

TALAT Lecture 2205

Special Design Issues

24 pages, 31 figures

Basic Level

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Objectives:

- to describe the measurement and amount of residual stresses in extruded and welded profiles which have to be accounted for in design
- to introduce the subject of corrosion and of preventive design measures
- to describe the behaviour and properties of structural aluminium alloys at ambient, low and elevated temperatures
- to give useful examples of structural applications of extrusions

Prerequisites:

- background in mechanical and structural engineering disciplines

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2205 Special Design Issues

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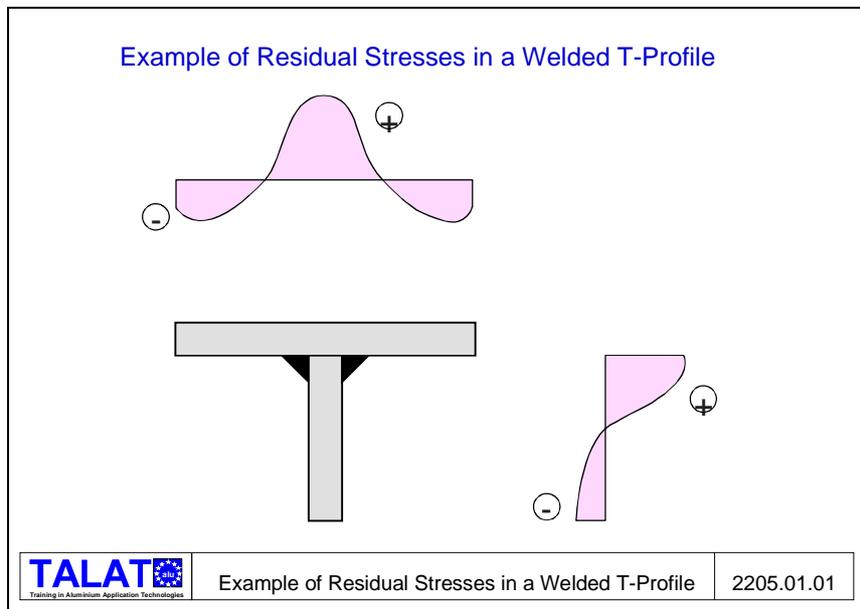
2205.01 Residual Stresses

- Introduction
- How to measure residual stresses
- Residual stress in extruded profiles
- Residual stresses in welded profiles
- Residual stress effects on fatigue behaviour

Introduction

If a part of a structural element has been subjected to non-uniform, plastic deformation, residual tension and compression stresses will remain which are within the elastic regime. The sum of internal tension and compression stresses is always zero, if there are no external forces. The inhomogeneous deformation field which generates residual stress is caused by processes such as cooling and quenching after extrusion, welding or cold working, e.g. bending and straightening of profiles.

For a welded T-profile the residual stresses may develop as follows: During solidification and further cooling the material of the weld zone experiences a larger shrinkage than the surrounding colder and more rigid base metal due to volume differences in the liquid and solid states and due to thermal contraction. The larger shrinkage of the weld zone induces tensile stresses in a magnitude limited by the momentary yield strength of the material in the warmer weld zone. The contraction of the weld and heat affected zone induces in turn compressive stresses in the the cross section of the surrounding colder base material, see **Figure 2205.01.01**.



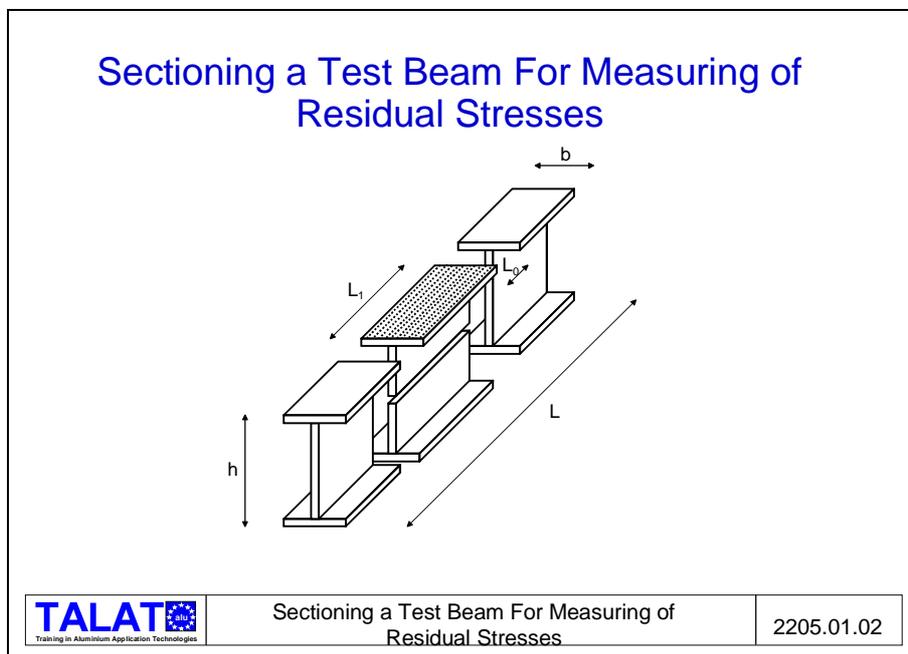
How to Measure Residual Stresses

The most common method is the destructive method which is based upon the technique of cutting the specimen in a number of strips (**Figure 2205.01.02**). The residual stresses are calculated from measurements on each strip.

