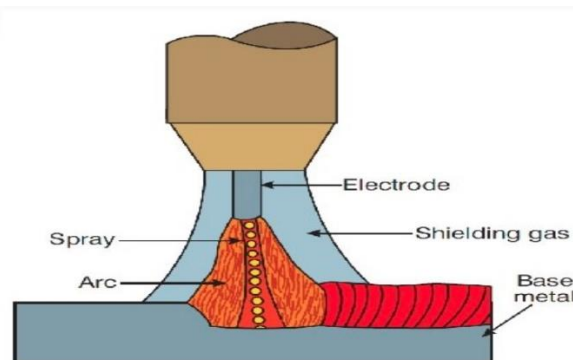
Figure 44. Schematic outline of a material transition in a spray arc [36]

When the current is increased further and a special He-containing shielding gas is applied, the rotating arc transition is formed. The magnetic field sets the arc and the detached droplets in rotation. The rotation causes the droplets to spread over a relatively large surface area, resulting in a wide, shallow fusion seam. Due to the high current and wire feed rate, the process is not suitable for manual welding and is mainly suitable for cladding due to the small fusion depth.
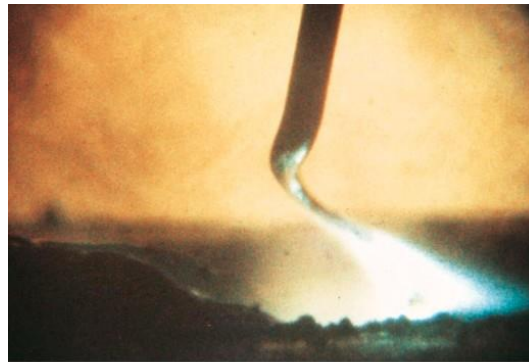
Rotating arc

Figure 45. Schematic outline of a material transition in a spray arc [37]

The switch between the transition modes listed so far is not sharp. There is a range where neither can really stabilize, but the two transitions alternate randomly, resulting in significant spattering. When welding, this range should be avoided if possible, because the instability of the welding process will make it impossible to ensure a good weld quality.

In terms of current, the transition region between short-circuit and spray-arc transitions is covered by the pulse-arc transition. In this case, the current is not constant, but varies pulse-like between two values.
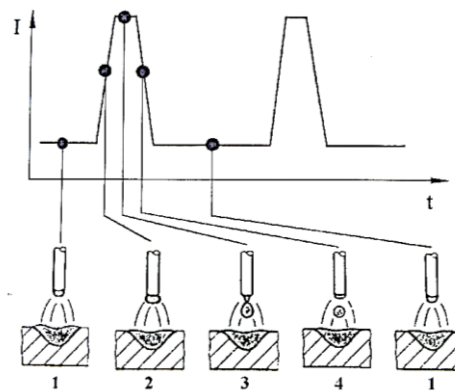
Figure 46. Variation of current versus time and droplet deposition phases in pulsed welding

In this case, many parameters need to be tuned to ensure that a single droplet is released from the end of the wire for each pulse. The main parameters are: pulse current, pulse time, base current, base current time, current rise time, current fall time and pulse frequency. These are not left to the welders to align, the welding machines work according to a programme optimised for the application through many, many experiments. The lower current value is the base current, which is just enough to maintain the arc but not to start droplet formation at the end of the wire. The pulse current causes the drop to start forming at the end of the wire. The pulse time must be set so that the droplet is not detached during the pulse time, but during the current run-off phase. The reason for this is that the pulse

current would cause the droplets to hit the weld pool at high velocity, causing significant spattering.

Technological developments are moving in the direction of reducing the human factor. This includes end crater filling, spatter-free arc ignition, constant arc length and welding current with variable wire elongation.

A number of process variants have been developed that extend the limits of the technology even further. Two of the variants of the controlled material transfer process will be mentioned without going into details, the CMT (Cold Metal Transfer) process of Fronius and the STT (Surface Tension Transfer) process of Lincoln.
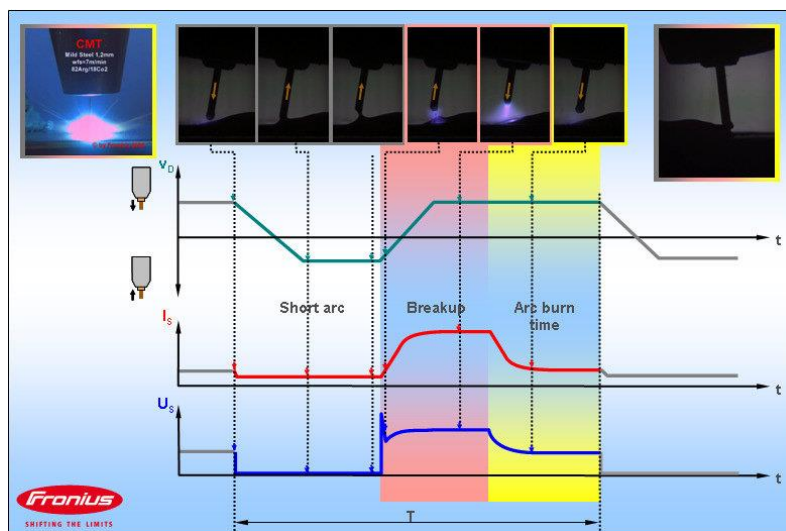
Figure 46. Principle of Fronius CMT (Cold Metal Transfer) process [38]
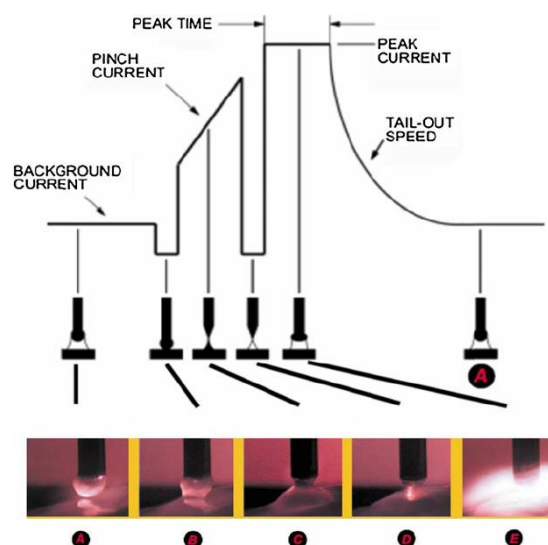
Figure 47. Current waveform control of STT and corresponding drop and short arc images [39]

Digitalisation has also caught up with welding machines. For the most modern machines, with the same hardware it's a matter of software what kind of welding machine you have. Welding machines transmit all their operational data to a database via an internet connection, which can be analysed to obtain information that was previously unimaginable (productivity, utilisation). Welding procedure specifications (WPS) can be created digitally for a given job, and if the welder does not follow the instructions, the machine will simply shut down and not weld.

1.4.3.7. TUNGSTEN INERT GAS (TIG) WELDING

The electric arc burns between the non-fusing tungsten electrode and the workpiece, and the weld, the filler material and the electrode are protected by a neutral shielding gas. In the fully manual welding version, the welder guides the welding torch with one hand and feeds the filler metal with the other. The technology is very similar to gas welding.

Figure 48. TIG welding [40]

The static curve of the current power source is the same as that of the MMA welding process, i.e. it provides a constant current during welding. The arc can be ignited by lifting the arc after a contact. In this case, the current source is limited to the value of the pilot current so that the tip of the electrode does not get stuck in the workpiece. For non-contact arc ignition, a high-frequency igniter is used, which applies a high voltage to the electrode in very short pulses, creating a spark between the electrode tip and the workpiece, which triggers the electric arc.

The electrode material used is pure tungsten or its alloys. The ends of the electrodes are colour coded to make them distinguishable. Electrodes are available in different diameters, the size is determined by the current to be applied.

Name	Color	Type	Current	Application
WP	Green	Pure	AC	Stable arc with alternating current, used to weld light alloys. Beware of the welding puddle contamination risk.
WT	Yellow 1% / Red 2% / Purple 3%	Thorium	DC	Easy arc ignition, high current capacity and low welding puddle contamination risk. The use of AC current is difficult. Radioactive risks.
WZ	White 0.7 to 0.9% / Brown 0.15 to 0.50%	Zirconium	AC	Identical WP, with higher current capacity and less welding puddle contamination risk.
WL	Black 0.8% to 1.2% / Gold 1.3% to 1.7% / Blue 1.8% to 2.2%	Lanthanium	AC/DC	Similar to WT, there is no radioactive risk, but it is less efficient.
WC	Grey 1.8% to 2.2%	Cerium	AC/DC	Similar to WT and WL but it has less current capacity.
WCL 1/1%	Pink	Cerium-Lanthan	DC	Simplified arc ignitionand a long life span. It offers an excellent compromise.

Figure 49. TIG electrodes marking and characteristics [41]

In terms of the type of current, both direct current and alternating current are used for welding. It is important to know that the heat distribution between the two poles is not uniform. 30% of the heat is generated at the negative pole and 70% at the positive pole.

When welding steels, copper, nickel, titanium, zirconium and their alloys, direct current is used for negative polarity, where most of the heat is generated on the workpiece and the electrode heat load is the lowest. The geometry of the electrode tip affects the arc shape, seam width and fusion depth.

The tip of the electrode should be tapered in the case of DC negative polarity so that the grinding scratches are parallel to the cone slant height. The optimum taper angle increases with the current. It is advisable to slightly flatten the tip of the electrode so that the electrode tip is not overloaded and the chance of contamination of the weld with tungsten is reduced.

CROSSWISE (RADIAL) GRIND   **LENGTHWISE GRIND**

INCORRECT PATTERN   *CORRECT PATTERN*

Lengthwise Grind Marks Do Not Restrict Current.   **Crosswise Grind Marks Restrict Welding Current and May Cause Arc Wander**
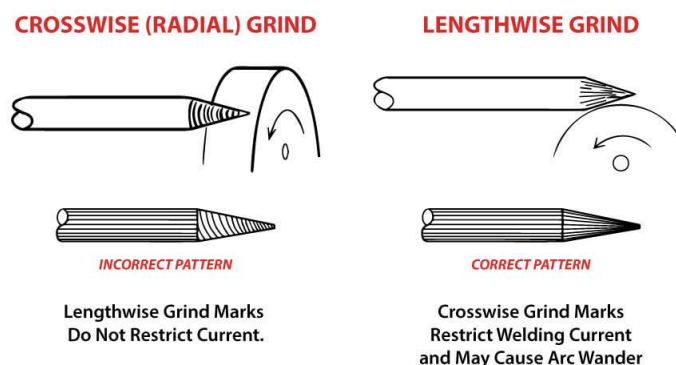
Figure 50. Correct and incorrect electrode tip formation for DC negative polarity [42]

TUNGSTEN ELECTRODE TIP ANGLE

| 15° | 35° | 45° | 60° | 90° | 120° | 180° |

SHARPER ELECTRODE TIP

Wider Weld Bead
Easier Arc Starting
Improves Arc Stability
Welding with Less Amps
Less Weld Penetration
Shorter Electrode Life

BLUNTER ELECTRODE TIP

Narrower Weld Bead
Harder Arc Starting
Potential Arc Wonder
Welding with More Amps
Better Weld Penetration
Longer Electrode Life
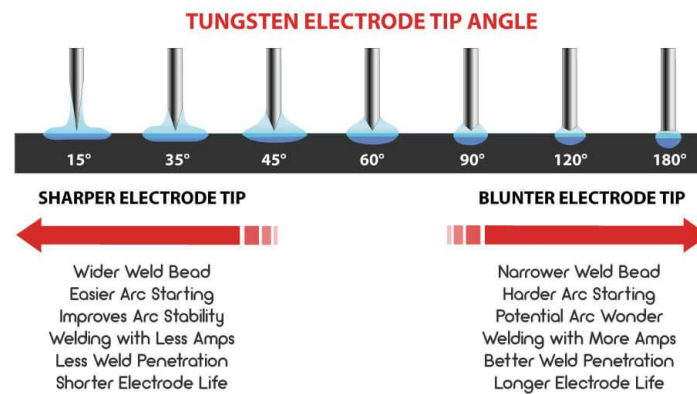
Figure 51. Effect of electrode tip cone angle [42]

When welding aluminium, magnesium and their alloys, DC negative polarity cannot be used because the oxide layer on the surface cannot be melted by the electric arc, thus preventing proper fusion of the parts to be welded. In the case of positive polarity, the phenomenon of cathodic etching occurs. Electrons exiting the workpiece break up the surface oxide layer, allowing the fusion of the filler metals on the pieces to be welded. The problem with this solution is that because the poles are reversed, most of the heat is transferred to the electrode, while less heat is transferred to the melting. The real workable solution is to use alternating current. Melting takes place in the half-period with negative polarity and oxide decomposition in the half-period with positive polarity. The ratio of the two half-periods should be set so that the oxide decomposition is just the right minimum level and the rest of the period is spent in melting. Compared to the negative polarity of a direct current, the thermal load on the tip of the electrode is still increased, which results in the tip becoming rounded, which is why it is not usually ground. When the current changes direction, the arc goes out for a short time and then reignites, with a relatively significant sound effect.
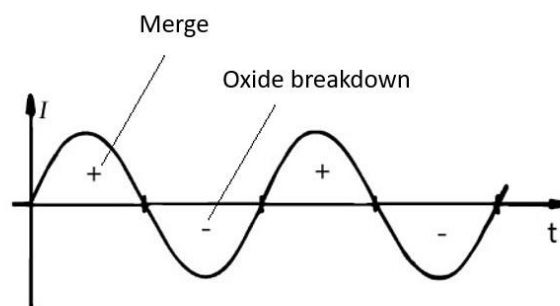
Figure 52. Stages of AC TIG welding

Pulse technology is also used in TIG welding. Compared to gas metal arc welding techniques, pulses of lower frequency (f=0.5-10 Hz) are used. In this case, the pulse parameters can be set independently. Its purpose is to control the size of the droplet separation and the size of the weld pool. The result is a nice regular scaling of the seam surface.
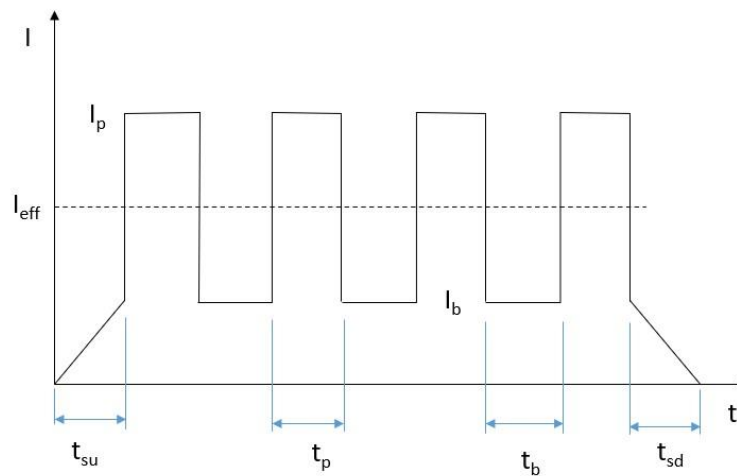
Figure 53. Parameters of pulse TIG welding

where I_p - pulse or peak current

I_b - background current

I_{eff} - effective current

t_{su} - slope up current time

t_p - pulse current time

t_b - background current time

t_{sd} - slope down current time

A newer development in DC welding technology is the use of high frequency pulses, where the frequency can go up to 15 kHz. Above 6 kHz, a narrowing of the arc occurs, resulting in a more controllable, concentrated heat source. The use of higher frequencies is justified by the strong sound effect, the frequency must be above the audible range so as not to disturb the welder.

There are several variations on the mechanisation of the process. The first step is the motorisation of the welding consumable feeding. In this case, a feeder is used to add the wire to the weld pool at a consistent speed or in a vibrating manner. A variant of the mechanised process of TIG for butt welding of pipes is orbital welding. For smaller diameter tubes, only the electrode is circulated along the weld line by means of a curved rack, and the device forms a closed space around the tube, which is filled with shielding gas. For larger diameter pipes, a TIG torch equipped with a gas nozzle circles the weld line. The process is also used to weld heat exchanger tubes into the tube wall, where the arrangement is slightly different from that of the butt weld, but the process is very similar.

