7.

Welding of Aluminium Alloys
Figure 7.1 compares basic physical properties of steel and aluminium. Side by side with different mechanical behaviour, the following differences are important for aluminium welding:

- considerably lower melting point compared with steel
- three times higher heat conductivity
- considerably lower electrical resistance
- double expansion coefficient
- melting point of $\text{Al}_2\text{O}_3$ considerably higher than that of Al; metal and iron oxide melt approximately at the same temperature.

Figure 7.2 compares some mechanical properties of steel with properties of some light metals. The important advantages of light metals compared with steel are especially shown in the right part of the figure. If a comparison should be based on an identical stiffness, then the aluminium supporting beam has a 1.44 times larger cross-section than the steel beam, however only about 50% of its weight.

Figure 7.3 compares qualitatively the stress-strain diagram of Aluminium and steel. In contrast to steel, aluminium has a fcc (face centred cubic)-lattice at room temperature. This is why there is no distinct yield point as being the case in a bcc (body centred cubic)-lattice. Aluminium is not subject to a lattice trans-
formation during cooling, thus there is no structure transformation and consequently no danger of hardening in the heat affected zone as with steel.

Figure 7.4 illustrates the effect of the considerably higher heat conductivity on the welding process compared with steel. With aluminium, the temperature gradient around the welding point is considerably smaller than with steel. Although the peak temperature during Al welding is about 900°C below steel, the isothermal curves around the welding point have a clearly larger extension. This is due to the considerably higher heat conductivity of aluminium compared with steel.

This special characteristic of Al requires a input heat volume during welding equivalent to steel.

Figure 7.5 lists the most important alloy elements and their combinations for industrial use. Due to their behaviour during heat treatment can Al-alloys be divided into the groups hardenable and non-hardenable (naturally hard) alloys.
Figure 7.6 shows typical applications of some Al alloys together with preferably used welding consumables.

Aluminium alloys are often welded with consumable of the same type, however, quite often over-alloyed consumables are used to compensate burn-off losses (especially with Mg and Zn because of their low boiling point) and to improve the mechanical properties of the seam.

The classification of Al alloys into two groups is based on the characteristic that the group of the non-hardenable alloys cannot increase the strength through heat treatment, in contrast to hardenable alloys which have such a potential.

The important hardening mechanism for this second group is explained by the figures 7.7 und 7.8. Example: If an alloy containing about 4.2% Cu, which is stable at room temperature, is heat treated at 500°C, then, after a sufficiently long time, there will be only a single phase structure present. All alloy elements were dissolved, Figure 7.8 between point P and Q.

When quenched to room temperature in this condition, no precipitation will take place. The alloy elements are forced to remain dissolved, the crystal is out of equilibrium. If such a structure is subjected to an age hardening at room or elevated temperature, a precipitation of a second phase takes place in ac-
cordance with the binary system, the crystal tries to get back into thermodynamical equilib-
rium.

Depending on the level of hardening temperature, the precipitation takes place in three possible forms: coherent particles (i.e. particles deviating from the matrix in their chemical composition but having the same lattice structure), partly coherent particles (i.e. the lattice structure of the matrix is partly retained), and incoherent particles (lattice structure completely different from the matrix), Figure 7.7. Coherent particles formed at room temperature can be transformed into incoherent particles by increase of temperature (i.e. enabling diffusion).

The precipitations cause a restriction to the dislocation movement in the matrix lattice, thus leading to an increase in strength. The finer the precipitations, the stronger the effect.

At an increased temperature (heat ageing, Figure 7.7) a maximum of second phase has precipitated after elapse of a certain time. Consequently a prolonged stop at this temperature does not lead to an increased strength, but to coarsening of particles due to diffusion processes and to a decrease in strength (less bigger particles in an extended space).
After a very long heat ageing a stable condition is reached again with relatively large precipitations of the second phase in the matrix. In Figure 7.7 is this stable final condition identical with the starting condition. A deterioration of mechanical properties only happens during hot ageing, if the ageing time is excessively long.

The complete process of hardening at room temperature is metallographic also called age hardening, at elevated temperature heat ageing. A decrease in strength at too long ageing time is called over-ageing.

Figure 7.9 shows a schematic representation of time-temperature curves during hardening with age hardening and heat ageing.