There are two methods of measuring. The first is to measure the length of the strip before and after cutting it from the section. If Young's modulus is known, it is easy to apply Hooke's law and determine the residual stress. The second method is to mount electrical resistance strain gauges on the strips and determine the residual stresses by applying Hooke's law. This method is the most commonly used one today. Note: Hooke's law can be applied since residual stresses are essentially within the elastic range. With the methods stated here only longitudinal residual stresses are determined, which, however, are of greatest importance from a structural point of view.

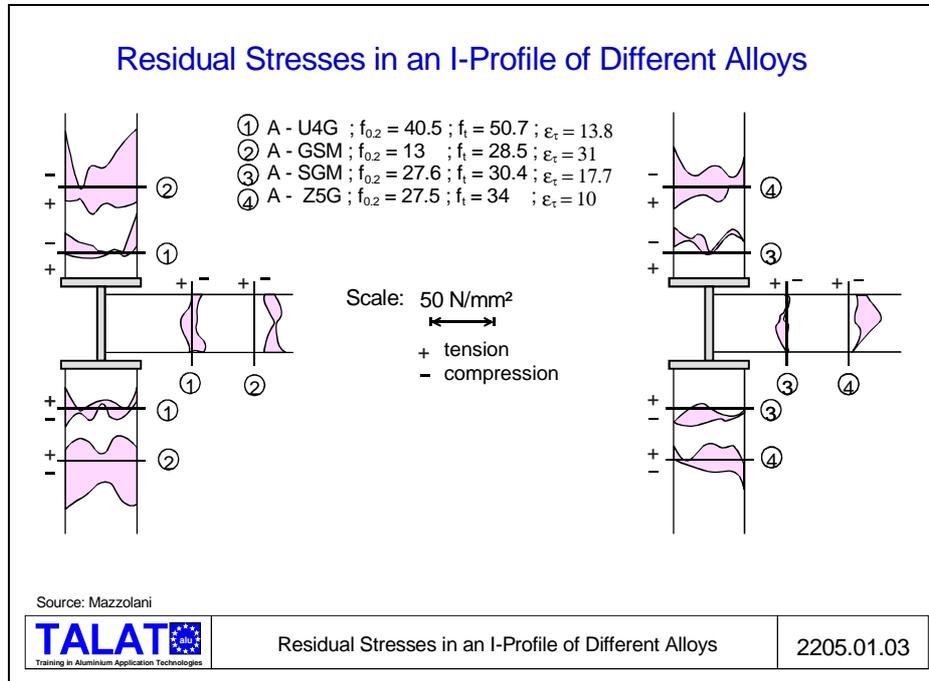
Residual Stress in Extruded Profiles

Mazzolani | 1 | shows results from a number of experiments where residual stresses were determined for different types of profiles. These consist of different alloys and were manufactured by various processes. The results from experiments on I-profiles are shown in **Figure 2205.01.01** and **Figure 2205.01.02**.



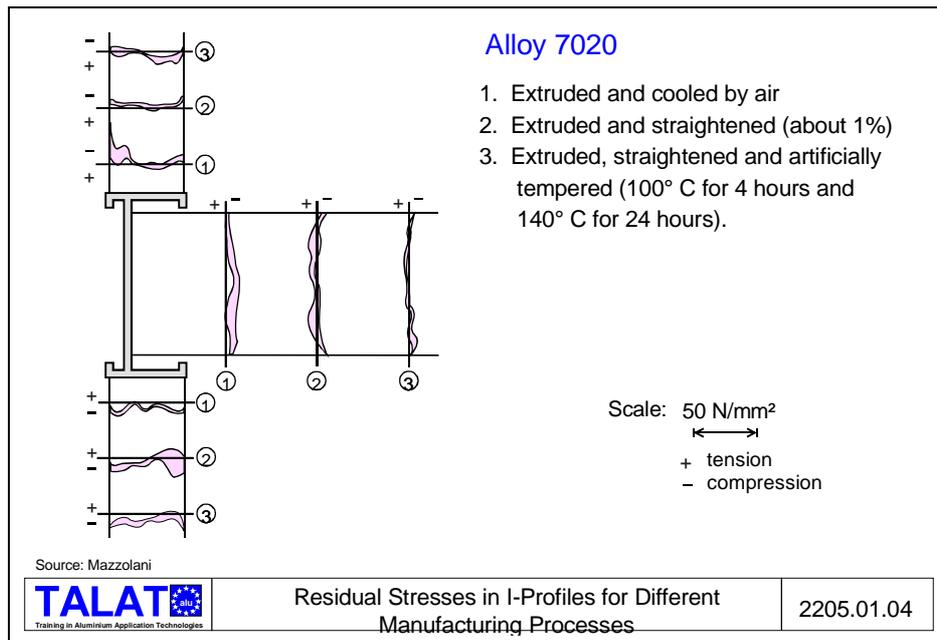
The results of experiments conducted on I-profiles consisting of four different alloys are shown in **Figure 2205.01.03**. The residual stresses seem to be randomly distributed over a cross section. No simple rule seems to apply to the stress distribution as is the case for rolled steel sections. Observations show that residual stresses are low, the compressive

stresses almost never exceed 20 MPa and tensile stresses are much lower. These values are measured on the surface of the profiles. At the center of the material the values are probably even lower, since residual stresses usually change sign from one side to the other.



The intensity and distribution of residual stresses in aluminium profiles seem to be not affected by alloy composition.

Figure 2205.01.04 shows the results of experiments on an I-profile at different stages in the manufacturing process.