Figure 54. Different orbital TIG welders [43]

Depending on the welding position, the pulse parameters vary, and without rotating the workpiece, a very nice, consistent weld can be produced. The weld is completed by a continuous reduction of the welding current, so that the finish is barely visible to the naked eye. Thin tubes are welded without filler metal, and thicker tubes are welded with mechanically fed filler metal. For wider welds, the welding head can also be swung sideways.
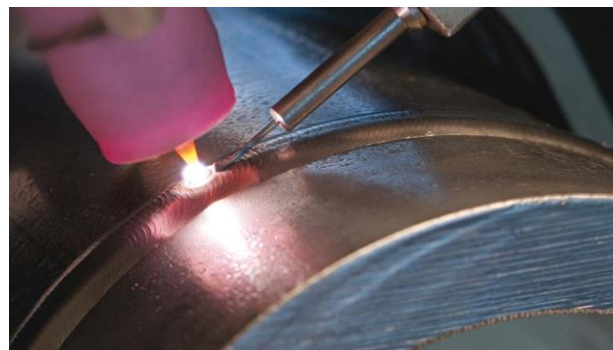
Figure 55. Multi pass orbital TIG welding with mechanically fed filler metal [44]

The main drawback of the process is its low productivity and a relatively low fusion depth. Using helium-containing shielding gas instead of pure argon can improve productivity and fusion depth.

An interesting variation of the process is the A-TIG process, which involves reversing the flow direction of the bath by influencing the surface tension of the bath. Normally, the weld pool flows laterally outwards from the centre, so heat is also transported laterally. Before welding, the activation powder (various oxides: SiO_2, TiO_2, etc.) applied to the surface of the workpiece or a few tenths of a percent of O_2 mixed into the shielding gas causes the pool to flow laterally in a central direction and then downwards, thus significantly increasing the fusion depth and reducing the weld width. The oxygen content in the shielding gas significantly reduces the lifetime of the electrode, so in this version a double gas nozzle is used, with neutral gas flowing

through the inner nozzle and the activating gas mixture containing oxygen coming through the outer nozzle.
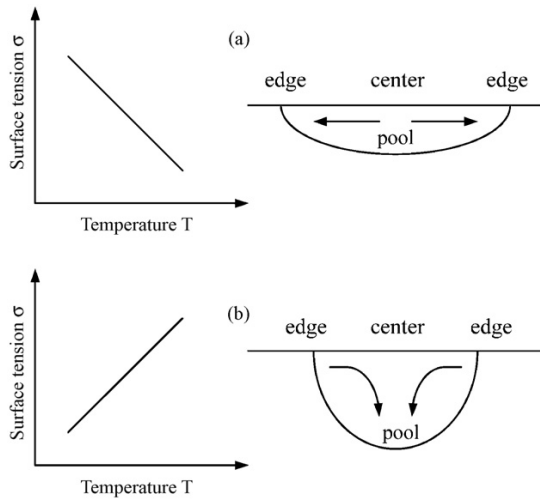
Figure 57. Marangoni convection mode in the weld pool [45]

Figure 58. Weld shapes at different welding speeds for pure He and He–0.4%O2 shielding gases [45]

1.4.3.8. PLASMA WELDING

Plasma is a medium containing atoms, ions and electrons at high temperatures. It can be characterised by the ionisation degree, which can be determined from the ratio of ions to atoms in the plasma. This is close to one for physical plasma and only around 10^{-4} for technical plasma. While the former is characterised by temperatures of several million degrees Celsius, the temperature of technical plasma varies between 5000 and 50000 °C. Various gases (Ar, He, H_2, N_2) are used for plasma formation. Plasma is produced by an electric arc in plasma welding. The energy input causes molecules in molecular gases to first decompose into atoms and then ionise. Plasma is a relatively static medium, and it is difficult to change its energy or position quickly. The plasma arc characteristic is the opposite of the arc characteristic, the voltage decreasing with increasing current.
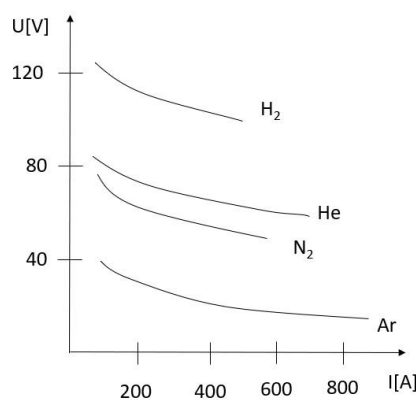
Figure 59. Plasma characteristics of different gases [46]

As the current increases, the number of charge particles (ions, electrons) increases, so the voltage decreases. Plasma is created by passing an electric arc and plasma-generating gas through a narrow hole called a plasma nozzle. The energy transfer takes place in the plasma nozzle between the arc and the plasma gas. There are two types of plasma arc welding: non-transferred arc, the arc burns between the electrode and the nozzle, while in transferred arc, the arc burns between the electrode and the workpiece. In latter case, the plasma is initiated with a non-transferred arc and then the system switches to the transferred arc.
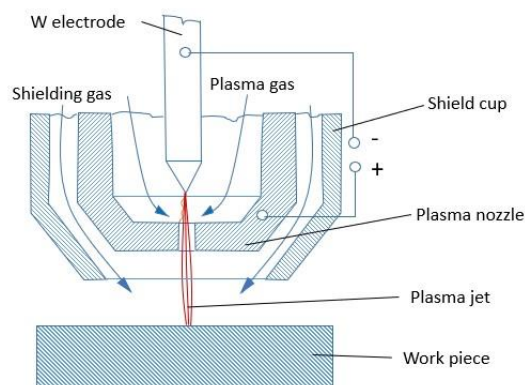
Figure 60. Schematic of a non-transferred arc plasma torch

In manual welding, the technology is similar to TIG welding. In machine welding, keyhole technology can be used to our advantage.
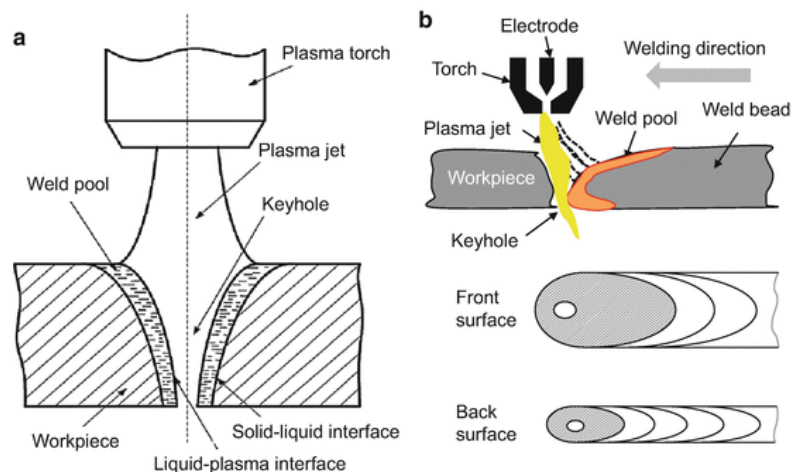
Figure 60. Plasma keyhole welding [47]

In case of a focused plasma arc, the plasma penetrates the gap between the plates to be welded and forms a keyhole-shaped opening in the pool of molten pool. This allows thicker plates to be welded in one step. It is characterised by a lower heat-affected zone, lower deformation and higher welding speed due to the higher energy density compared to arc welding. Even at low current, the plasma is stable and well controlled. It is not sensitive to change in arc length.

1.4.3.9. LASER WELDING

The term laser is an acronym derived from Light Amplification by Stimulated Emission of Radiation. The basic laser physics concepts relevant to the operation of lasers are mentioned without detailed explanation: stimulated emission, population inversion. The laser-active material is brought into a state of population inversion by external excitation and the stimulated emission is amplified in a particular direction by means of a resonator, this amplified emission being the laser itself, which exits the resonator through the so-called opening mirror.
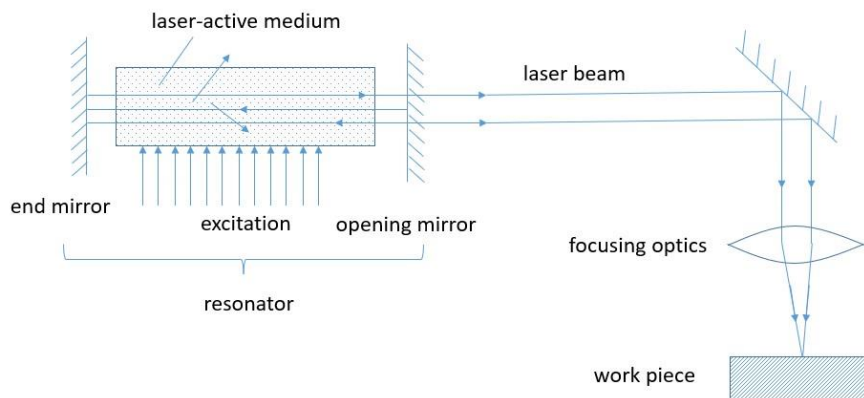
Figure 61. Laser beam source schematic scheme

A laser is therefore a special form of electromagnetic radiation. It is characterised by very high power and low divergence. The latter means that the intensity of the beam changes little as you move away from the light source. Lasers can be classified according to the laser active medium. The three most important types of lasers from an industrial point of view are CO_2 lasers, semiconductor lasers and solid-state lasers.
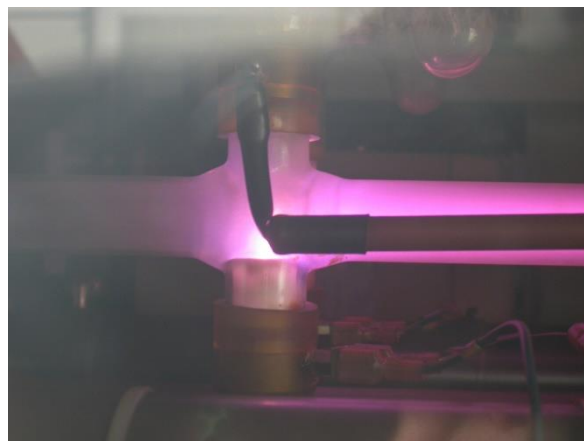
Figure 62. Discharge tube of a CO_2 laser source in operation

They have become widely used in industry because of their superior efficiency compared to other types of lasers. Within the laser beam, the intensity distribution is not uniform, and the

best focusable beam is the so-called Gaussian beam, where the intensity distribution varies according to a Gaussian curve.
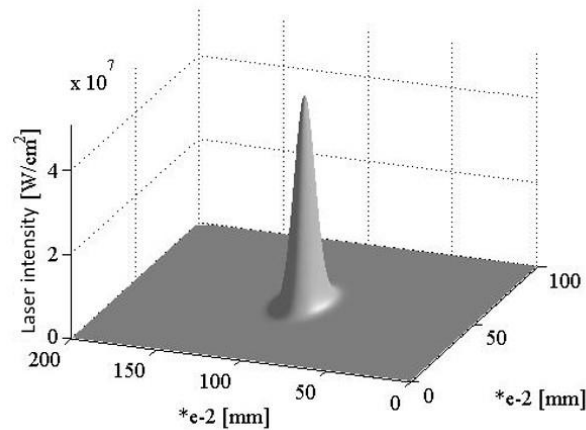
Figure 63. Focused laser beam intensity distribution in focus
P=7.8 kW, f=127 mm, w_0=0.1 mm

The utilisation of laser energy is influenced by the wavelength of the laser, the angle of incidence, the roughness of the surface, the quality of the illuminated material - all of which are described by the adsorption coefficient. It is important to know that certain materials act as mirrors to certain lasers and reflect the energy of the laser back towards the source, so it can damage itself in this way. Welding is typically carried out with a focused laser beam, where the important parameters are the power of the laser beam, the power density at the focus, the position of the focus relative to the workpiece, the length of the laser optics focus, the welding speed, and, in the case of CO2 lasers, the quality and amount of shielding gas. When the power density on the surface of the workpiece reaches 10^6 W/cm^2 for steels, a narrow, deep hole is formed on the workpiece and this ensures that the laser energy is effectively transmitted to the deeper layers. This technological variant is called keyhole welding.

Figure 64. Deep penetration weld using a 5 kW CO_2 laser, s=5 mm

Then, a narrow seam with a deep fusion is obtained. The process is not that stable, the surface of the seam is not that smooth. At lower power densities, the energy is transferred to the deeper layers by thermal conduction, so the width of the weld and the fusion depth will be almost the same, this is called conduction method. Aesthetically, these welds are more attractive than deep penetration welds. If the aesthetics of the weld are important, it is possible to improve the appearance of the weld with a cosmetic heat-conductive remelt after the deep weld. The use of laser beam welding requires more careful preparation of the workpieces and in many cases the weld configurations have to be redesigned to take the specialities of laser beam welding into account. In case of a butt joint, the focused laser beam can pass through the joint gap without touching the parts. This can be done by splitting the beam in two or by swinging the beam with an oscillating mirror. As a hybrid process, gas metal arc welding is combined with laser welding. The deep penetration is provided by the laser, while the greater seam mass and the possibility of lower precision is provided by arc welding.

1.4.3.10. ELECTRON BEAM WELDING

In electron beam welding, the kinetic energy of the electrons moving at high speed in the beam is converted into thermal energy on impact with the workpiece. The electrons are accelerated in the electron gun using an electric field. The electron beam can be focused and directed by a magnetic field. At atmospheric pressure, the accelerated electrons would be rapidly decelerated by colliding with air particles, so the welding is carried out in a vacuum chamber. The size of the vacuum and the working distance affect the electron beam, as electrons also collide with gas particles remaining in the working chamber. Magnetic materials must be demagnetised before welding because the magnetic field of the piece would deflect electrons. X-rays are also produced when electrons collide with the material to be welded, so adequate radiation protection must be provided. Great care must be taken to keep the workpieces clean. Moisture, grease, oil and surface oxide on the surface can interfere with the vacuum system and cause severe spattering during welding.
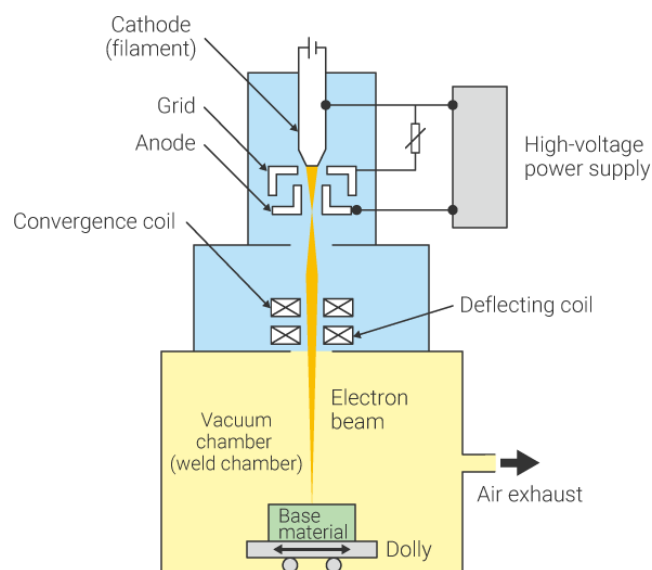

Figure 65. Electron beam welding equipment [48]

High vacuum equipment is used in laboratories for welding high purity metals and reactive metals. Then, the applied accelerating voltage is high (U=100-200 kV). Pre-vacuum equipment uses less vacuum, so the suction time is shorter. Because of their shorter cycle times, these machines are mainly used in industry. Their accelerating voltage can be high or medium (U=60kV). The previously mentioned keyhole welding also works for this process. Among the welding processes used in industry, electron beam welding has the highest energy density available and therefore the lowest heat input for the same fusion depth.
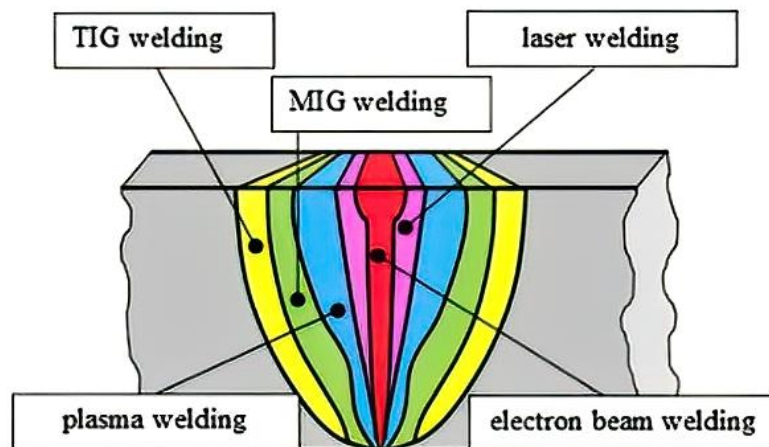
Figure 66. Weld cross-sections available with different welding processes [49]

The cooling rate of the seam is very fast, so the grain structure is very fine, which is not conducive to the formation of cracks. The vacuum makes it the cleanest source of heat and even reduces the gas content of the weld pool during welding. The best thermal efficiency process, the electron gun has an electron efficiency of 95-98%. The focused electron beam heats the material to be welded to above the vapour deposition temperature in a few thousandths of a second, so heat conduction plays little role in the deposition process. Electron beam is also suitable for welding high melting point metals (W, Mo, Ta, Nb). Parameters that determine the shape of the weld: beam power, power density in the weld plane and welding speed.

