Welding

Definitions of welding and weldability

Welding of metal parts is a joining process designed to ensure metallic continuity across the joint. This continuity is obtained by heating to produce local melting (in fusion welding) or diffusion. In most processes the heat is applied directly, e.g. using an electric arc, flame or laser beam, or it is the result of, for example, friction or electrical resistance (Joule heating). In addition to heat, the joining process can include the addition of a filler metal, the application of pressure and/or protection from atmospheric gas contamination.

The quality of the weld is related to the skill with which the weld was made, and thus refers to the severity and quantity of imperfections such as pores, undercut and cracks found in the weld. The quality is ascertained by means of appropriate test techniques, which can be destructive (e.g. bend testing or cross-sectioning) or non-destructive (e.g. ultrasonic testing or radiography). The properties, on the other hand, refer to the mechanical performance and physical properties of the weld, examples of which are tensile strength, ductility and impact toughness.

Weldability, or the ability of steel to be welded to another material by the application of heat, is a very relative concept. It can be broken down into a number of different criteria involving various considerations in particular situations, and the boundaries between the different terms are not always exact. Physical or metallurgical weldability, for example, depends on the nature of the materials and their physical ability to be welded together whilst giving satisfactory properties. Operational weldability, on the other hand, considers the suitability of a material to be joined using a specific welding process and is thus somewhat more dependent on technological advances in these processes and equipment. What might be termed regulatory weldability involves criteria stipulated in specifications, standards and general codes of practice and, as such, combines the two. These different weldability factors all have an essential impact on the economics of welding.

One property that is often used as an indication of weldability is the hardenability of the steel, which links the chemical composition and cooling rate during welding to the microstructure and thus weld properties. This is explained in more detail below.

Successive improvements in steel welding techniques enable good-quality joints to be obtained with high productivity. Significant further progress has been achieved by the use of highly localised energy sources, such as laser, laser-MAG hybrid welding or cold metal transfer (CMT) arc welding, with considerably narrower heat-affected zones (HAZ). This is particularly important for maintaining the properties of sophisticated modern steel products.

Consequences of welding

In spite of their differences (heat source, energy density etc), all welding techniques have one thing in common. The welding operation can be physically described as a brief high-temperature heating cycle locally applied to a small quantity of metal, followed by cooling, mainly due to conduction into the base metal and the welding equipment (dies, clamps, spot-welding electrodes etc).

The local heat supply may be introduced either without relative displacement of the source with respect to the parts to be welded (e.g. resistance welding), or with displacement of the source, as in arc welding, laser beam welding etc. The heating and cooling cycle during welding has a large influence on the welded parts, via changes to the microstructure and properties, but also through the creation of non-uniform stress fields due to the local expansion and contraction of the metal, which can lead to residual stresses and thermal distortion.

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Carbon equivalent and "hardness vs cooling rate" curves

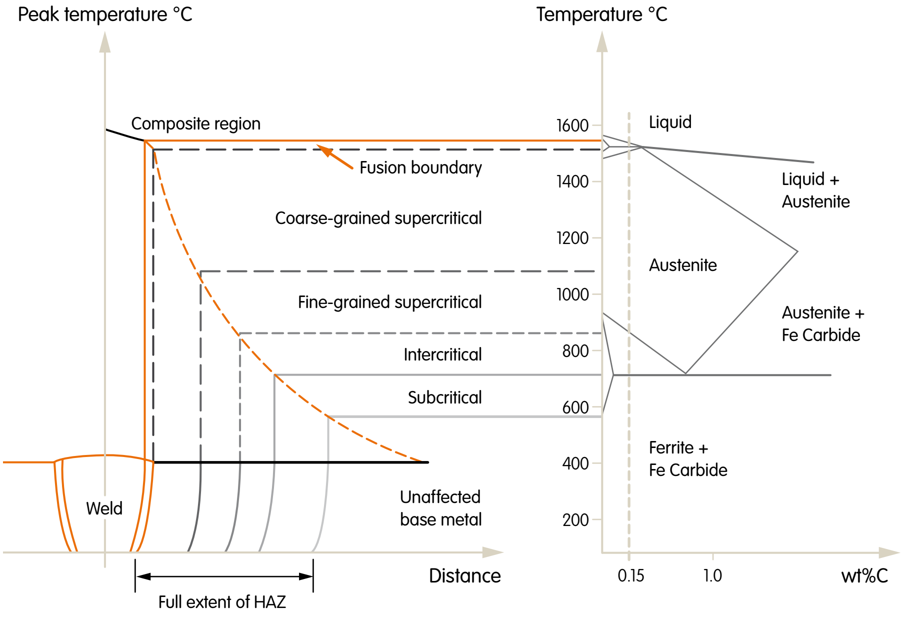
Whatever the process, a given point in the weld metal or heat-affected zones (where the metal has been heated but is not molten) will undergo a thermal cycle corresponding to rapid heating, followed by cooling at a variable rate. This cycle determines the final metallurgical structure that is formed at the point considered; this is often significantly different from that of the base metal.