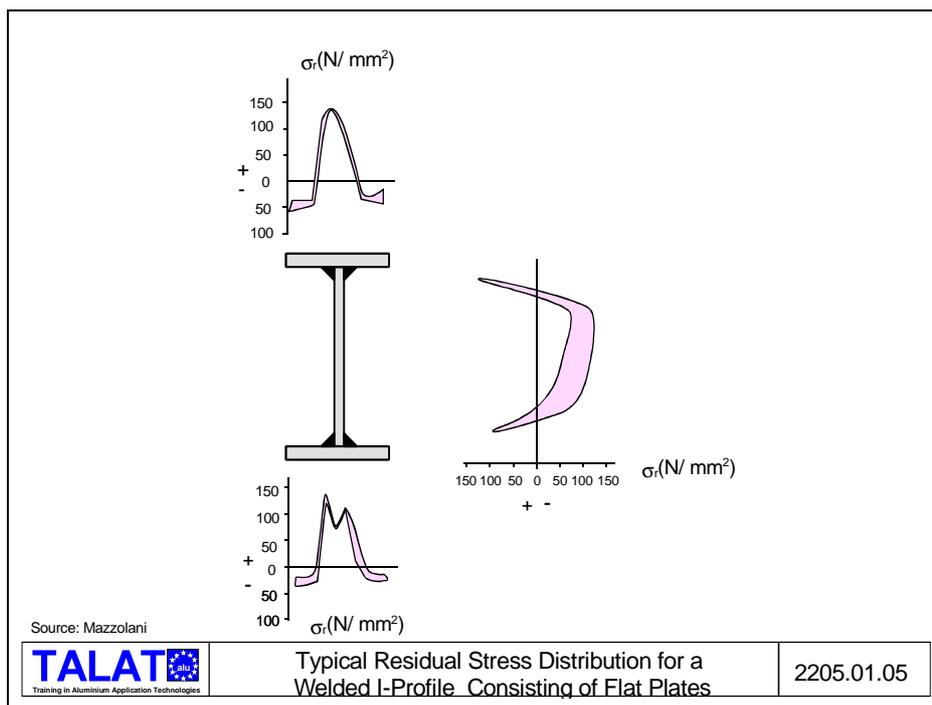


The residual stresses for these cases are rather small and seem to change from compression to tension during refinement. The reduction of residual stresses is due to the straightening process that the profiles are subjected to during manufacturing. The remaining residual stresses have a negligible effect on the load bearing capacity.

Residual Stresses in Welded Profiles

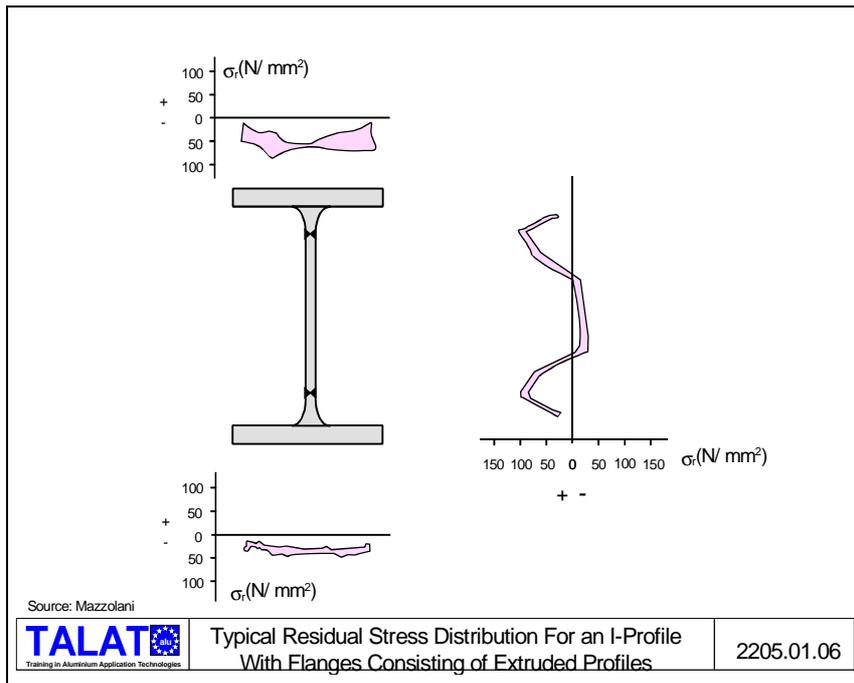
In contrast to what has been said for extruded profiles, residual stresses cannot be neglected in welded profiles. Welding produces a concentrated heat input which causes the remaining stresses (see above). Large tensile stresses in connection to the web and balancing compression stresses in other parts are characteristic.

Figure 2205.01.05 shows the results of residual stress measurements for an I-beam fabricated by welding aluminium plates of different sizes and alloys. Both, heat-treated and non-heat-treated alloys were used. The resulting differences were very small. The maximum tensile stress was 90 - 100 N/mm² and the maximum compression stress 30 - 40 N/mm². The lower values correspond to the heat-treated alloy.