1.5.   KEY WELDING STANDARDS

Welding standards are intended to help ensure the quality of welding. The whole welding process must be controlled to guarantee the right quality. There are many standards related to welding, some of which are mentioned here without describing their exact content. We highlight some of the essential elements of each standard, which is of course not a substitute for full knowledge of the standards.

It is very important to clarify the activities, tasks and responsibilities related to welding, and this is addressed in EN ISO 14731.

Proper weld quality can only be ensured by well-trained welders. Welders can prove their skills by passing a welding qualification exam. The exam consists of a theoretical and mainly practical part. The qualification is valid within the validity period if the welder works on a daily basis and the person responsible for the welding signs the qualification certificate annually, thus validating the qualification. A welder qualification is valid for a relatively narrow field. Criteria determining the scope of validity: welding procedure, type of material (plate, tube), dimensions (thickness, diameter), quality group of the material, type of welded joint, manufacturing conditions (welding position, number of layers, etc.). The basic principle is that qualifications requiring more expertise apply to easier-to-perform welds. The requirements for the qualification of welders are set out in the EN ISO 9606 series of standards, the first part of which covers welding of steels, but there are separate standards for welding of aluminium, copper, nickel, titanium-zirconium and their alloys.

The welder receives his work instruction for welding a specific weld on the so-called WPS (welding procedure specification), which contains the specifications for all technological parameters (welding current, welding speed, heat input, etc.). The qualification of the technology is done by a process test, where the sample, prepared according to the WPS specifications, is subjected to a full test. If the technology passes the tests, the certification body will issue a WPQR (welding procedure qualification report), which the technologist can use to prepare welding instructions for similar welding tasks. In such cases, reference should be made to the WPQR on which the WPS is based. Specifications for the qualification of welding technology are given in EN ISO15609 standard.

No seam is perfect, it always contains imperfections compared to the ideal seam. The EN ISO 5817 standard includes quality levels of imperfections (gas porosity, slag inclusion, misalignment between plates, overlapping, undercut, lack of fusion, cracking, etc.). It classifies seams into three categories (D - moderate, C- medium, D - increased level) and gives the limits for imperfections for each. If the imperfection is above the allowed level, it is considered a defect and must be repaired.

The standard for welded structures as a whole, their size and shape accuracy is EN ISO 13920, where several quality classes are distinguished. It defines categories A, B, C, D for length and angles and E, F, G, H for straightness, flatness and parallelism.

Welders should also be familiar with the drawing marks for welds. Welding drawings shall specify the location, type, continuity and discontinuity of welds, welding procedure, necessary tests, etc. Drawing marks for welding are given in EN ISO 2553 standard.

As technology changes, so do the standards, with the year of commencement of validity separated by a colon after the standard number. When a new standard is issued, the previous version is always withdrawn. Professionals must keep up to date with changes in standard specifications and always follow the requirements of the standards in force.

2. HEAT TREATMENT

One way to change the properties of metals and alloys is by heat treatment. Heat treatment is the process of subjecting a workpiece to a predetermined temperature-time cycle without partial melting. There are processes where only heat is used, but other methods can be added to the thermal cycle. The additional effect may be chemical, mechanical or other physical. In the machinery industry, thermal and thermochemical processes are the most commonly used. Thermomechanical processes are mainly used by raw material manufacturers. Thermomechanical rolling can produce material with a much finer grain structure than normal rolling processes.

Heat treatment can be used to increase hardness, toughness and machinability. The altered properties can cover the entire cross-section or just the near-surface layer.

2.1. FUNDAMENTALS OF HEAT TREATMENT

Common metals and alloys have a crystalline structure, so understanding their behaviour requires a basic knowledge of materials science, especially crystallography and metallurgy. The mechanical properties of alloys are determined by their microstructure. The microstructure can be both equilibrium and nonequilibrium depending on the cooling conditions. The microstructure of a material is made up of different phases, including the grain structure within the phases. Phases can be classified into the following groups: pure metals, solid solutions and compounds. The microstructure can be significantly influenced by heat treatment if it undergoes different transformations when the temperature changes:

- an allotropic transformation occurs in the metal,
- there is a eutectoid reaction in the alloy,
- in solid solution, solubility is limited and decreases with decreasing temperature, especially if a compound phase is formed above the solubility limit.
- the material has undergone significant plastic cold working

The heat treatment process can be structured in the following steps: heating, holding, cooling.
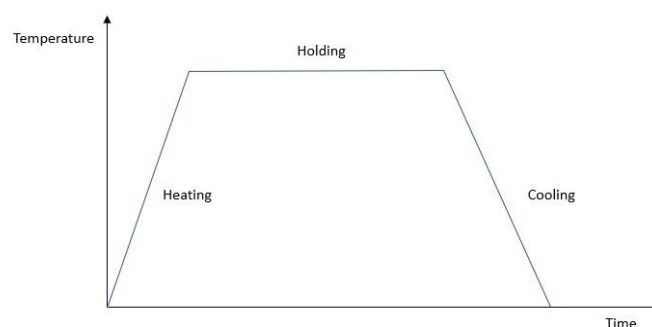

Figure 67. Simple heat treatment cycle and its stages

Economy demands that heating should be as fast as possible. During heating, temperature differences develop in the workpiece, which increase as the heating speed increases. This creates thermal stresses in the material, which can cause the piece to deform or even crack. Therefore, heating should be determined by knowing the material, dimensions and shape of the workpiece. In critical cases, preheating may be necessary, where the heating is not continuous, but heat equalisation stages are introduced into the heating process.
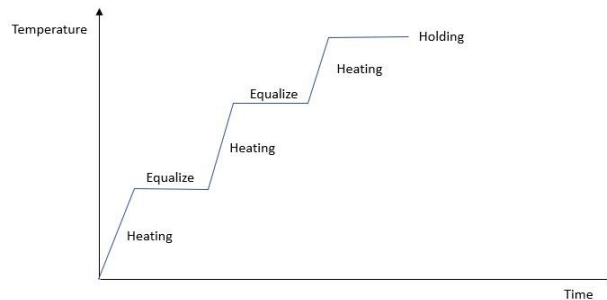

Figure 68. Heating process in several steps

On holding, one has to wait for the phase changes one wants to achieve. Further holding is unnecessary and harmful, because at higher temperatures it leads to a coarsening of the grain structure and consequently to a deterioration of the mechanical properties.

Cooling is always done with some kind of cooling medium. The cooling rate is determined by the quality of the cooling medium and its flow conditions. This can be characterised by the quench severity factor, which can be defined as the ratio of the heat transfer coefficient to the thermal conductivity. Its symbol is H and unit is [mm^{-1}]. To complicate matters further, H also varies with temperature.

"H" factors – coefficient of severity of quench			
Agitation	**Cooling medium**		
	Oil	**Water**	**Brine**
None (20-bar N$_2$)	0.25 – 0.30 (0.20)	0.9 – 1.0	2.0
Mild (20-bar He)	0.30 – 0.35 (0.35)	1.0 – 1.1	2.0 – 2.2
Moderate	0.35 – 0.40	1.2 – 1.3	
Good	0.4 – 0.5	1.4 – 1.5	
Strong (approx. 150 fps velocity)	0.5 – 0.8	1.6 – 2.0	
Violent	0.8 – 1.1	4.0	5.0

Figure 69 Influence of flow rate on the quench severity factor for different coolants [50]

The transformations can occur at a constant temperature, in which case they are called isothermal heat treatment, or they can occur during continuous cooling.

Under near equilibrium cooling conditions (slow cooling), the phase diagram of the alloy can be used to provide information on the expected microstructure and properties, and the

required heating temperature for a given alloy can be determined from the phase diagram A phase diagram describes a whole alloy system at equilibrium conditions, so it does not contain all the information needed to accurately develop a heat treatment technology for a particular alloy.
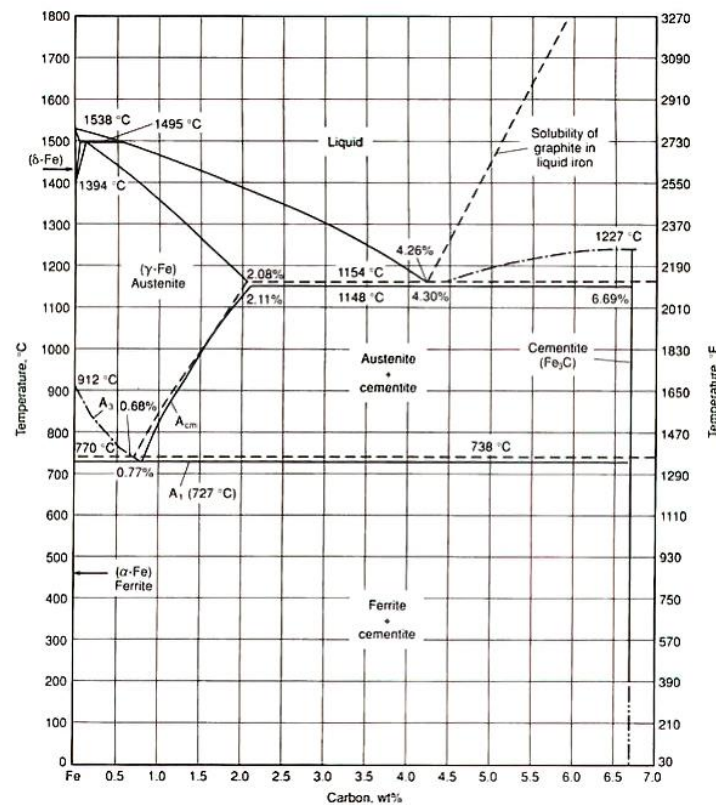
Figure 70. Fe-C phase diagram [51]

For the development of heat treatment technologies the TTT (time-temperature-transformation) diagrams are used, which can be used for heat treatments with both equilibrium and non-equilibrium transformations. These diagrams have a characteristic C-shape, which always are valid for a given alloy. These diagrams show phase transitions in the material as a function of temperature and time. In the figures, the curves indicate the beginning and end of the transformations, and the resulting phase or microstructure is entered in the fields of the figure. The transformations occur over a very wide time scale, so the time axis of these diagrams is logarithmic, allowing very fast processes and slow transformations to be represented with sufficient accuracy in the same diagram. Two types of TTT diagrams have been developed: isothermal transformation (IT) and continuous cooling transformation (CCT) diagrams.
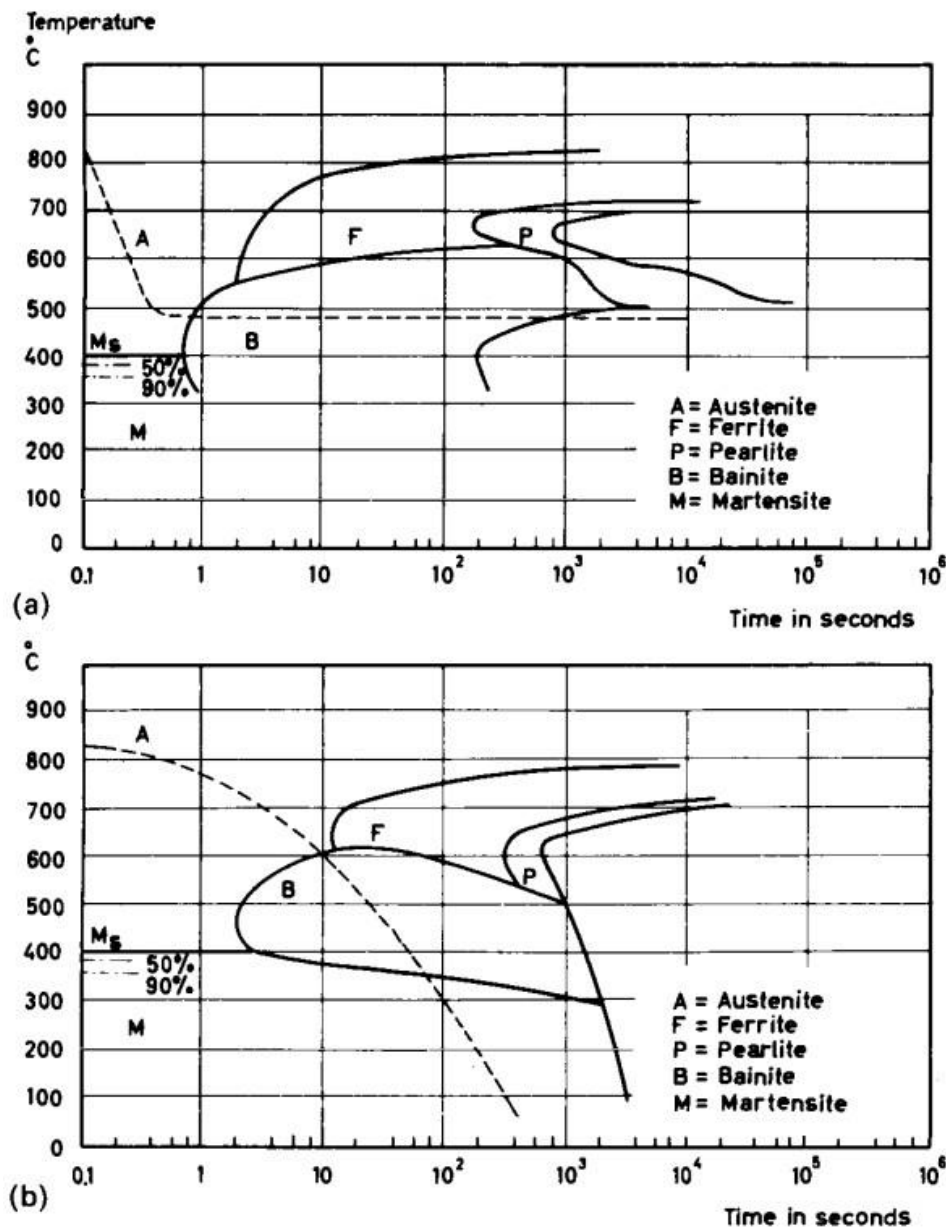
Figure 71. Isothermal transformation (upper)
and continuous cooling transformation (lower)
diagrams for BS 708A37 (34CrMo4, 1.7226) steel [52]

In isothermal heat treatments, the transformations occur at constant temperature. Such heat treatments can be used if the incubation time of the transformation is longer than the time needed to reach the desired temperature. In some cases this means size limits on the size of the pieces that can be heat treated. If the incubation time is short, only small pieces can be heat treated in this way to ensure that microstructural changes do not start before the desired temperature is reached. The great advantage of isothermal heat treatments is that the whole piece undergoes the transformations simultaneously, providing a uniform microstructure and no warpage occurs as a result of the heat treatment.

Continuous cooling is used because the pieces to be heat treated cannot be cooled to the desired temperature suddenly. As cooling occurs through the surface, the surface of the piece cools the fastest and the cooling rate decreases as one moves inwards. The lowest cooling rate is in the middle of the piece, in the core. Since the nature of the transformations depends on the cooling rate, the microstructure of the material is usually not homogeneous in continuous cooling heat treatments. The thermal stress caused by temperature differences during heat treatment can deform the piece, and if the resulting phases have a low deformation ability, it can even crack.