Figure 7.10 shows the strength increase of AlZnMg 1 in dependence of time. The difference between age hardening and heat ageing is here very clear. Due to improved diffusion conditions is the strength increase in the case of heat ageing much faster than in the case of age hardening. The strength maximum is also reached considerably earlier. The curve of hot ageing shows clearly the begin of strength loss when held at a too long stoppage time. This figure shows another specialty of the process of ageing. During ageing, a
second phase is precipitated from a single-phase structure. To initiate this process, the structure must contain nuclei of the second phase. However, a certain time is required to develop such nuclei. Only after formation of nuclei can the increase in strength start. The period up to this point is called incubation time.

Figure 7.11 shows the effect of the height of ageing temperature level on both, mechanical properties of a hardenable Al-alloy and on incubation time. The lower the ageing temperature, the higher the resulting values of yield stress and tensile strength. If a low ageing temperature is selected, the ageing time as well as the incubation time become extremely long.

Figure 7.11 shows that the maximum yield stress is reached after a period of about one year under a temperature of 110°C. An increase of the ageing temperature shortens the duration of the complete precipitation process by a certain value raised by 1 to a power. On the other hand, such an acceleration of ageing leads to a lowering of the maximum strength.

As the lower part of the figure shows, the fracture elongation is counterproportional to the strength values, i.e. the strength increase caused by ageing is accompanied by an embrittlement of the material.
Figure 7.12 shows a method of how to increase the strength of non-hardenable alloys. As no precipitations are present to reduce the movement of dislocations, such alloys can only be strengthened by cold working.

Figure 7.12 illustrates two essential mechanisms of strength increase of such alloys. On one hand, tensile strength increases with increasing content of alloy elements (solid solution strengthening), on the other hand, this increase is caused by a stronger deformation of the lattice.

Figure 7.13 shows the effect of the welding process on mechanical properties of a cold-worked alloy. Due to the heat input during welding, the blocked dislocations are released (recovery), in addition, a grain coarsening will start in the HAZ. This is followed by a strong drop in yield point and tensile strength. This strength loss cannot be overcome in the case of a welding process.

Figure 7.14 illustrates the mechanisms in the case of a hardenable aluminium alloy. As a consequence of the welding heat, the precipitations are solution heat treated and the strength values decrease in the weld area. Due to the age hardening, a re-strengthening of the alloys takes place with increasing time.
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Figure 7.15 shows another problematic nature of Al-welding. Due to the high thermal expansion of aluminium, high tensions develop during solidification of the weld pool in the course of the welding cycle. If the welded alloy indicates a high melting interval, cracks may easily develop in the weld.

A relief can be afforded by preheating of the material, Figure 7.16. With an increasing preheat temperature, the amount of fractured welds decreases. The different behaviour of the three displayed alloys can be explained using the right part of the figure. One can see that the manganese content influences significantly the hot crack susceptibility. The maximum of this hot crack susceptibility is likely with about 1% Mg content (corresponds with alloy 1). With increasing MG content, hot crack susceptibility decreases strongly (see also alloy 2 and 3, left part).

To avoid hot cracking, partly very different preheat temperatures are recommended for the alloys. Zschötge proposed a calculation method which compares the heat conductivity conditions of the Al alloy with those of a carbon steel with 0.2% C. The formula is shown in Figure
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7.17, together with the related calculation result. These results are only to be regarded as approximate, the individual application is subject to the information of the manufacturer.

Figure 7.17

Another major problem during Al welding is the strong porosity of the welded joint. It is based on the interplay of several characteristics and hard to suppress. Pores in Al are mostly formed by hydrogen, which is driven out of the weld pool during solidification. Solubility of hydrogen in aluminium changes abruptly on the phase transition melt-crystal, i.e. the melt dissolves many times more of the hydrogen than the just forming crystal at the same temperature.

Figure 7.18

Figure 7.19
This leads to a surplus of hydrogen in the melt due to the crystallisation during solidification. This surplus precipitates in form of a gas bubble at the solidifying front. As the melting point of Al is very low and Al has a very high heat conductivity, the solidification speed of Al is relatively high. As a result, in the melt ousted gas bubbles have often no chance to rise all the way to the surface. Instead, they are passed by the solidifying front and remain in the weld metal as pores, Figure 7.18.

To suppress such pore formation it is therefore necessary to minimise the hydrogen content in the melt. Figure 7.19 shows possible sources of hydrogen during MIG welding of Al.

Figure 7.20 and 7.21 show the effect of pure thermal expansion during Al welding. The large thermal expansion of the aluminium along with the relatively large heat affected zones cause in combination with a parallel gap adjustment a strong distortion of the welded parts. To minimise this distortion, the workpieces must be set at a suitable angle before welding, Figure 7.21.