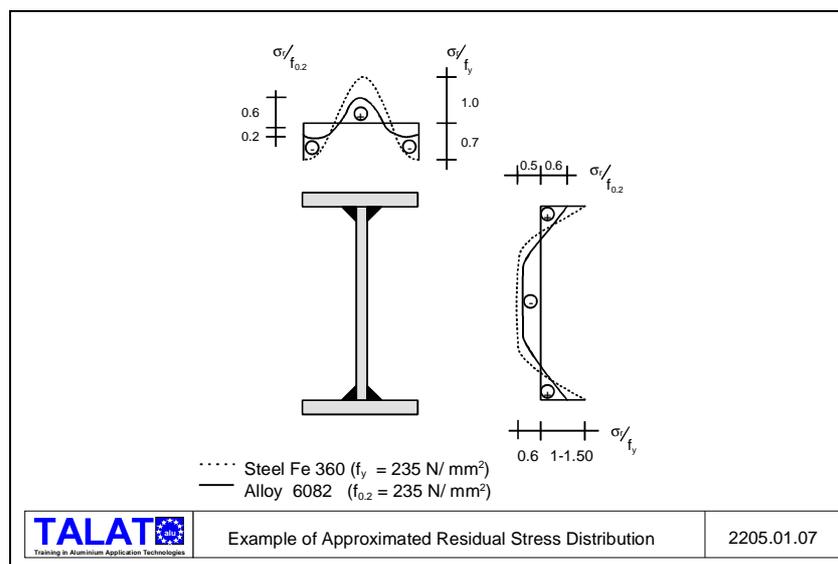


Typical residual stress distributions for two different I-profiles are shown in **Figure 2205.01.05** and **Figure 2205.01.06**. The highest values of tensile stress in both cases were 140 N/mm². The greatest values of compressive stresses were 50 N/mm² except for the web of the specimen in **Figure 2205.01.06** where compressive stresses reached 100 N/mm². An important conclusion reached from these experiments is that welded connections between extruded profiles should be placed in areas where they cause a minimum reduction of strength.

These experiments also show that the residual stresses in relation to the yield limit of the material are much lower for aluminium profiles than for corresponding steel profiles. In the experiments, the residual tensile stresses were less than 60 % of the 0,2 % proof stress. For steel residual stresses may be greater than the yield stress of the material. The residual compressive stresses are typically 20 % for aluminium and 70 % for steel. Therefore, considering residual stresses, it is more favourable to weld aluminium than it is to weld steel. However, for aluminium the strength of the material is reduced up to 50 % in the zone around the weld. This counterbalances the effect of the residual stress distribution.

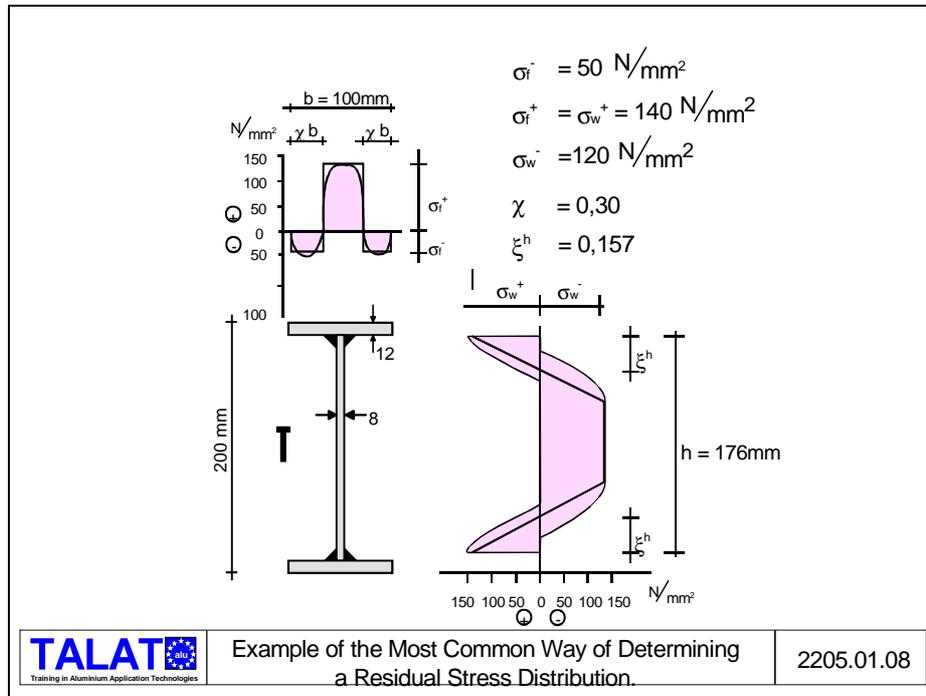


In order to take residual stresses into consideration when solving numerical problems, e.g. in stability problems, the stress distribution is approximated for different cross sections (**Figure 2205.01.07**).



The stress distribution model is convenient when simulating problems by use of computer calculations.

Normally, a further simplification is adopted. Often the continuous curves are replaced by equivalent block curves as those shown in **Figure 2205.01.08**. These curves are easier and faster to use in numerical models. The last type is the one used for the determination of load-bearing curves for design regulations.



Residual Stress Effects on Fatigue Behaviour

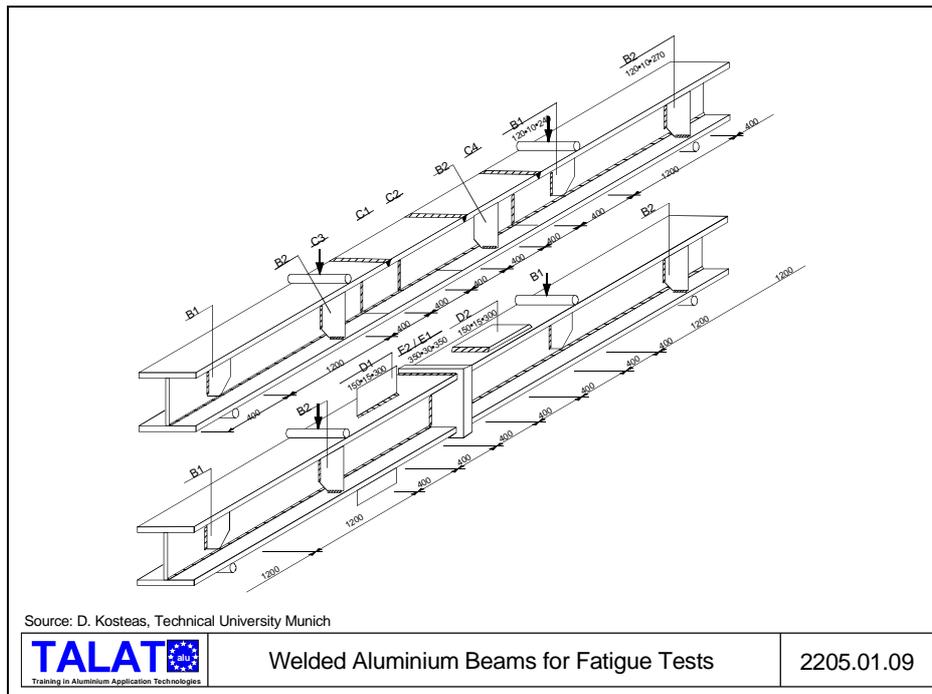
Earlier we have already mentioned the difficulties in detecting, measuring or in any way quantifying the residual stress situation of a structural component. Indirectly, this situation has been reflected in the proposals for the „fatigue reduction factor“ $f(R)$.