In order to evaluate the metallurgical structures that are likely to be obtained, a very rough first approximation is generally made using the Fe-C equilibrium diagram in conjunction with the maximum temperatures θ_M attained at different distances from the heat source. Thus, in the fusion zone, θ_M is above the solidus of the base metal. The edge of the fusion zone is at the fusion line, where the transition between metal that was molten and metal that remained solid is found, corresponding to the solidus isotherm. Next to the solidus line is the heat-affected zone (HAZ), which can broadly be broken down into four regions:

- The coarse-grained part of the supercritical HAZ, where full phase transformation took place, followed by (austenite) grain coarsening
- The fine-grained part of the supercritical HAZ, where full phase transformation took place but the material only remained transformed briefly
- The intercritical HAZ, heated between Ac_1 and Ac_3 and thus partially recrystallised
- The subcritical HAZ, where tempering took place

The exact temperatures reached that correspond to these transitions depend on the chemical composition of the steel, and the amount of carbon (C) in particular. The example below is given for a steel with 0.15 wt% carbon.

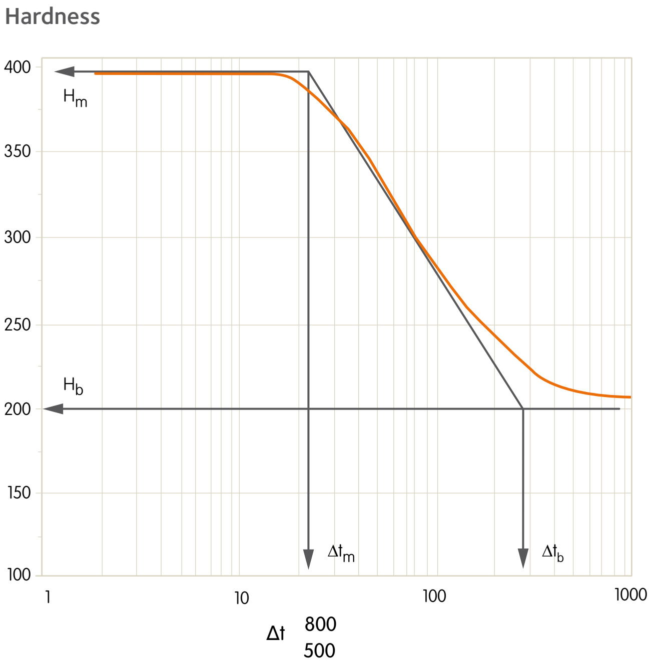
The different structural regions of a heat-affected zone



The aptitude of a steel to form different transformation products of varying hardness and brittleness depends on its chemical composition. Particularly for the HAZ this is evaluated by means of the carbon equivalent value (C_{eq}), which aims to allow the hardening effect of different alloying elements to be combined in a single value, thus making it possible to compare different steels. The simplest form of the C_{eq} is given by:

$$C_{eq} = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Cu + Ni}{15}$$

For example, in arc welding, the risk of cold cracking is limited if the hardness does not exceed 350 HV, which corresponds to a C_{eq} value of less than 0.49, for common cooling rates.
If a wider variety of welding processes is considered, the consequent variation in cooling rates requires a more detailed approach, in which case the "hardness-cooling rate" curve is used. This curve shows the variation in hardness of the steel (as a result of the different phases that form, in this case martensite and bainite) as a function of the cooling rate, commonly in the critical temperature range from 800 to 500 °C.



H_m = hardness of the martensite
H_b = hardness of the bainite
Δt_m = critical cooling rate for martensite formation
Δt_b = critical cooling rate at the bainite/ferrite transition

Typical "hardness-cooling rate" curve

The figure on the next page shows the hardness-cooling rate curves for four typical carbon steels.