In addition to the curves indicating the start and end of the transformations, some characteristic cooling curves for different cooling rates are often plotted on the CCT diagrams. When designing the technology, the cooling curves must be determined by taking into account the initial temperature of the piece, its size and the cooling medium, and plotting them on the CCT curve will help determine the expected microstructure.
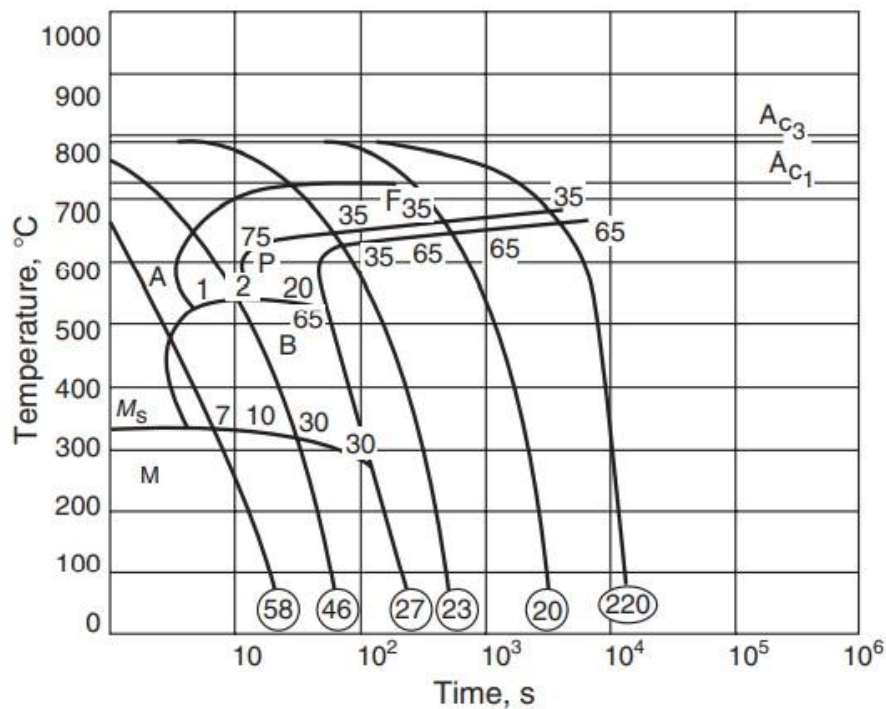
Figure 72. Continuous cooling transformation diagram for hypoeutectoid steel,
with the relative amounts of structural components and hardness indicated on the cooling curves [53]

These calculations can now be carried out with a high degree of accuracy using finite element programs and the expected result of the heat treatment can be accurately predicted. It is important to know, however, that without accurate knowledge of the appropriate material properties, the reliability of the result is doubtful!

Heat treatment can only affect the surface of the parts, these are surface modification heat treatment processes. These are usually aimed at improving hardness and wear resistance.

2.2. EQUIPMENT AND AUXILIARY MATERIALS FOR HEAT TREATMENT

In individual and small series production, modern heat treatment equipment cannot be operated economically, so these tasks are carried out in specialised contract heat treatment workshops. For large production series it is worth installing heat treatment equipment optimised for the task in the production plant.

2.2.1. TYPES OF HEAT-TREATING FURNACES

The most important heat treatment equipment are the furnaces, which ensure the heating, heat holding and sometimes cooling of the piece according to the appropriate programme. Furnaces commonly used in heat treating are classified in two broad categories, batch furnaces and continuous furnaces. In batch furnaces, workpieces normally are manually loaded and unloaded into and out of the furnace chamber. The continuous furnace has an automatic conveyor system that provides a constant heat cycle for each piece.

2.2.1.1. BATCH FURNACES

The basic batch furnace normally consists of an insulated chamber with an external reinforced steel shell, a heating system for the chamber, and one or more access doors to the heated chamber. Standard batch furnaces such as box, bell, elevator, car-bottom, and pit types are most used when a wide variety of heat-hold-cool temperature cycles are required. Batch furnaces are normally used to heat treat low volumes of parts, to handle special parts for which it would be difficult to adapt a conveying system for continuous handling, to process large parts in small numbers, to process various parts requiring a wide range of heat-treat cycles that can readily be changed.

Figure 73. Box-type batch furnace [54]

Figure 74. Bell-type batch furnace [55]

2.2.1.2. CONTINUOUS FURNACES

Continuous furnaces consist of the same basic components as batch furnaces. However, the furnaces operate in uninterrupted cycles as the workpieces move through them. Consequently, continuous furnaces are readily adaptable to automation and thus are generally (though not always) used for high-volume work. Another advantage of continuous furnaces is the precise repetition of time-temperature cycles, which are a function of the rate of travel through the various furnace zones.
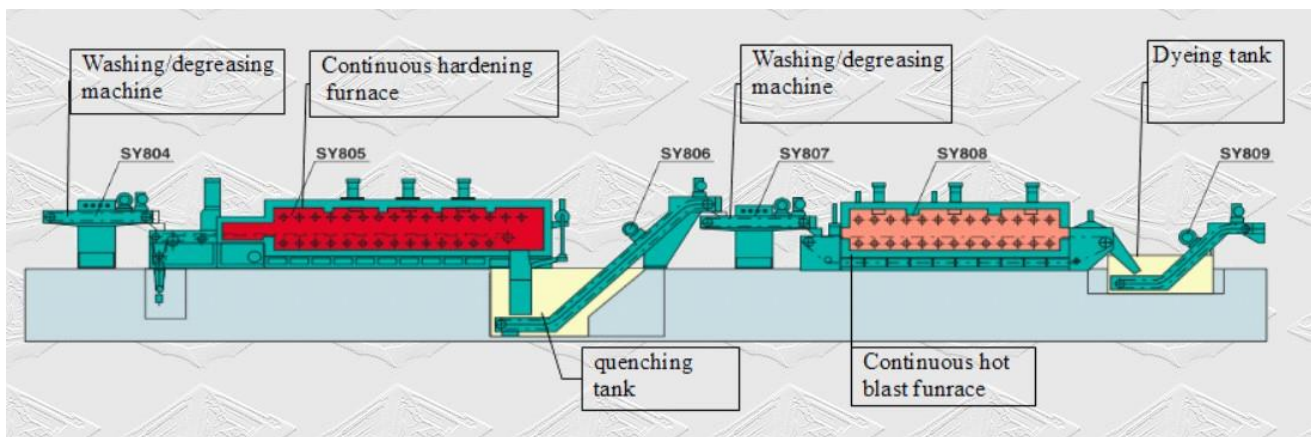
Figure 75. Continuous furnace [56]

In a general sense, continuous-type furnaces can be classified as either rotary-hearth furnaces or straight-chamber furnaces. Rotary-hearth furnaces are useful in shops or operations where only one operator is employed, because the charging and discharging can be located next to one another. Straight-chamber continuous furnaces include various types, which can be classified as: pusher-type furnaces, walking-beam furnaces, conveyor-type furnaces that use rollers or belts, continuous furnaces with tumbling or inertia action of the parts for movement.

2.2.1.3. HEATING OF FURNACES

With direct-fired furnace, work being processed is directly exposed to the products of combustion. Direct flame furnaces can also use different gases (natural gas, straight propane or propane-air mix) or oil. Almost any grade of oil that can be satisfactorily atomized can be burned in direct-fired equipment. To minimise the effect of scale (oxide) on the work, the flue gas products can be controlled by adjusting the fuel/air ratio of the combustion system.

Electrically heated furnaces are generally used in all temperature ranges: from low-temperature tempering furnaces, through the various heat treatment ranges, up to forging temperatures. The heating elements can be of the open type, exposed to the furnace environment, or of the indirect type, protected from the furnace environment by some means. The material of the heating elements is selected according to temperature and atmosphere.

2.2.2. MEDIA USED FOR HEAT TREATMENT

The result of the heat treatment is greatly influenced by the medium in which the process takes place. The medium can be gaseous or liquid of its consistency and neutral or active of its chemical action.

2.2.2.1. GASEOUS HEAT TREATMENT MEDIA

Heat treatment in air is the cheapest and simplest solution, but steels are subject to oxidation and decarburisation, which increase with temperature.

2.2.2.1.1.   NEUTRAL PROTECTIVE GASES

One way to avoid the harmful effects of air is to use a protective gas. For heat treatment, a gas generator is used to produce the appropriate shielding gas from a hydrocarbon by partial combustion. It is a gas mixture containing nitrogen, oxygen, water, carbon dioxide, carbon monoxide, methane, etc. They can control the composition by adding air during combustion. With a small amount of air, the combustion process is not self-sustaining and requires external energy, so-called endogas, which has a reducing effect. At higher air volumes, combustion is self-sustaining, producing exogas, which has an oxidising effect. With the carbon potential adjusted to the carbon content of the steel, it is possible to carbonise, not change the carbon content or decarbonise at will.

Nitrogen protective gas always contains a small amount of oxygen, so it has a small oxidising effect, which can be compensated by mixing with endogas if necessary. In nitrocarburizing or carbonitriding, endogases and ammonia are mixed.

The best neutral protective gases are noble gases (He, Ar), but they are not commonly used for heat treatment because of their high cost. Hydrogen is used in metal powder metallurgy for sintering, as it reduces the surface oxide and thus significantly speeds up the process.

2.2.2.1.2.   ACTIVE GASES

When active gases are used, the shielding gas reacts with the heat-treated material, so a thermochemical process takes place.

Endo gases are used for gas carburizing. Nitriding can be done with nitrogen compounds whose decomposition provides the atomic nitrogen needed for the process, such as ammonia.

The active protective atmosphere is the hydrogen atmosphere, which has a decarburising effect. Hydrogen is used in metal powder metallurgy for sintering, as it reduces the surface oxide and thus significantly speeds up the process.

2.2.2.1.3.   VACUUM TECHNOLOGY

When heating in a vacuum, there is no medium to react with the material to be heated and even surface impurities evaporate. However, low melting point alloys can also evaporate from the surface due to vacuum and high temperatures, changing the composition there. For vacuum heating, only carefully cleaned pieces should be used, because the evaporating material hinders the formation of a proper vacuum. Since only radiative heat transfer is possible in a vacuum, the process is accelerated by initially heating under a protective gas and only later creating a vacuum at a higher temperature. During quenching, the pieces are cooled in the furnace by blowing high-pressure nitrogen. Oil quenched steels up to 50 mm

diameter can be hardened in this way. The cooling effect of the high-pressure gas is uniform, so there are fewer distortions and no need to wash the pieces after heat treatment.

2.2.2.2. LIQUID HEAT TREATMENT MEDIA

This includes salt baths, metal baths, water, emulsions, oils.

Salt baths are also used for quenching and tempering. Their great advantage is the very good heat transfer and the resulting short heating time, as well as the possibility of rapid cooling. It does not start to boil like water, so it does not form a vapour blanket. Their use is being phased out because the salts used are hazardous waste, so nowadays gas and vacuum heat treatment are used instead.

The use of metal baths is also being phased out because of the harmful metal vapours that are emitted.

Water is the most intense cooling medium, but the cooling rate is not uniform during cooling. Up to 400 °C, a so-called quenchant vapour blanket is formed, where the cooling rate is lower due to the insulating effect of the stable vapour film. Between 400 and 200 °C is the nucleate boiling stage, and heat is rapidly removed from the surface as liquid quenchant contacts the metal surface and is vaporized. Below 200 °C convective cooling takes place and the cooling rate decreases. Each cooling phase can be present at the same time, which further deteriorates the uniformity of cooling.

The cooling rate up to 500 C is the most important, because it is here that it is decided whether the nose point of the C curve can be avoided and other non-martensitic transformations of the steel can be avoided. It is precisely in this range that the cooling effect of water is not the best, due to the formation of vapour blanket. By adding salt or a polymer, the upper limit of the nucleate boiling can be raised up to 600 C, creating more favourable conditions for quenching. The water provides the initial intense cooling, and the lower cooling effect of the oil is beneficial for lower residual stresses.

2.2.2.3. FLUID TECHNOLOGIES

It is an advanced process to replace metal and salt baths. Fine-grained ceramic powders (usually aluminium oxide) are kept in suspension by gas injection. The suspended powder behaves as a liquid, with an apparent density that can be controlled by the intensity of the blowing. It can be used both as a heating medium and as a cooling medium, depending on the temperature of the blowing gas. A temperature span of ±2 °C is easily achieved, giving high quality, consistent heat treatment results. The blowing gas can be neutral or active. Newer furnace designs extend fluidized bed technology to the higher temperature ranges (540-1040 °C) required for the most common heat treatments.
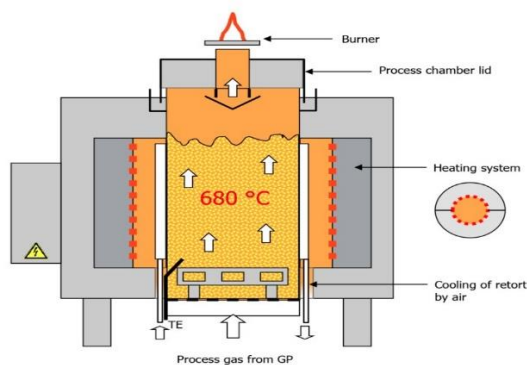
Figure 76. Fluidized bed furnace [57]

Figure 77. Fluidized bed [58]

2.3.   HEAT TREATMENT OF STEELS

Steels are still the most important raw materials in the machinery industry. This is due to their relative cheapness and their wide range of mechanical properties. Depending on the carbon and other alloying contents, a wide range of phases with different properties can form the microstructure. Just to list the possible phases, textural elements: austenite, ferrite, perlite, cementite and other carbides, bainite, martensite, spheroidite. In addition to having different properties, they can also be mixed within a steel in different proportions and structures, extending the range of properties available.

2.3.1. ANNEALINGS

The basic aim of different annealing technologies is to improve machinability.

2.3.1.1.   STRESS RELIEVING

The aim of this procedure is to eliminate residual stresses in the working parts. In most machining processes, residual stresses are always present. An internal residual stress not depending on external forces resulting from such factors as cold working, phase changes, or temperature gradients. For steels, the yield point decreases significantly above 400 °C, so above this temperature stress reduction becomes effective. However, it should also be considered that we do not want to change the material structure and mechanical properties. Therefore the upper temperature limit for this heat treatment process is A_{c1}. As most of the stresses are built up during the heating process, there is no point in prolonged holding of the heat. Finally, the piece needs to be cooled down slowly to avoid further residual stresses.
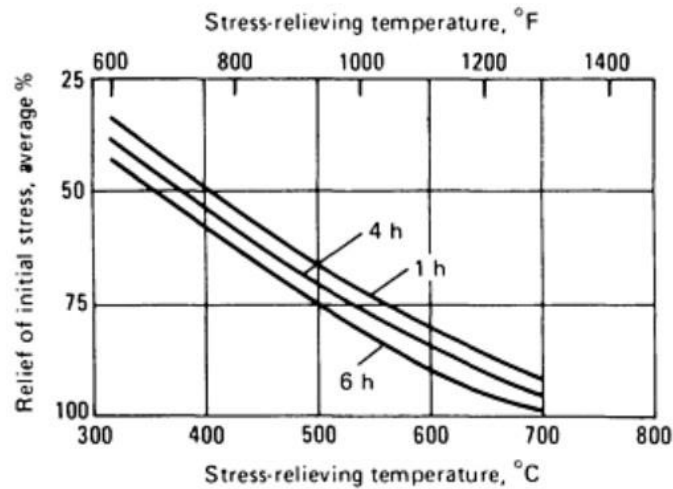
Figure 78. Relationship between time and temperature of residual stresses [51]

When determining the heating temperature, it must be considered that the higher the heating temperature, the greater the reduction in residual stresses. Scale formation is negligible up to 500 °C. For quenched and tempered pieces, the annealing temperature should be kept 20-30 °C below the tempering temperature so that the original mechanical properties are not altered. For structural elements operating at high temperatures, the annealing should be carried out 20-30 °C above the operating temperature.