Currently efforts are being undertaken to quantify the residual stress pattern of welded aluminium constructions. During the course of the drafting of the ECCS-ERAAS (European Recommendation for Aluminium Alloy Structures) information was used which was obtained from the comprehensive welded-beam fatigue testing programmes at the Technical University of Munich (TUM). Residual stress measurements were made of full-size welded components of 7020 and 5083 alloys, see **Figure 2205.01.09**.

The measurements themselves and the difficulties associated with the interpretation of these limited results together with other somewhat contradictory information being described elsewhere allow presently only the following general conclusions:

- Residual stresses in welded components of aluminium are of considerable magnitude, reaching values up to the 0,2 - yield limit of the HAZ, see **Figure 2205.01.10**

- Scatter is an inherent feature in measurements made by the hole-drilling method. Efforts were undertaken to make measurements sufficiently close to the welds, approximately 1 mm off the weld toe, by using rosettes with the strain gages arranged on one side only.
- There were some but not significant differences in residual stresses in the structural details of the 7020 and 5083 alloy.



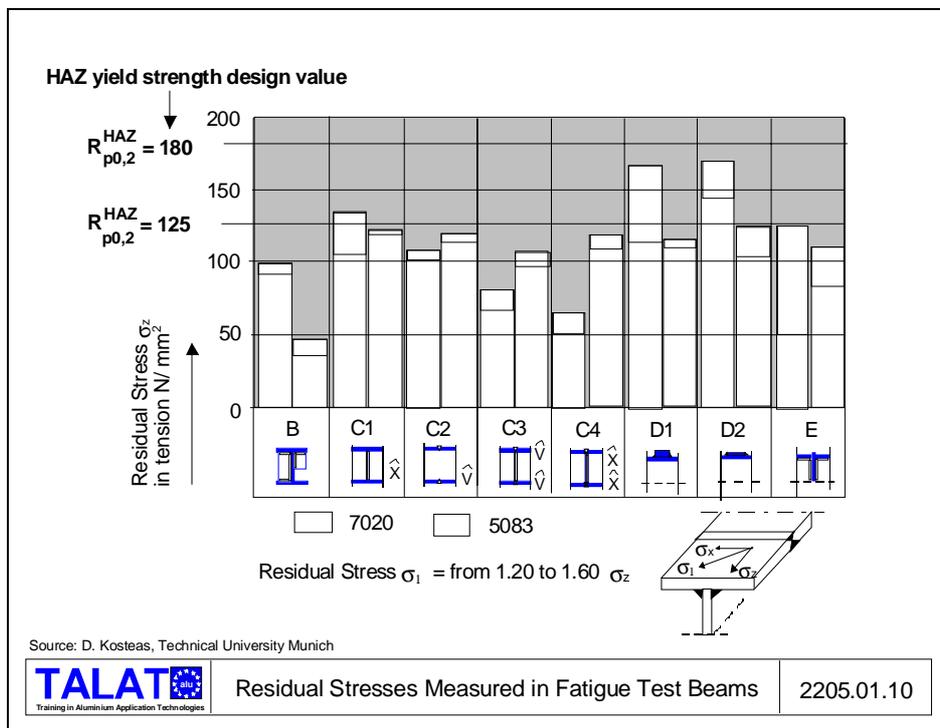
As seen in **Figure 2205.01.10** the highest values of residual stresses were recorded at fillet welded longitudinal or transverse attachments on the beam flanges. Residual stresses in these details reached values of over 180 MPa. Residual stress measurements at butt welded splices and cruciform joints made with butt-like full penetration welds attained values of between 120 and 140 MPa.

No answer can be offered for the time being to the question of whether initially measured residual stresses are maintained, and at what magnitude, during subsequent load cycling of the components. Indirect measurements at strain gauge monitored crack initiation sites showed values up to 120 MPa. These gauges may not have been sufficiently close to the maximum residual stress site, though. Residual stresses, therefore, may have been higher.

The generally lower level and steeper slope of S-N curves of full-size components vs. small specimen data agree with similar findings in steel weldments (see DIN 15015 and Eurocode 3 or ECCS TC6).

There are still difficulties in interpreting differences between S-N curves with stress ratios of $R = -1$ and $+0,1$. The first show at times approximately 40 % higher fatigue strength values of stress range plotted in a log-log diagram at two million cycles. The

effect is more pronounced in the case of 7020 alloy details. It does not seem prudent, though, to allow for a bonus in design values in cases of large components, since sufficiently reliable data is still missing.