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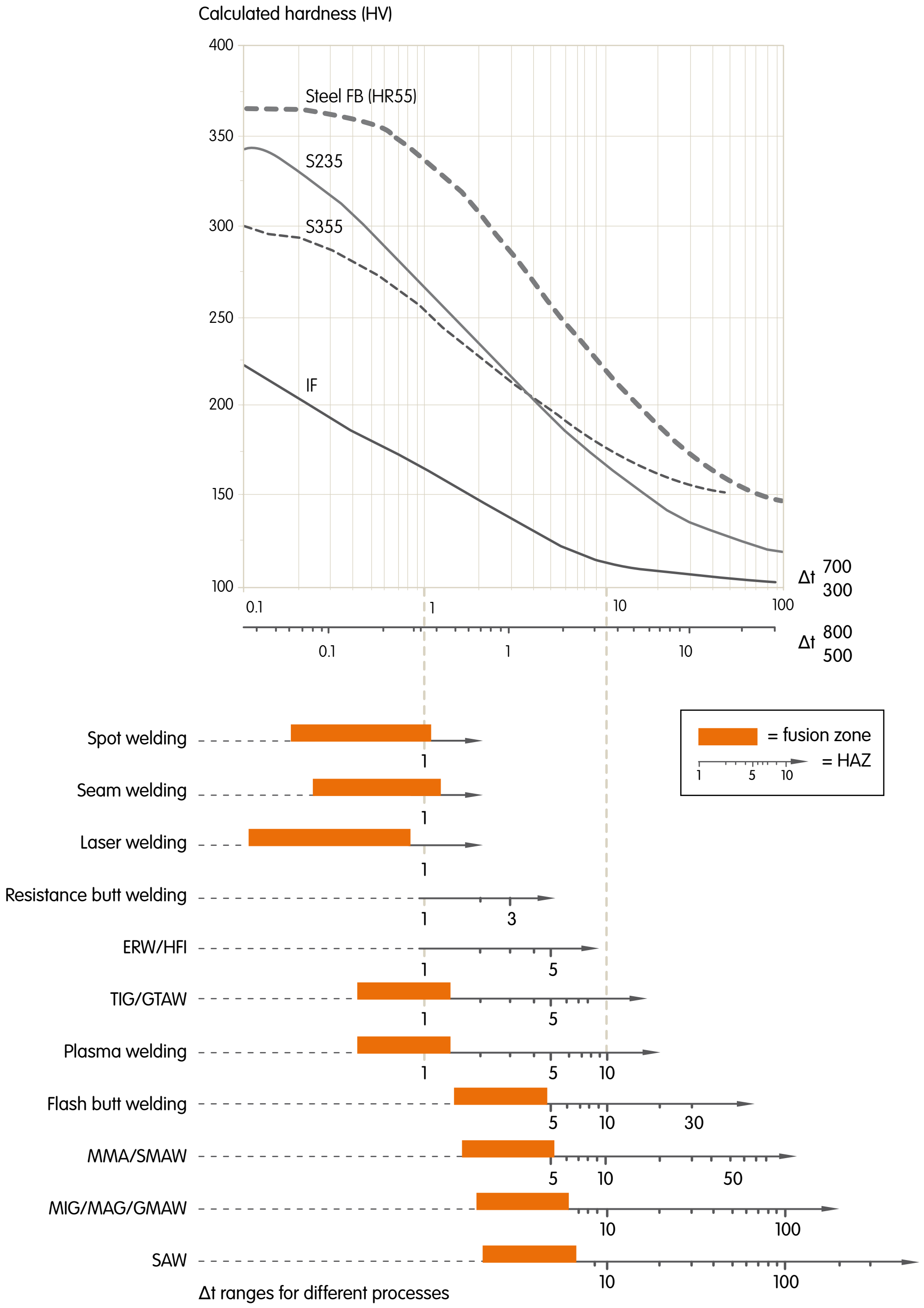
The following figure compares the hardness-cooling rate curves for four typical carbon steels and shows common cooling rates for the fusion zone and the HAZ for different welding processes. As the hardness-cooling rate curve shows, both the steel grade (i.e. chemical composition) and the cooling rate (and thus process) have a determining influence on the resulting hardness.

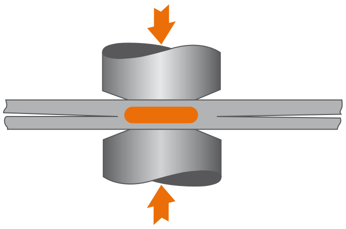
HV = f (Δt) curve (from the CRDM internal data bank)



"Hardness-cooling rate" curves for four common steels, and typical cooling rate ranges for various welding processes

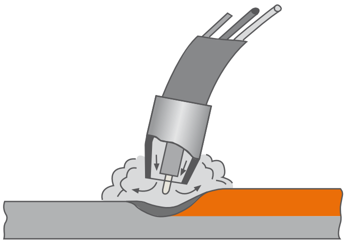
Welding processes

Various welding processes are used to join thin carbon steel sheets. The choice of welding technique will mainly depend on the thickness and geometry to be welded and on the required productivity (number of joints to be made, repeatability of the operation, possible welding rates, automation etc), but obviously also on the resultant properties. Some of the common processes are briefly described below.