2.3.1.2. RECRYSTALLIZATION ANNEALING

This heat treatment is applicable not only to steels, but to all cold worked metals and alloys. During plastic deformation, the increase in dislocation density causes the material to harden, increasing its strength. By recrystallization, the deformed grain structure and the dislocation density can be approximated to equilibrium state. The recrystallization temperature is not a constant value for a material, but its value depends on the degree of previous plastic deformation. Below a certain degree of deformation, the material cannot be recrystallised. Below a certain degree of deformation, the material cannot be recrystallised, a threshold must be reached to start the process. During recrystallisation, a fine-grained structure should generally be aimed for. Recrystallisation can be complete or partial depending on the heat treatment time applied. In full recrystallisation, the degree of pre-forming plays an important role. In cases where the material has been formed to a small extent, recrystallisation starts from a small number of crystal nuclei, so that they can grow to a large size. As the degree of deformation increases, the number of crystal nuclei increases and the crystal structure becomes finer.
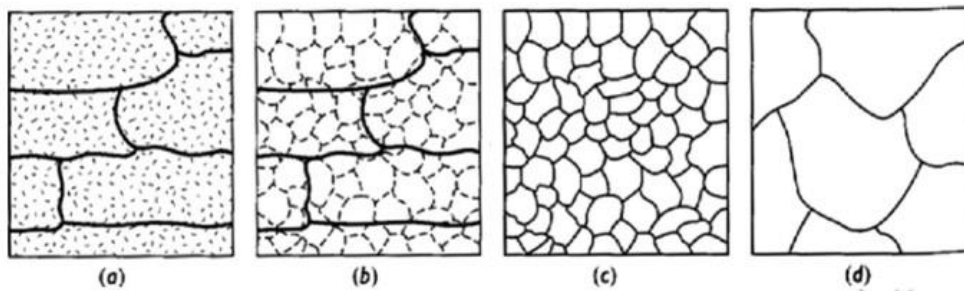
Figure 79. Annealing temperature effect on the microstructure of cold work metals
(a) cold work, (b) recovery, (c) recrystallization, (d) grain growth. [59]

In the case of ferrite-pearlite structural steels, the ferrite suffers the plastic deformation, while the pearlite hardly changes at all due to its higher strength. It also follows that the quality of the steel, i.e. the proportion of ferrite perlite, also influences the recrystallisation process. For the same plastic deformation with different ferrite content, the degree of deformation of the ferrite will be different, and hence the recrystallisation temperature.
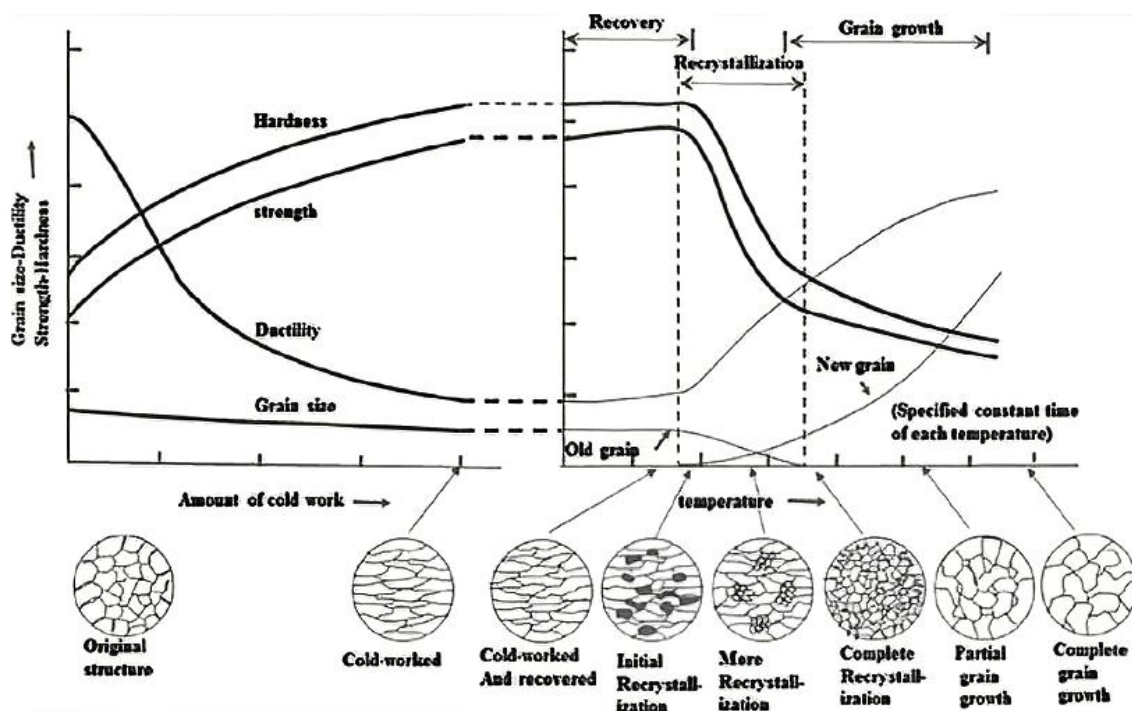

Figure 80. Annealing stages of recovery, recrystallization, and grain growth along with cold work process. [59]

The recrystallization diagrams and annealing curves help to develop the technology.

2.3.1.3. COARSE-GRAIN ANNEALING

When machining materials with high ductility, especially at low cutting speeds, the quality of the machined surface will be poor. By deliberately coarsening the grain structure, machinability can be improved. Low carbon mild steels behave in this way. Annealing should be carried out well above A_{c3} temperature. The grain size is mainly determined by the

annealing temperature and time, but also by the cooling rate. At a given temperature, grain size growth slows down over time, so after a certain time it is pointless to continue annealing. During cooling, the growth of the grains continues above Ar_3, so it is advisable to leave the piece to cool with the furnace, as this saves some of the annealing time and energy.
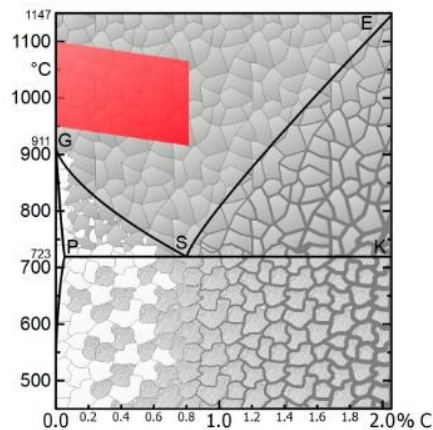

Figure 81. Coarse-grain annealing temperature range. [60]

The poor mechanical properties caused by the coarse grain structure can be eliminated by a further heat treatment after machining, so they do not affect the usability of the part.

2.3.1.4. SPHEROIDIZING

The purpose of heat treatment is to improve the machinability and ductility of ferrite-pearlite and ferrite-cementite microstructural steels. The cementite lamellaes in the perlite and the network of secondary cementite make the steel hard and poorly ductile. When machining, the tool shears the cementite lamellaes, which puts a lot of stress on the tool edge and causes rapid tool wear. By spheroidising cementite, the ductility and machinability of steel can be significantly improved. Under load, the ferrite embedding the cementite changes its shape, significantly increasing the ductility of the material. During machining, the cementite grains are pressed into or out of the embedding ferrite, significantly reducing tool wear and machining energy requirements. It is used for turning above 0.4% C content and for plastic cold forming at lower carbon contents.
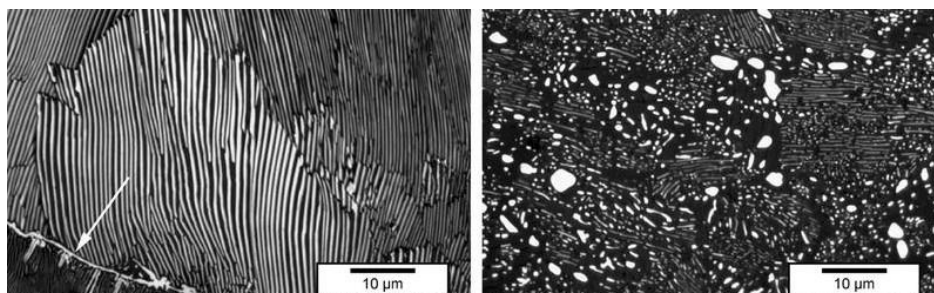

Figure 82. Microscopic image of lamellar perlite and spheroidite. [61]

This process is driven by a decrease in surface energy. The energy level at the phase boundaries is always higher than inside the phase. The transformation from lamellar form to globular results in a reduction in surface area. When heated directly below A_{c1} temperature, the cementite is dissolved and recrystallised, resulting in its spheroidizing. The carbon solubility of ferrite and the diffusivity of carbon are much higher at this temperature than at room temperature. First the cementite plates fragment, then they converge to a spherical shape. On further annealing, the smaller ones dissolve and the larger ones grow. The process is accelerated by a preliminary plastic cold forming.
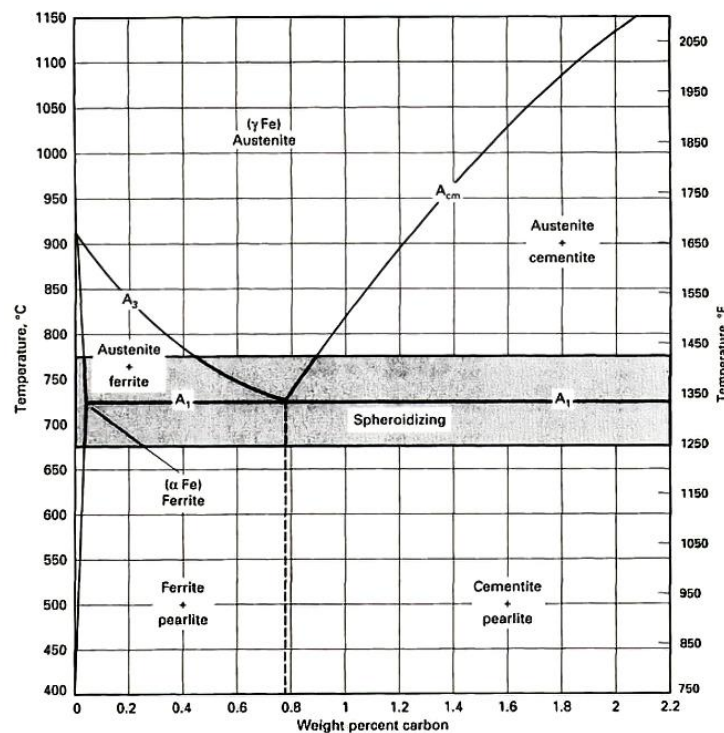

Figure 83. Spheroidizing temperature range. [51]

Depending on the quality of the steel, different technologies are used. In the case of hypoeutectoid steels, annealing is carried out at 20 °C below A_{c1} for several hours and the piece is then left to cool with the furnace.

In the case of hypereutectoid steels, partial dissolution of the secondary cementite requires heating above A_{c1} temperature, which produces some austenite, which dissolves carbon two orders of magnitude better than ferrite. Due to the higher solubility, the dissolution and fragmentation of carbides is faster. After holding above A_{c1}, very slow cooling to 600 °C or cooling below A_{r1} is followed by further holding. Final cooling can be done together with a furnace. This technology is also used for tool steels and rolling bearing steels.
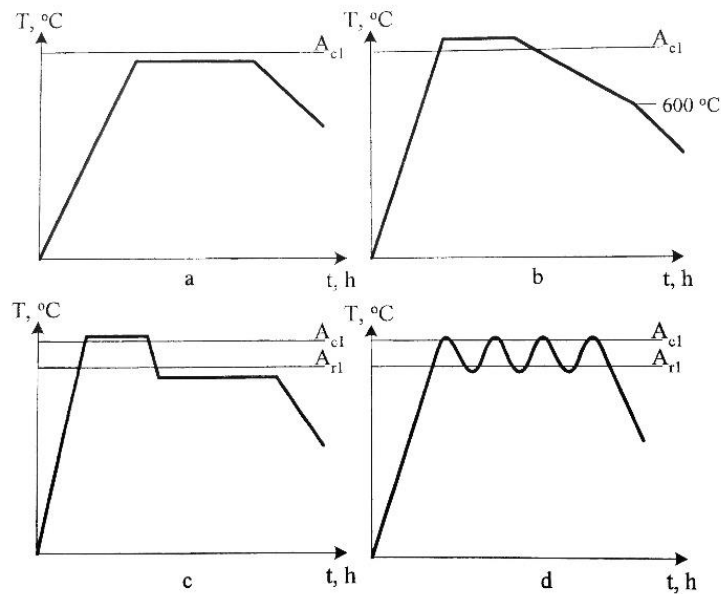
Figure 84. Conceptual temperature-time diagrams for different methods of spheroidizing annealing.
a, unalloyed hypoeutectoid steel, alloyed structural steel
b, c, unalloyed hypereutectoid steel, tool steel, rolling bearing steel
cast steel [62]

The spheroidizing of coarse lamellar pearlite in steel castings is carried out by a complex heat treatment. The temperature is raised above A_{c1} and then lowered below A_{r1}, repeated several times in sequence (swinging annealing). This method is an effective way to reduce the duration of the heat treatment. Care must be taken, however, to ensure that some cementite is always retained during the austenitizing process, as this is necessary as a crystallisation nucleation sites to achieve a suitable microstructure.

2.3.1.5. NORMALISING

The aim is to achieve a uniformly distributed ferrite-pearlite or pearlite-carbide microstructure. This is a heat treatment based on an equilibrium α-γ-α transformation, where cooling is done in still air. The γ-α phase transformation results in significant grain refinement if the original material was coarse grained. The austenitizing occurs at temperatures of 30-50 °C above A_{c3} for hypoeutectoid steels and Ac1 for hypereutectoid steels. For the latter, A_{cm} temperature is used when the network structure of the secondary cementite is to be eliminated
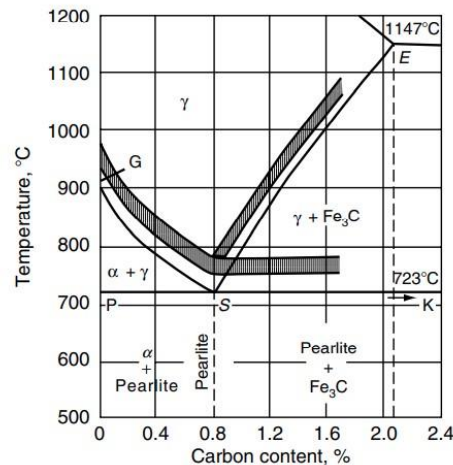
*Figure 85. Range of austenitizing temperatures for normalizing
unalloyed steels depending on their carbon content [53]*

The aim is to achieve a homogeneous austenite, which should take 10-30 minutes. Cooling should be carried out in still air with all sides of the piece in contact with the air.
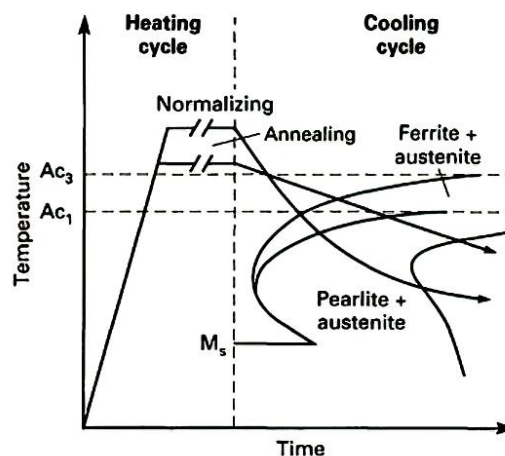

Figure 86. Comparison of time-temperature cycles for normalizing and full annealing [51]

Normalising is mainly used for unalloyed and low-alloyed steels. It can be used as an intermediate operation before hardening, or to improve the mechanical properties of steel castings and weldments by normalising.

2.3.1.6. SUPERCRITICAL OR FULL ANNEALING

In this process, the aim is to ensure good machinability and a finer grain structure. In the case of cast and hot worked non-uniform, or even coarse-grained materials, the uniform and finer grain structure achieved during full annealing has a positive effect on subsequent quenching and tempering operations. The first step is to convert the material to austenite, followed by a controlled slow cooling. The cooling rate can be determined from the CCT diagram of the material based on the desired hardness. Controlled cooling should be carried out until the

perlite transformation is complete, after which the final cooling can take place in an oven or in still air. For high alloyed steels, where diffusion is much slower, this heat treatment can take an uneconomically long time.

For hot-formed pieces, austenitizing is carried out at A_{c3}+ (30-50 °C) with a holding time of 20 minutes. Higher temperatures and longer times are required for steel ingots.