2205.02 Corrosion

- Introduction
- Galvanic corrosion
- Differential aeration corrosion
- Design examples for avoiding corrosion

Introduction

Aluminium and its alloys are always protected by a film of Al_2O_3 or $Al_2O_3 \cdot H_2O$ of various thicknesses due to their large oxygen affinity. Due to this protective film, the alloys have a good resistance to sea water, most neutral solutions, many weak acid solutions as well as sulfurated hydrogen, hydrocarbons and carbonic acid. The pH has to be between 4,5 and 9,0 if inhibitors are not added.

Aluminium is a metal with a large electronegative potential. Contact between aluminium and more electropositive metals such as copper, lead and steel when

moisture is present, must be avoided. This can be done by using correct electrical insulation between the two metals, i.e. by use of neoprene, plastic or equivalents.

However, in certain conditions, the use of stainless steel bolts or explosion welded plates as connection can be accepted due to the mass and passivation effect.

Because of the protective film on the aluminium surface, no painting is needed, leaving aluminium almost maintenance free in many environments.

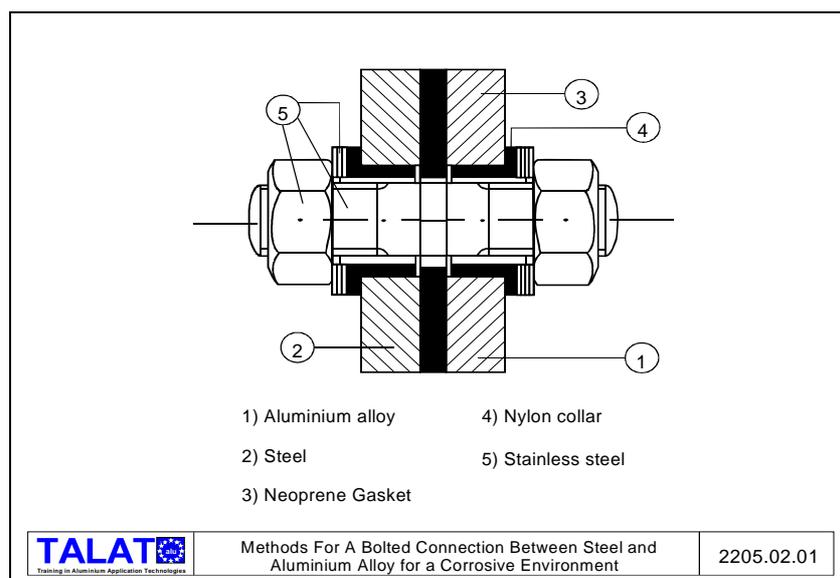
The causes for corrosion damages can be avoided in the design phase. Two types of corrosion are of particular importance when designing an aluminium alloy structure for a corrosive environment:

- galvanic corrosion
- differential aeration corrosion

Galvanic Corrosion

When aluminium alloys are in electrical contact with more electropositive metals and submerged in a corrosive electrolyte, galvanic corrosion will take place. To avoid this type of corrosion, therefore, the flow of current has to be interrupted by insulating the two dissimilar metals and the surface has to be protected against the electrolyte.

An example is given in **Figure 2205.02.01** which shows an aluminium alloy/steel connection. Bolting aluminium alloy to aluminium alloy, stainless steel bolts (A4 quality) may be used without any insulation, except when the connection is permanently submerged in water or in another fluids which will act as electrolyte. This solution has proved to be acceptable through many years of experience in the North Sea oil industry (Helideck structures).



When designing bolt connections with gaskets and collars, one should be aware of the weakness of both, the gasket and the collar. The shearforces of such a connection must be small to avoid damages of the collar and electrical contact between bolt and metal. The best solution for an insulated bolted connection is to transmit the forces through the connection by compression.

Connections between steel and aluminium will be dependent on the environments. **Figure 2205.02.02** (table) shows four different methods for connections in six different environments.

Environments	Explosion-welded joints, painted	Stainless steel bolts, neoprene gaskets, nylon collar	Stainless steel bolts, neoprene gaskets, no collars	No precautions
Sea water immersion	no	yes	no	no
Humid marine atmosphere	yes	yes	no	no
Aerated marine atmosphere	yes	yes	yes	no
Industry pollution atmosphere	yes	yes	yes	no
Rural atmosphere Condensed/ fresh water immersion	yes	yes	yes	no
Indoor atmosphere RH < 60 %	yes	yes	yes	yes



Connections Between Steel and Aluminium
in Six Different Environments

2205.02.02

Differential Aeration Corrosion.

This type of corrosion occurs when an oxygen concentration gradient exists in the electrolyte in contact with the metal surface.

Differential aeration corrosion may take place in crevices filled with water, spaces filled with stillstanding water or areas covered by wet materials.

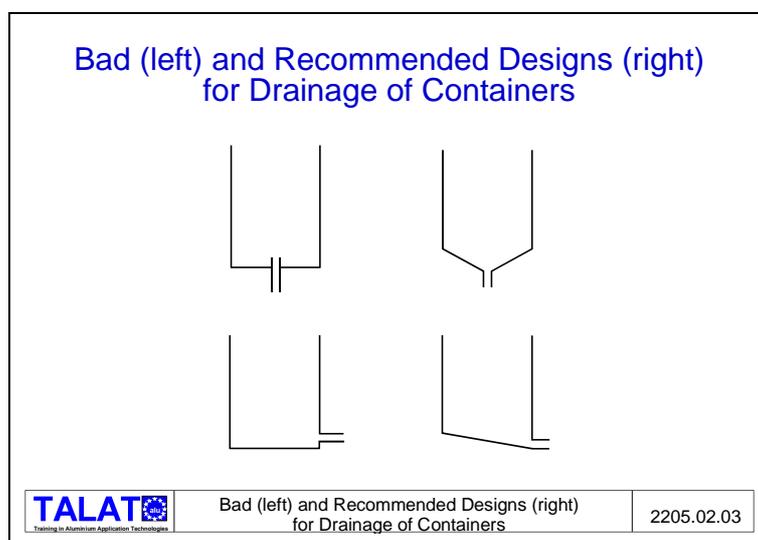
In the design phase many of these corrosion problems can be solved. Some simple rules are as follows:

- Avoid crevices which can be filled with water or other liquids acting as an electrolyte. Crevices should be permanently sealed.
- Avoid structural details or cross sections which collect stillstanding water or other corrosive liquids. If such details cannot be avoided, they must be drained properly.