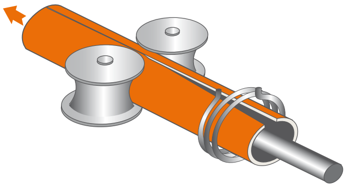
Resistance welding

This kind of welding is only suitable for joining thin-gauge sheets in overlapping configuration. The heat supply in resistance welding processes is produced by the passage of a high current (several kA), which causes melting at the interface of the sheets to be welded. The current is applied via copper contacts or electrodes, which usually take the form of wheels in the case of continuous (seam) welding, pressed against the assembly to be welded. The processes usually employed using this principle are resistance spot welding, resistance seam welding, projection welding, resistance and flash butt welding.



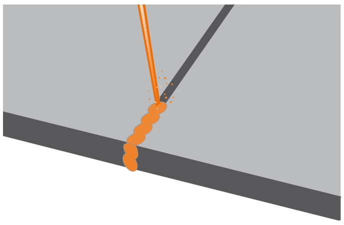
Arc welding

The heat source in arc welding is an electric arc struck between an electrode and the workpiece. The electrode may be non-consumable, as in the TIG (tungsten inert gas) process, or may be consumable in that it melts to provide the filler metal, as in the MIG/MAG (metal inactive/active gas) and MMA (manual metal arc) welding processes. The weld pool is protected against oxidation either by an inert gas (argon, helium) in MIG and TIG welding, or by an active gas in MAG welding (carbon dioxide/oxygen in mixtures with inert gases), or by a flux produced from the electrode covering or fed separately onto the weld (e.g. submerged arc welding, SAW). The electrode flux covering in MMA also forms a protective atmosphere, and may also add some flux to the weld bead. Arc welding processes are the most commonly used welding processes in industry, and of these MIG/MAG is used most.



High-frequency welding of small-gauge tubes (ERW process: electric resistance welding)

The ERW process is commonly used for producing small-diameter tubes. A thin sheet is progressively formed into a tube with a roll and the edges are brought together and heated by induction, followed by mechanical forging and cutting or grinding of the flash. The induction heating is obtained by passing the tube blank through a coil. With this process, very high welding speeds can be reached (tens of metres per minute).



Power beam processes

This category includes laser beam and electron beam welding, which are processes in which the energy is highly concentrated, giving a very high power density at the workpiece. As a result, they can form a so-called keyhole weld pool, which allows the creation of very narrow, deep welds. These techniques are suitable for very thin up to very thick sheets, and can also be applied for welding overlapping sheets without further joint preparation (so-called stake welding). More recently, laser and arc processes have also been combined in what is known as laser-arc hybrid welding. This process combination gives the best of both worlds, with wider energy distribution and possibly filler wire addition of the arc process and the speed and deep penetration of the laser process.

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Effect of coatings used on steel

The use of a metallic and/or organic coating must be considered when evaluating weldability. Generally speaking, welding parameters must be adapted when switching from uncoated sheet to a coated product, to maintain operational and/or metallurgical weldability.

During spot resistance welding of coated sheets, for example, the current application time and the holding time must be increased for a given current. Furthermore, during welding of galvanised sheets, local heating at the electrode/coating interface causes alloying between the copper and the zinc, accelerating electrode deterioration. Welding current must be adjusted and electrodes must be more frequently dressed.

When coated sheets are welded using the resistance seam welding method, the electrodes must also be regularly cleaned and dressed to eliminate the layer contaminated by the coating material. When welding small-gauge tubes (ERW process), the weld zone must be protected in order to safeguard against uniform corrosion (for example by spraying a layer of metal of equivalent composition).

MIG/MAG welding of zinc-coated sheets also requires certain precautions. Zinc does in fact boil at 906 °C, well below the melting point of the steel filler metal, leading to the formation of zinc vapour bubbles in the weld pool, causing porosity in the solidified joint if the zinc vapour cannot be evacuated in the gap between the two sheets. Failing that, porosity can be limited either by decreasing the welding speed or by using a copper-based filler metal, with a lower melting point.

Laser and electron beam welding techniques are most suitable for joining coated products in a butt configuration, particularly in the case of complex metallic coatings. In overlap configuration, the evaporation of coating products may again lead to porosity and blowholes.

Available data concerning the weldability of ArcelorMittal steels

Welding characterisations are available for most of our steels. The ArcelorMittal laboratories have acquired widely recognised competence in the fields of carbon steel sheets, tubes and component welding. This expertise is supported by a wide range of equipment covering the principal welding processes (resistance spot welding, projection welding, seam welding, arc welding, laser welding, laser-MAG hybrid welding, brazing etc).

Furthermore, the laboratories have all the common characterisation techniques at their disposal (bending, tensile, shear and impact tests etc).

Equipped with these resources and a wealth of accumulated experience, ArcelorMittal is able to perform specific parametric research and particular characterisation studies, depending on the processes and the assembly configurations employed.

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