2.3.1.7. ISOTHERMAL ANNEALING

Isothermal annealing is used for forged low carbon mild steel and quenchable steel pieces. The aim of heat treatment is to reduce the time required for annealing (it requires the shortest time), ensure uniform hardness (140-185 HB) and minimum residual stress. As a result of the heat treatment, machinability is improved, and the distortion is reduced during carburisation and tempering. The resulting fabric structure is ferrite + fine pearlite, harder than full annealing, but this does not affect machinability.
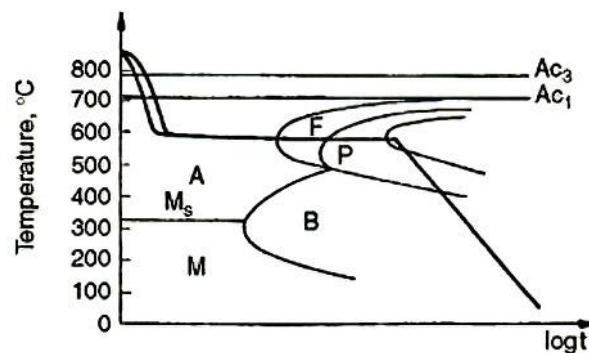

Figure 87. The principle of isothermal annealing [63]

In order to homogenise the austenite sufficiently, it is advisable to choose a higher temperature and a longer time than usual. After austenitizing, the smaller pieces are cooled with cold blown air or a protective gas and then placed in a furnace at the right temperature. The annealing temperature and the annealing time can be determined from the IT curves. The temperature of the isotherm is usually chosen as the point on the curve indicating the completion of the perlite transformation at the shortest time. The recommended temperature is 20-30 degrees above this and the required annealing time can be read on the time axis. Final cooling takes place outside the furnace in air.
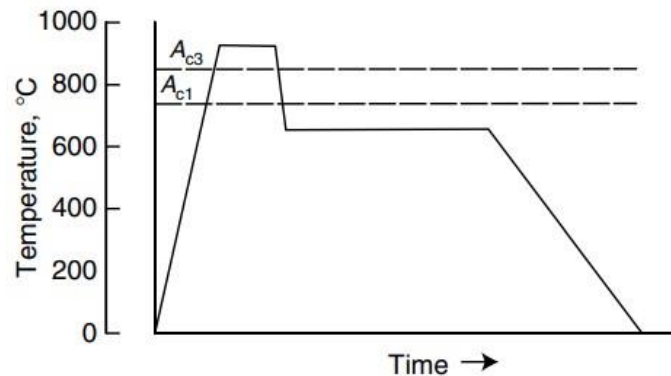
Figure 88. Temperature–time cycle of isothermal annealing [53]

2.3.1.8. ANNEALING OF AUSTENITIC STEELS

Heat treatment applied to austenitic Cr-Ni and Mn steels, where the aim is to achieve a homogeneous austenitic microstructure.

For austenitic stainless Cr-Ni steels, this heat treatment may be necessary if they are susceptible to intergranular corrosion. Heat causes $Cr_{23}C_6$ carbide to precipitate at the grain boundary, removing the dissolved Cr content from the austenite, resulting in a loss of corrosion resistance in the near grain boundary regions. On the raw material side, this can be dealt with by reducing the carbon content of the steel (a costly solution) or by binding (stabilising) the carbon with carbide-forming alloying agents stronger than Cr. Once chromium carbide has appeared at the grain boundary, the steel can be converted into a homogeneous austenite by annealing above its dissolution temperature (1050 °C) and then cooling rapidly in water to avoid re-precipitation of chromium carbide.

Austenitic Mn steels (Hadfield steel) have a significant 12% Mn and 1.2% C content. The elements are mostly produced from this material by casting, and during slow cooling, $(Fe,Mn)_3C$ complex carbide is formed on the grain boundaries, which makes the steel brittle. Carbide can be brought into solution by annealing at 1000 °C, followed by rapid cooling to avoid its re-precipitation. When heating, it must be considered that the material is brittle due to its poor thermal conductivity and high coefficient of thermal expansion, so it can easily crack when heated. Therefore, the heating should be carried out in several stages, with the introduction of thermal holdings to ensure thermal equilibrium.

The impact energy of the material increases significantly (150-350 J/cm2) as a result of the heat treatment. Impact surface stresses transform austenite into martensite, resulting in a significant increase in hardness and wear resistance.

2.3.2. HARDENING HEAT TREATMENTS

In steels, high hardness is provided by martensite and interstitial metallic compounds.

2.3.2.1. QUENCHING OF STEEL

Martensite is produced during quenching. Martensite is formed from austenite by cooling rates above the critical upper cooling rate. Martensite is not an equilibrium constituent, the transformation occurs without diffusion and is determined by the final temperature of cooling. The transformation starts at the temperature M_s and ends at the temperature M_f. The austenite face-centred cubic lattice is transformed into a body-centred cubic lattice by lattice tilting, without the atoms changing neighbours at the lattice points. Since there is a significant difference in carbon solubility between the two lattice types in favour of austenite, the resulting body centred cubic lattice becomes oversaturated and the trapped C atoms distort it into a tetragonal lattice. The higher the C content in martensite, the greater the distortion effect and the greater the hardness of the martensite.
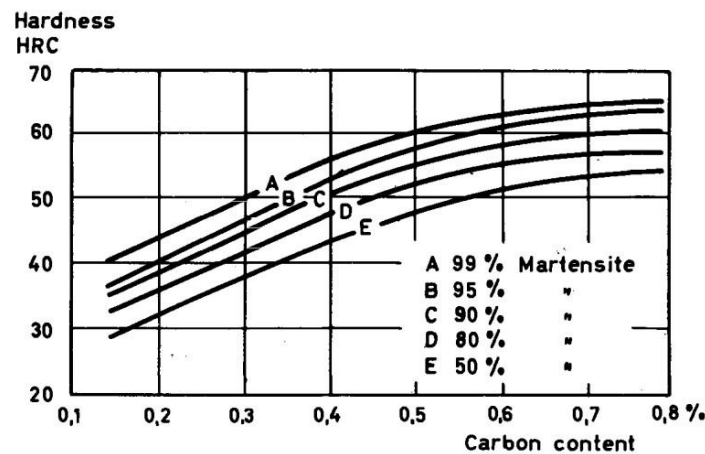

Figure 89. Relationship between hardness, carbon content and amount of martensite [52]

In the case where the final cooling temperature is between M_s and M_f, the martensitic transformation will not be complete, leaving residual austenite. Residual austenite reduces the hardness, and its subsequent alteration leads to a change in specific volume, and therefore size.
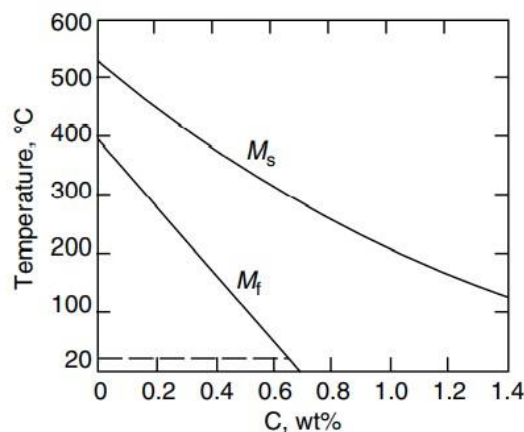

Figure 90. M_s and M_f temperature of unalloyed steels as a function of C content [53]

The critical upper cooling rate depends on material quality and can be determined from the CCT diagram of the material. At slower cooling rates, not only martensite is produced, but martensite transformation is preceded by other transformations. Another critical cooling rate is commonly defined, and this is the critical lower cooling rate. This marks the lower limit of the occurrence of martensite in the microstructure. This is important if one wants to avoid the formation of martensite, for example because of the risk of cracking during welding.
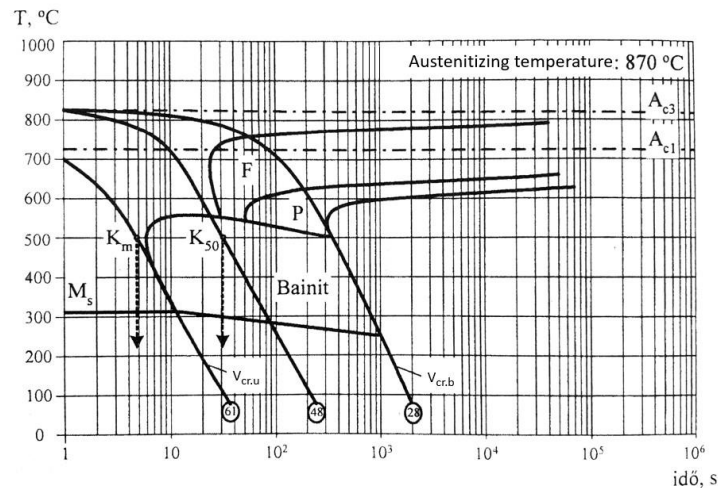

Figure 91. The critical cooling curves and the 50% martensitic cooling curve on the CCT diagram
$v_{cr\,u}$- upper critical cooling rate, $v_{cr\,b}$- bottom critical cooling rate [62]

Pure martensite is very difficult to form in the full cross-section, and usually not even necessary. In practice, a microstructure containing 50% martensite is considered to be hardened. Therefore, a distinction is made between fully hardened (at least 95% martensite content) and hardened (at least 50% martensite content) microstructures. The amount of martensite produced is a function of the cooling rate below the critical upper cooling rate. The hardenability of steels is usually characterised by the diameter that can be hardened. A distinction is made between a fully hardenable diameter, which is the diameter of the cylindrical piece with just 95% martensite content in the axial line, and a hardenable diameter, where the criterion is 50% martensite content in the axial line. In addition to the quality of the material, the hardenable diameter also depends on the quench severity factor mentioned above.

The hardenable diameter can be determined experimentally using the Jominy test. The exact test conditions are described in EN ISO 642:2000 standard. A Ø25x100mm specimen is machined from the steel batch to be certified, and then austenitized in a furnace at a temperature appropriate to the material quality. The austenitized test specimen is cooled in the device designed for this purpose by a jet of water directed onto its end face. After cooling, the test specimen is ground flat along its face to a width of 5 mm to measure its hardness. Near the end plate, the workpiece is completely quenched, and away from it the amount of martensite decreases.
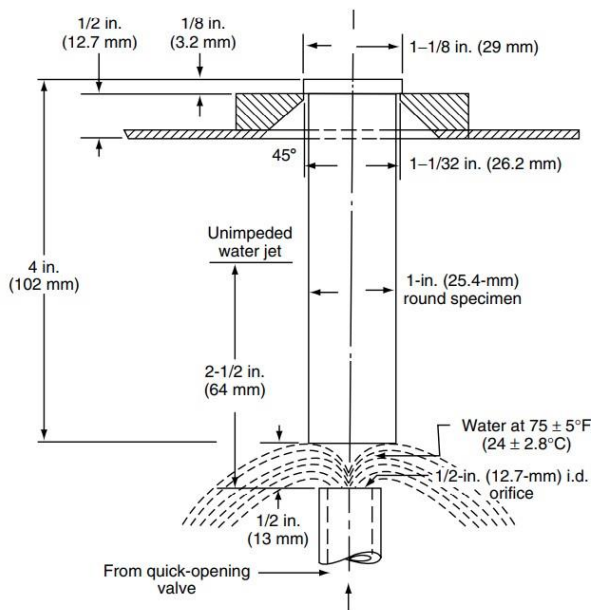
Figure 92 Jominy specimen and its quenching conditions for end-quench hardenability test [53]
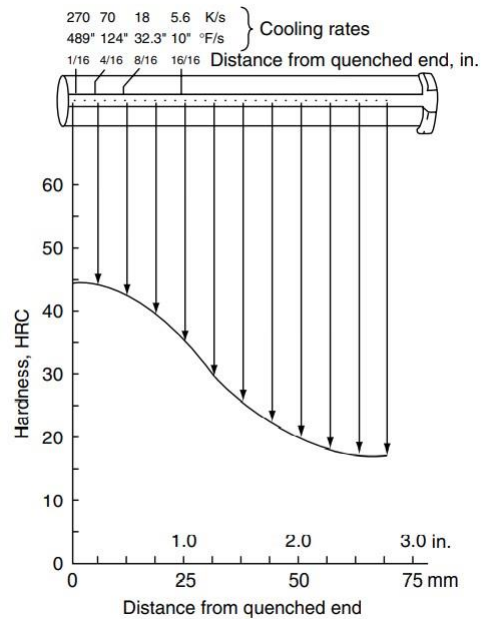

Figure 93. Measuring hardness on the Jominy specimen and plotting the Jominy hardenability curve [53]

Plotting the hardness as a function of the distance from the end plane gives the Jominy hardenability curve. If the C content is known, the diagram in Figure 89. can be used to determine the hardness of 50% and 95% martensite containing microstructure. By intersecting the Jominy curve with these hardness values, the Jominy distance l_{50} and l_{95} can be determined.
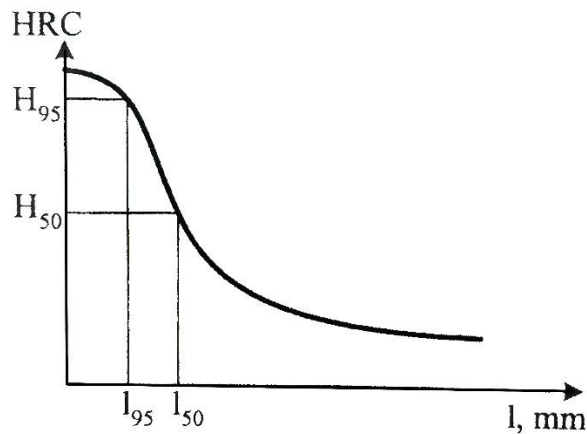
Figure 94. Jominy curve with distances l_{50} and l_{95} [62]

If the material composition is not known, the inflection point of the Jominy curve gives an approximate Jominy distance for 50% martensite content. From the hardness associated with this distance l_{50}, the C content, the hardness of the microstructure with 95% martensite content and the Jominy distance l_{95} can be determined. The Jominy distance is not the same as the diameter that can be hardened, as the cooling conditions are different during

quenching. The hardenable diameter can be determined from the Jominy distance for a given cooling medium and a given amount of martensite using diagrams or tables.
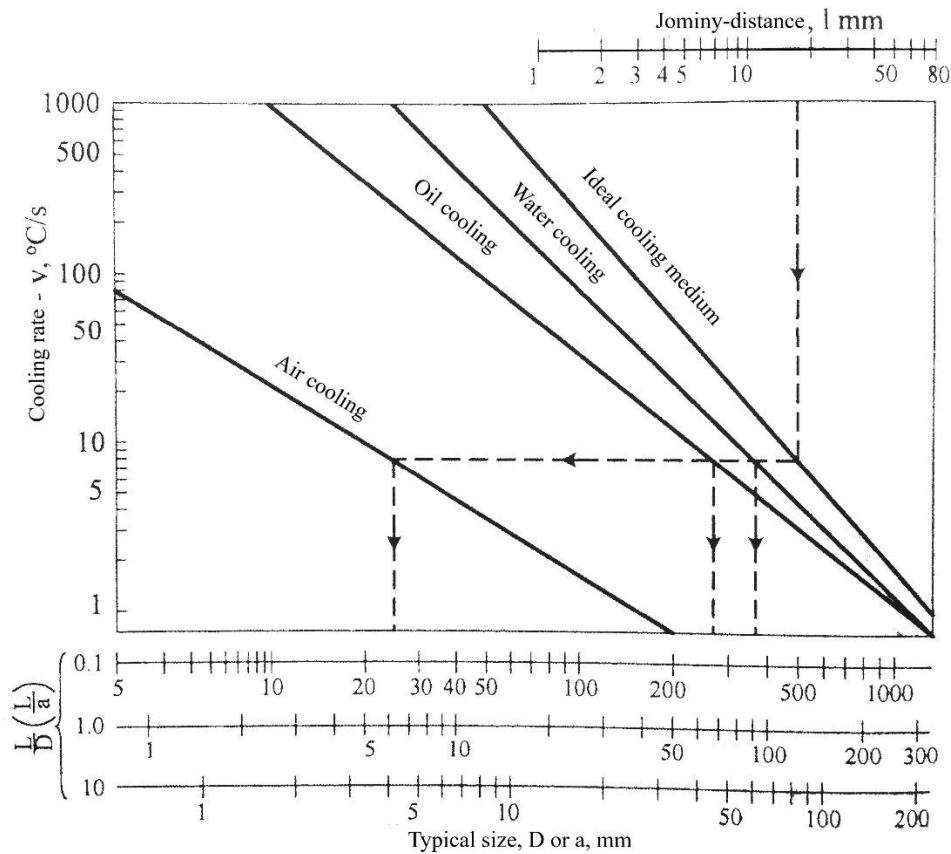
Figure 94. Monogram for the determination of hardenable diameter [53]

Theoretical calculations can also be used to determine the diameter of the steel that can be hardened, but the exact composition (carbon and other alloying contents), grain size and cooling severity (Grossmann method) must be known. The calculations give an ideal hardenable diameter, from which the actual hardenable diameter can then be determined using monograms, taking into account the cooling mode.