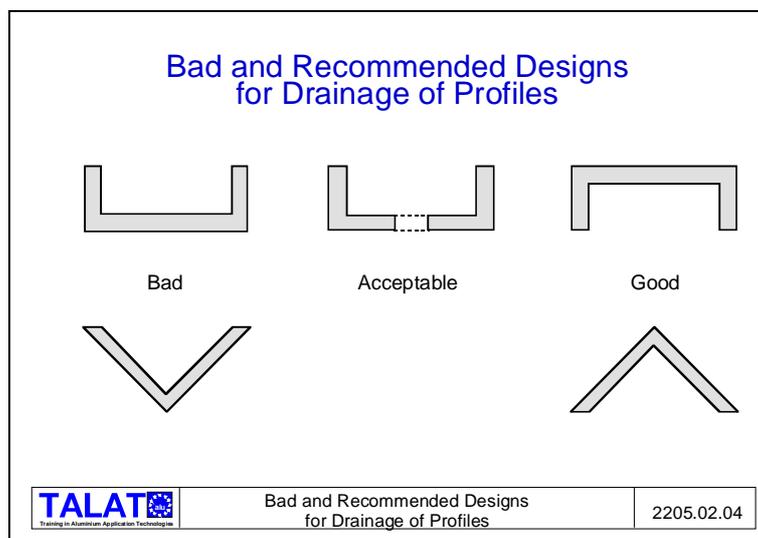
- Avoid structural details or cross sections which will collect dirt. If this is impossible, design a detail which is easy to clean.
- Do not use insulation materials which are porous and absorbent between metal surfaces.
- Do not cover aluminium surfaces with porous and absorbent materials which can get wet.

Design Examples for Avoiding Corrosion

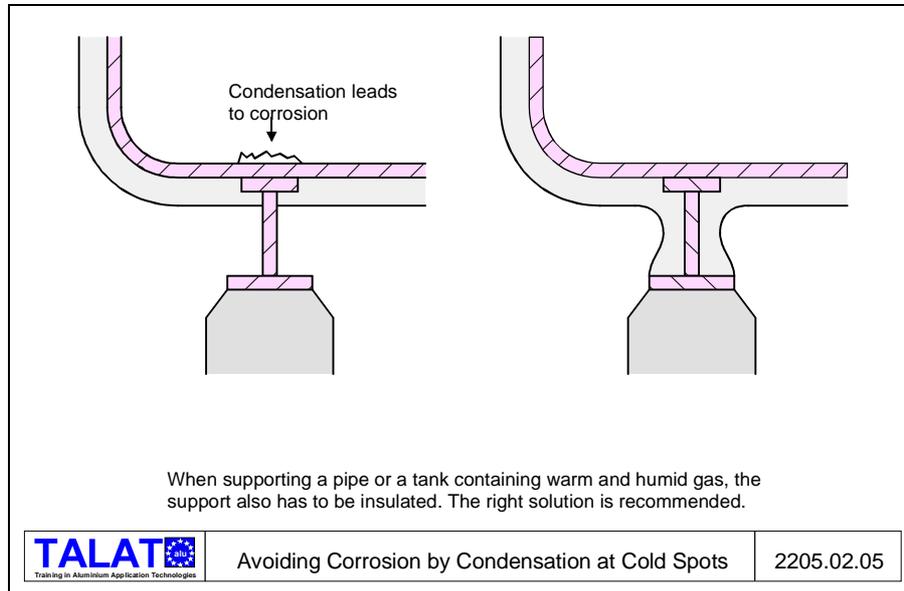
(Figures 2205.02.03 till 2205.02.12)



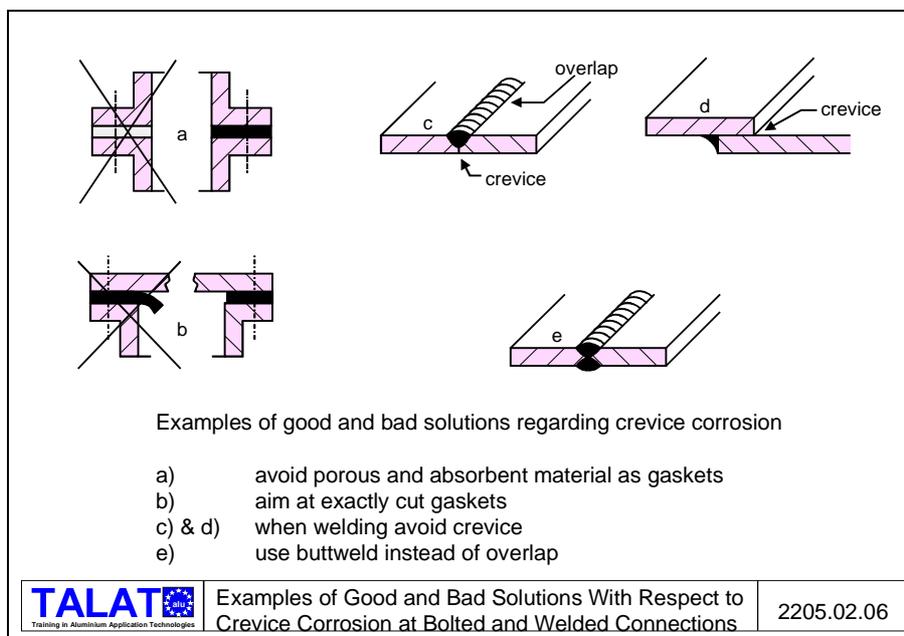
Tanks must be designed in such a way that cleaning and draining are easily achieved (**Figure 2205.02.03**). Profiles exposed to moisture must be arranged in such a way that they will be drained and cleaned easily (**Figure 2205.02.04**).