Figure 95. The chart for converting the values of the critical diameter D_{crit} into the ideal critical diameter D_I [53]
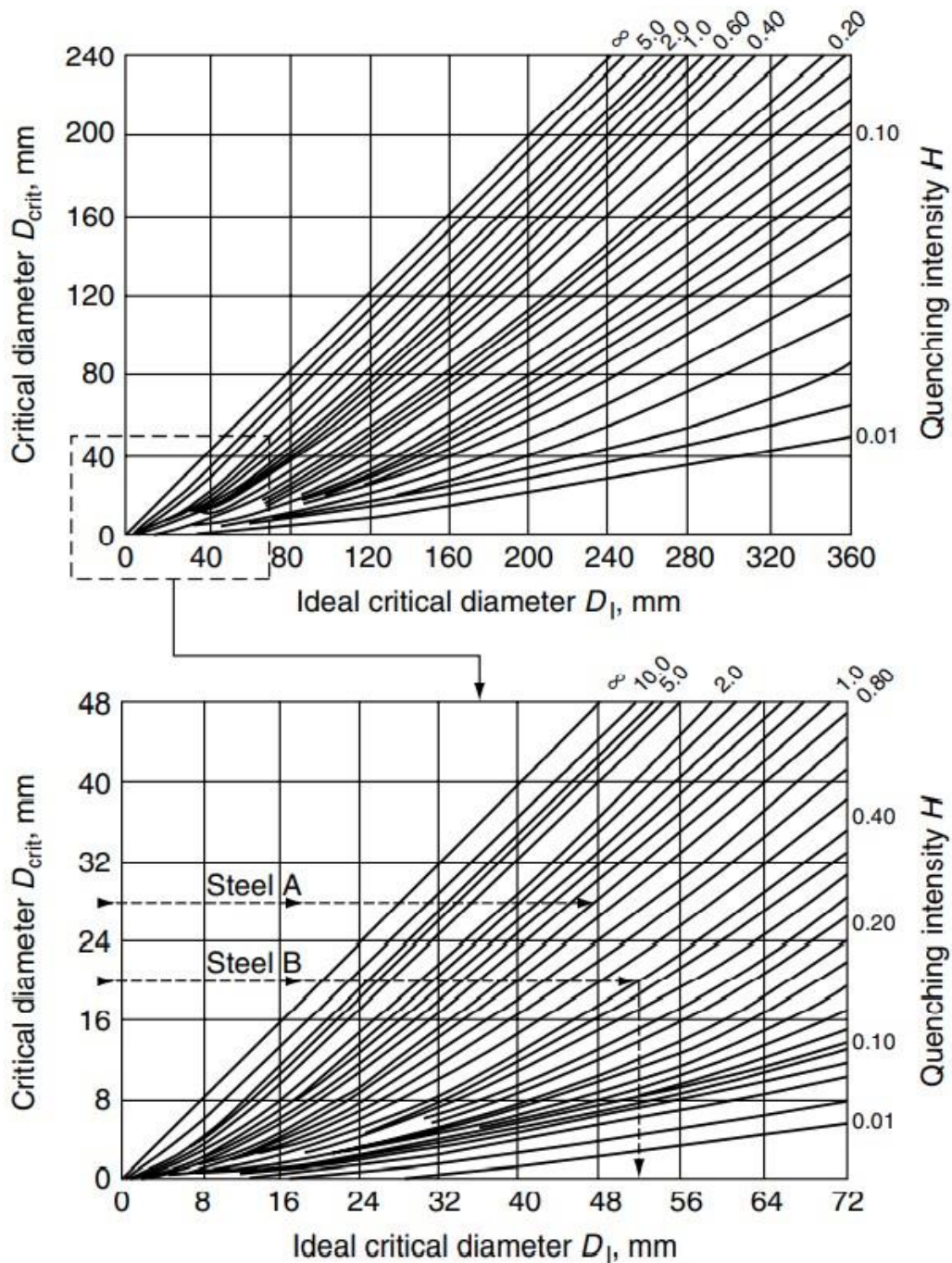
In the case of hypoeutectoid steels, the austenitisation is carried out above Ac_3, in the case of hypereutectoid steels above Ac_1. In the latter case, heating above A_{cm} would increase the amount of residual austenite, the unchanged secondary cementite, but not decrease the hardness. The heat holding time required is usually 10 minutes, 30 minutes for coarser microstructures. Quenching temperatures for alloyed steels can be found in standards and manufacturers' catalogues. Water is used as a coolant for unalloyed steels, oil for alloyed steels and possibly high-pressure gas cooling. The direction of immersion in the coolant is

important for the risk of warping and cracking, because the cooling effect of oil and water is not constant at different temperatures.
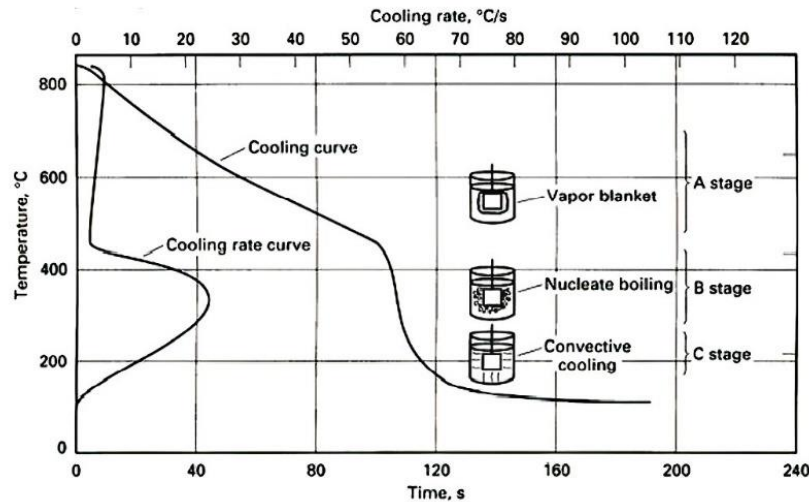

Figure 96. Cooling curve and cooling rate curve at the centre of a 25 mm diameter probe quenched with 95 °C water flowing at 15 m/min [51]

The resultant martensitic microstructure will have significant residual stress during the transformation, so a 2-hour annealing at 180-200 °C immediately after quenching is required. Carbides are then precipitated from the martensite, reducing the carbon content of the martensite and the distortion of its lattice, while the hardness is practically unaffected.

2.3.2.2. SURFACE HARDENING

This procedure only affects the layers close to the surface, while the inner parts remain unchanged. Prior to surface hardening, the properties of the core part of the piece are achieved by normalising or quenching and tempering as required. The pre-heat treatment also improves the properties of the surface hardened layer. An intense heat source is used to rapidly heat the surface layer to austenitizing temperature and then it is almost instantly quenched. Heating can be by gas flame, induction, immersion in a salt or metal bath, laser or electron beam. The C content of steel is typically between 0.34 and 0.6%, with higher carbon contents causing a high risk of cracking. In many cases, the surface hardening is followed by a stress relieving heat treatment.

It should be mentioned that there are several variants of surface hardening processes, where the composition of the surface layer is changed by diffusion of some kind of alloying element into the surface layers. These are various thermochemical processes that require high temperatures. Such as carburizing, where the surface layer is enriched with C, thus making the otherwise non-heat-treatable base material hardenable, and then the quenching is performed. Another common process is nitriding, where nitrogen is introduced into the surface layer, the nitrogen forming various nitrides to form a very hard, wear-resistant layer near the surface of the piece.

2.3.2.3. MARTEMPERING

Martempering process used for more complex, oil and air-quenched alloyed steel pieces and for smaller section sizes in the case of water-quenched materials. It aims to produce a martensitic microstructure with minimum thermal and transformation stresses to avoid distortion and cracking.
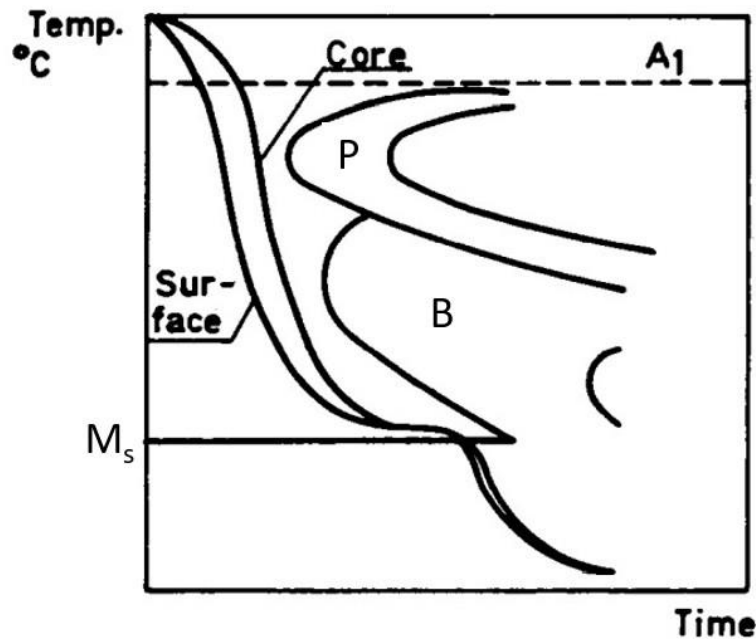

Figure 97. Time temperature transformation diagram with superimposed cooling curve showing martempering process [52]

After austenitizing, the piece is cooled in a metal bath (e.g. lead) or salt bath to above Ms and then is held to equalise the temperature of the internal and external parts. Before the bainitic transformation begins, the piece is removed from the bath and further cooled to below the M_s-M_f range in air. This is followed by a tempering under M_s. The time lapse before tempering is not as critical because the stress is greatly reduced.

2.3.3. TOUGHENING HEAT TREATMENTS

Resistance to dynamic stresses is called toughness. The easiest way to determine the toughness of a material is the Charpy impact test.

The toughness of steels with low C content can be increased by grain refining, which can be achieved by normalisation because the C content is below the hardenability limit. Normalisation is also carried out for large cross-section unalloyed hardenable steels because of their small quenchable diameters, since the hardening effect of tempering does not prevail at large diameters. Normalisation, on the other hand, covers the entire cross-section, even for large sizes.

2.3.3.1. QUENCHING AND TEMPERING

Spheroidite is formed when martensite is tempered at high temperatures. This also implies that the piece should be tempered if the conditions for quenchability are met. Spheroidite is a biphasic constituent of a dispersely distributed cemetite embedded in ferrite.
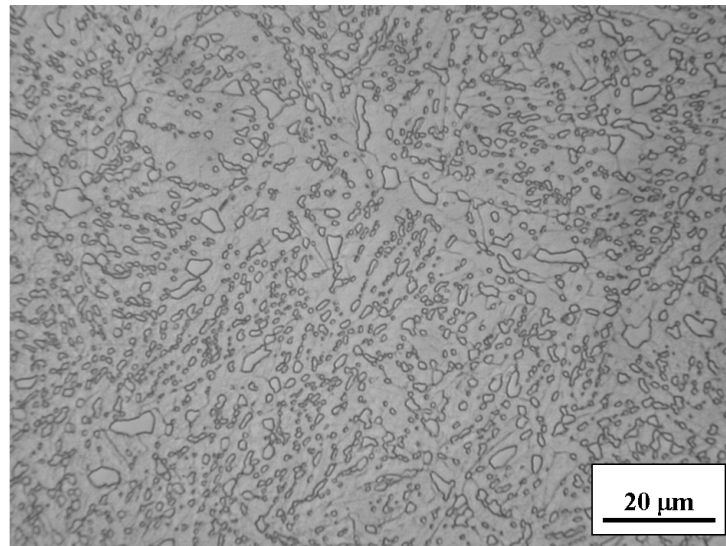

Figure 98. Optical micrograph of very large spherodised cementite particles [64]

During tempering, the diffusion causes the appearance of carbides in the microstructure, while reducing the distortion and hardness of the body centred cubic lattice. With the appearance of carbides, the precipitation hardening mechanism is activated, which provides greater strength the smaller the precipitate spacing. Initially, the precipitating carbides are small and the distance between them is small. During the tempering process, some of the carbides dissolve and others start to grow. As the distance between them increases, the material loses strength while its ductility increases. This precipitation process can be controlled by the right choice of annealing time and temperature. Here, temperature and time are substitutes within certain limits. Tempering diagrams help to develop the technology.

At the same hardness, the tempered microstructure will have the highest impact when pure martensite has been achieved during quenching. Bainite, which appears beside martensite, only deteriorates the impact energy under room temperature, while perlite deteriorates it even at room temperature. For certain types of steel, temper embrittlement occurs in the 450-600 °C range. Such steels must be tempered below 400 °C or above 600 °C. In the latter case, rapid cooling after tempering is very important.
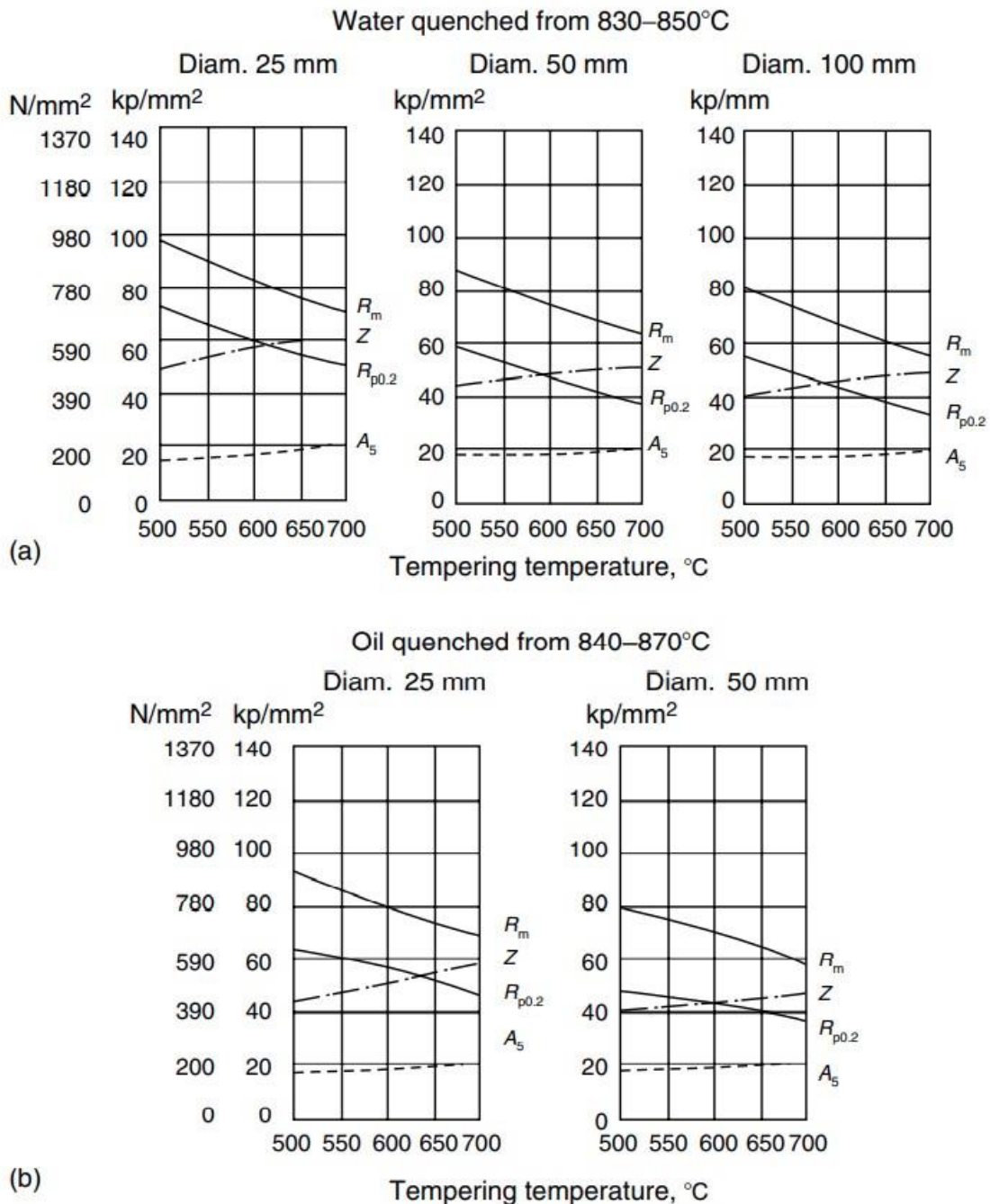
Water quenched from 830–850°C

(a)

Oil quenched from 840–870°C

(b)

Figure 99. Tempering diagrams for unalloyed steel C45 [53]

2.3.3.2. AUSTEMPERING

The aim of austempering is to obtain a pure bainitic microstructure, which can only be achieved by isothermal annealing. Austempering is mainly used for steels with a C content of 0.5-1.2 %, which are typically oil-quenched steels with longer incubation times. It is also used to heat treat ductile cast iron (ADI – austempering ductile iron).

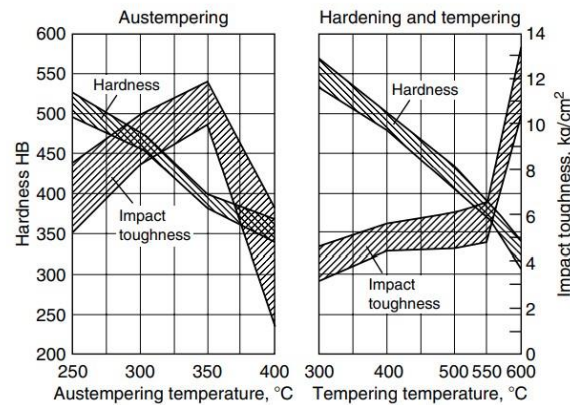Too long incubation and transformation times make the process uneconomic.

*Figure 100. Impact toughness and hardness (HB) of five heats of a Cr–Mn–Si steel
after conventional hardening and tempering and after austempering, as a
function of tempering temperature and austempering temperature, respectively. [53]*

Pure bainite microstructure gives the heat-treated pieces favourable properties. At the same hardness, it results in a better toughness and yield strength than tempering. Temper embrittlement does not occur when austempering. The bainitic microstructure shows a more favourable behaviour in creep. Heat treatment reduces the risk of warping and cracking. No tempering is required, the heat treatment can be carried out in one step.
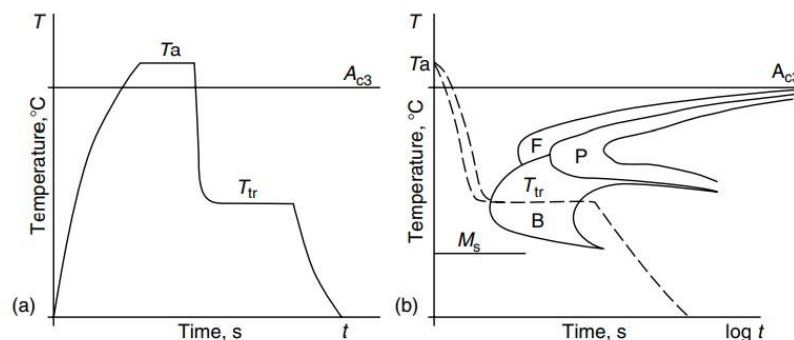

Figure 101. Scheme of austempering process [53]

In a salt bath ($NaNO_3$, $NaNO_2$, KNO_3), the austenitized workpiece is quenched to the temperature below that of pearlite formation and above that of martensite formation (260-400°C), avoiding the nose point of the IT curve during cooling. Before the transformations start, the temperature difference between the surface and the inside of the piece is equalized. The holding time must be long enough to ensure that the bainite transformation is completed, otherwise martensite and residual austenite will be present in the microstructure, which will impair the strength properties. After the bainitic transformation, the pieces are left to cool in air.

2.3.3.3. PATENTING

In wire making, a heat treatment applied to medium-carbon or high-carbon steel before the drawing of wire or between drafts. This process consists of heating to a temperature above

the transformation range and then cooling to a temperature below A$_{c1}$ in air or in a bath of molten lead or salt. It differs from austempering in that the cooling curve does not avoid the nose of the IT curve.
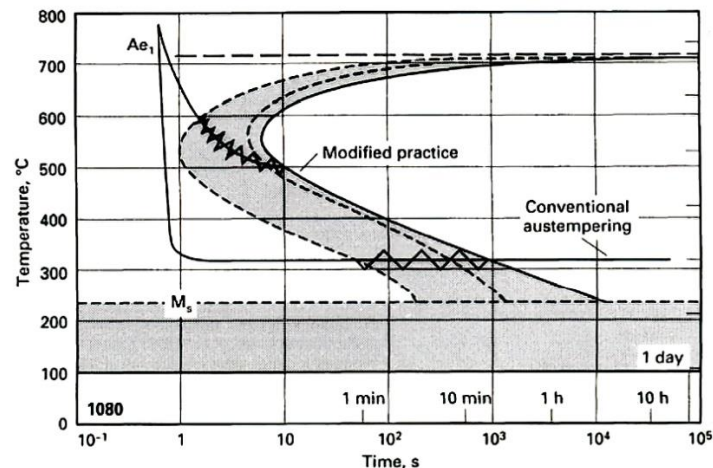

Figure 102. Time-temperature transformation diagram for C86D steel, showing difference between conventional and modified austempering. When applied to wire, the modification shown is known as patenting [51]

The dwell time in the bath is around 10 s for wire and 90 s for rod materials. The aim is to increase the formability of steels with a carbon content of more than 0.35%. The heat treatment produces a homogeneous, fine pearlite and the microstructure is free of primary ferrite. When drawing wire, the wire surface is not smooth due to the presence of ferrite. The ferrite is softer and until it approaches the strength of perlite due to strain hardening, only the ferrite is deformed. The ferrite pearlite grain boundaries are the crack initiation sites for hypoeutectoid steels, and therefore the diameter reduction during drawing is much smaller than for pure pearlite microstructures.

The heat treatment results in a good ductile material of moderately high strength.

2.4.   HEAT TREATMENT OF ALUMINIUM ALLOYS

Aluminium has several favourable properties for use as a structural material. These include excellent corrosion resistance, low specific weight and good formability. Its biggest drawback in this respect is its low strength. Aluminium does not have an allotropic transformation, so it does not have as many possibilities for heat treatment as steels.

The strength of pure aluminium can only be increased by plastic cold forming, which of course can be at the loss of ductility. Recrystallisation heat treatment can restore plasticity with a loss of strength, which occurs at 300-350 °C. It is important to know that if the grain structure becomes coarse during recrystallisation, it cannot be eliminated by further heat treatment.

The low strength of aluminium is improved by alloying, at the cost of less of the previously mentioned favourable properties. Cu, Mg, Si and Zn are the most important strength-

enhancing alloys of aluminium. One way to increase strength in alloying is solid solution hardening. Alloying elements that form a solid solution by substitution with aluminium distort the aluminium crystal lattice and thus increase its strength. The distortion effect of the lattice and the resulting increase in strength is not as large as, for example, the effect of carbon interstitially soluble in iron in ferrous alloys.

The other strengthening mechanism is precipitation hardening. The solubility of the alloying elements used in aluminium is limited, and when the solubility limit is exceeded, some metallic compound phase is often formed. These metallic compounds are intrinsically hard and brittle. In large amounts they make the alloy brittle in the microstructure, but in the right amounts and distribution they can help to achieve significant strength improvements. When using different alloying elements, it should also be taken into account that alloying elements can form a compound phase not only with aluminium, but also with each other, and even complex compounds can be formed. Elements that form coarse precipitates within the aluminium are considered contaminants because they cause the alloy to become rigid.

For an aluminium alloy to be heat treatable, the following conditions must be fulfilled:

- Form a limited solid solution with the alloying element.
- Solubility should decrease as the temperature decreases.
- Form a compound above the solubility limit.
- The compound phase should have a sufficiently high diffusion coefficient.
- The composition should be within the range between the minimum and the maximum of the solubility limit.

The precipitation hardening of aluminium alloys is a complex heat treatment process that can be divided into the following stages:

1. Solution heat treatment
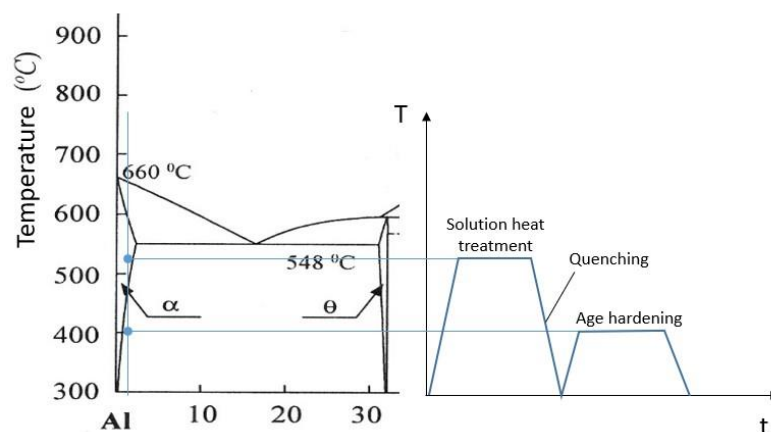2. Quenching
3. Age hardening

Figure 103. Temperature-time diagram of the precipitation hardening of an aluminium alloy, with the temperatures used marked on the equilibrium phase diagram section [65]

At near equilibrium, the alloy is in two phases at room temperature. A major part of the microstructure is constituted by a solid solution of α, in which the main alloying element is present in the solute state in an amount corresponding to the solubility limit. Thus, its strength is slightly higher than that of pure aluminium, and its ductility is only slightly worse. The part above the main alloying element solubility limit forms a metallic compound with aluminium. These compound phases form relatively large segregations in the embedding solid solution, but as their amount is not significant, they do not have a brittle or strength-enhancing effect.

As a first step, the alloy is heated in a homogeneous solid solution field and kept there. The compound phases in the microstructure are then dissolved and a homogeneous solid solution is formed. The holding temperature must be above the solubility limit, which varies with the composition, but below the eutectic temperature. The latter is important because an alloy containing a small amount of eutectic would result in partial melting, which is undesirable in a heat treatment.
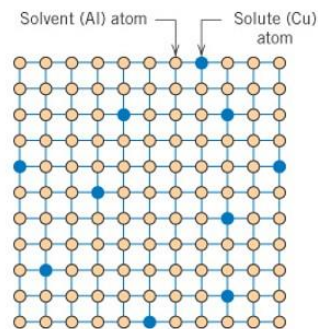

Figure 104. Supersaturated solid solution model

The next essential step in the heat treatment process is the rapid cooling of the homogeneous solid solution α, called quenching. This produces an oversaturated solid solution, because the compound is formed by diffusion, which does not occur with rapid cooling. The strength of the aluminium alloy is then only slightly higher compared to its equilibrium state.
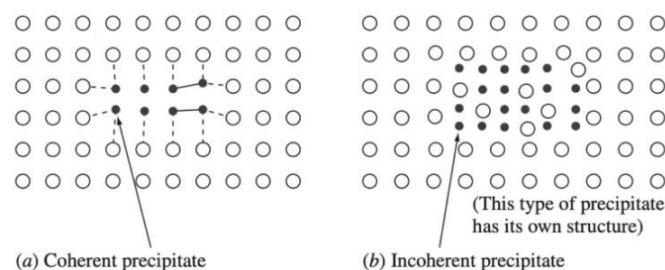

Figure 105. Coherent and incoherent precipitates [66]

The next step is to age hardening. The alloy is then heated to near the solubility limit, but remains in the two-phase field. The increased temperature accelerates diffusion. In the

supersaturated solid solution, diffusion of the dissolved atoms starts the formation of the compound phase. As a first step, the dissolved atoms accumulate along certain crystallographic planes, forming a so-called Guinier-Preston I (GP-I) zone. These zones are one to two atomic layers thick and a few hundred atoms across. They are coherently connected to the embedding phase, effectively preventing dislocations from moving, resulting in a significant increase in strength. Continuing the ageing process, the dissolved atoms in the GP-I zones bind as many aluminium atoms as necessary to form the compound, while increasing in size and transforming into GP-II zones. GP-II zones can form when alloying elements form a compound with aluminium. The phase boundary is still coherent, with the thickness of the zones increasing by a factor of roughly five and the extent by a factor of ten. It is at this stage of ageing that the hardness will be greatest. With further ageing, the coherent phase boundaries disappear, but the equilibrium lattice structure of the compound phase is not yet formed. This phase is called the θ' phase, and with the appearance of this phase the decrease in hardness begins. If ageing is continued, a compound phase, denoted θ, is formed, which precipitates will increase over time and the hardness will continue to decrease. It can be seen from the process that there is an optimum time for ageing, the material can be overheated when the result is not the maximum hardness. It is also important to know that there is an optimum temperature for ageing, if a higher temperature is applied, the GP-I zones are not formed, the GP-II zones appear immediately and the maximum hardness is below the maximum achievable.

The next step is to age hardening. The alloy is then heated to near the solubility limit, but remains in the two-phase field. The increased temperature accelerates diffusion. In the supersaturated solid solution, diffusion of the dissolved atoms starts the formation of the compound phase. As a first step, the dissolved atoms accumulate along certain crystallographic planes, forming a so-called Guinier-Preston I (GP-I) zone. These zones are one to two atomic layers thick and a few hundred atoms across. They are coherently connected to the embedding phase, effectively preventing dislocations from moving, resulting in a significant increase in strength. Continuing the ageing process, the dissolved atoms in the GP-I zones bind as many aluminium atoms as necessary to form the compound, while increasing in size and transforming into GP-II zones. GP-II zones can form when alloying elements form a compound with aluminium. The phase boundary is still coherent, with the thickness of the zones increasing by a factor of roughly five and the extent by a factor of ten. It is at this stage of ageing that the hardness will be greatest. With further ageing, the coherent phase boundaries disappear, but the equilibrium lattice structure of the compound phase is not yet formed. This phase is called the θ' phase, and with the appearance of this phase the decrease in hardness begins. If ageing is continued, a compound phase, denoted θ, is formed, which precipitates will increase over time and the hardness will continue to decrease. It can be seen from the process that there is an optimum time for ageing, the material can be overheated when the result is not the maximum hardness. It is also important to know that there is an optimum temperature for ageing, if a higher temperature is applied, the GP-I zones

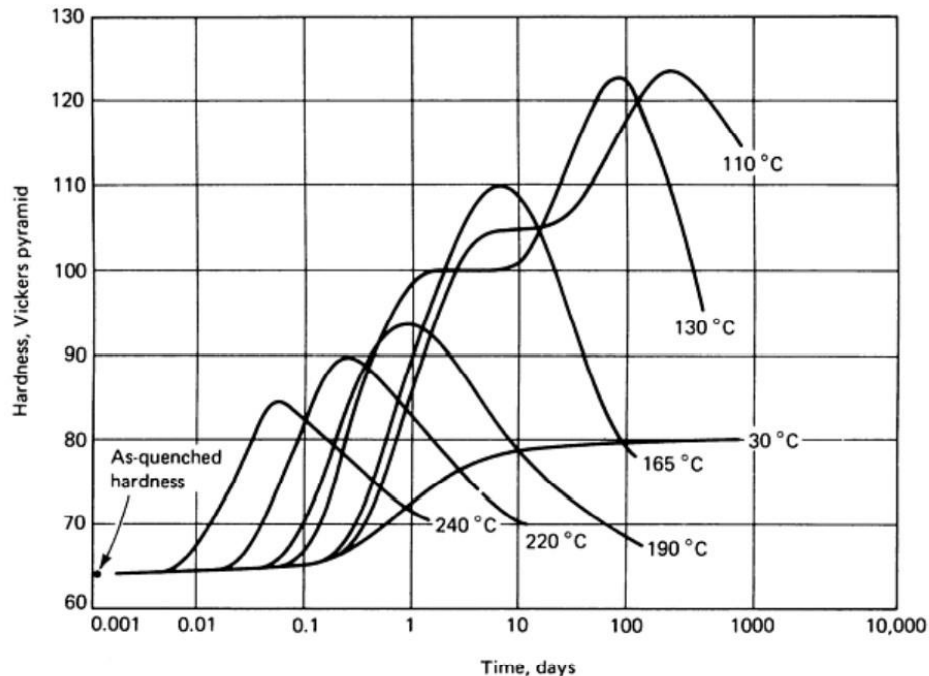are not formed, the GP-II zones appear immediately and the maximum hardness is below the maximum achievable.

Figure 106. Hardness as a function of aging time for an Al-4Cu alloy.
The alloy was solution annealed for at least 48 h at 520 °C, then cooled quickly (water quenched) to 25 °C [51]

Diffusion also occurs slowly at room temperature and is called natural ageing. For reasons of economy, it is not possible to wait months for the process to be completed, so the same can be done in a few hours at elevated temperature. It's called artificial ageing.

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Module_4

Machine Industrial Technology

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Welding and heat treatment