Often humidity collects around cold spots in poorly insulated structures, e.g. on a pipe or tank containing warm and humid gas. **Figure 2205.02.05** shows the recommended solution (at right).



Particular attention should be given to crevice corrosion at connections or joints. **Figure 2205.02.06**, **Figure 2205.02.07** and **Figure 2205.02.08** show examples of good and bad solutions with respect to crevice corrosion at bolted and welded connections.



Avoiding Unfavourable Fillet Welds and Fillet Welds With Difficult Accessibility

TALAT <small>Training in Aluminium Application Technologies</small>	Avoiding Unfavourable Fillet Welds and Fillet Welds With Difficult Accessibility	2205.02.07
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Avoiding Crevice Corrosion at Beam

Crevice between crossing beams can be avoided if the upper beam has shape as shown on the sketch.

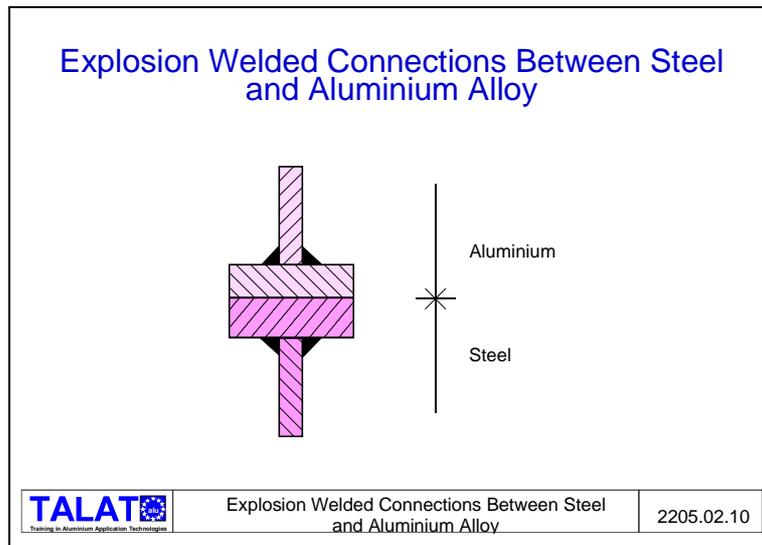
TALAT <small>Training in Aluminium Application Technologies</small>	Avoiding Crevice Corrosion at Beam	2205.02.08
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Example of galvanic corrosion with precipitation of Cu-ions in a pipe of aluminium alloy. If the stream is opposite, there is no corrosion problem.

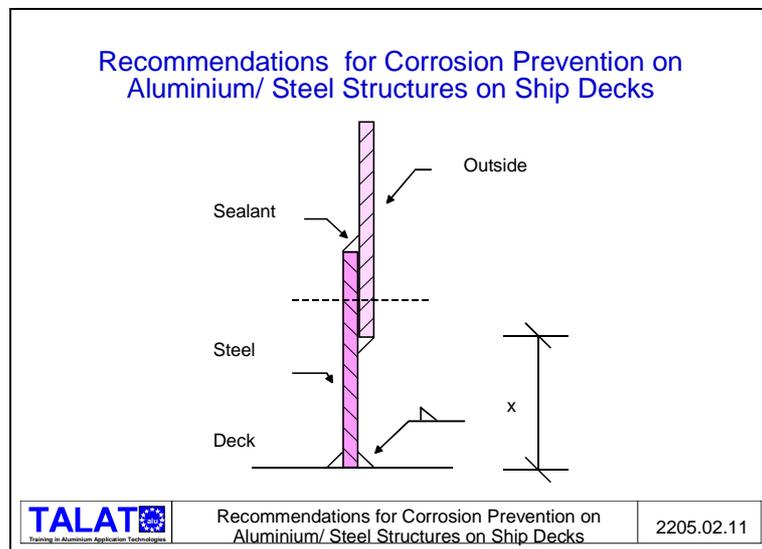
TALAT <small>Training in Aluminium Application Technologies</small>	Galvanic Corrosion Caused by Precipitation of Cu - Ions in an Aluminium Pipe	2205.02.09
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Special care should be given to galvanic corrosion problems when dissimilar metals are joined together. **Figure 2205.02.09** shows an example of a pipe connection between aluminium and copper. Despite perfect insulation copper-ions can precipitate on the

walls of the aluminium pipe if the fluid flow direction is from right to left (**Figure 2205.02.09**). If the flow direction is opposite no corrosion will occur.



Explosion welded connections between steel and aluminium alloys have successfully been used in the ship building industry for many years. To avoid corrosion at such dissimilar metal connections protective painting is recommended. The arrangement of the aluminium/steel connection on a steel deck is shown in **Figure 2205.02.10**. Even though, the distance x should be sufficiently large avoiding continuous wetting of the aluminium structure by sea water on deck (**Figure 2205.02.11**).



Bolted connections should be designed with full electrical insulation. Stainless steel bolts are recommended. In a dry atmosphere galvanized bolts will perform satisfactorily. **Figure 2205.02.12** gives an example for a flange connection between two dissimilar metals.

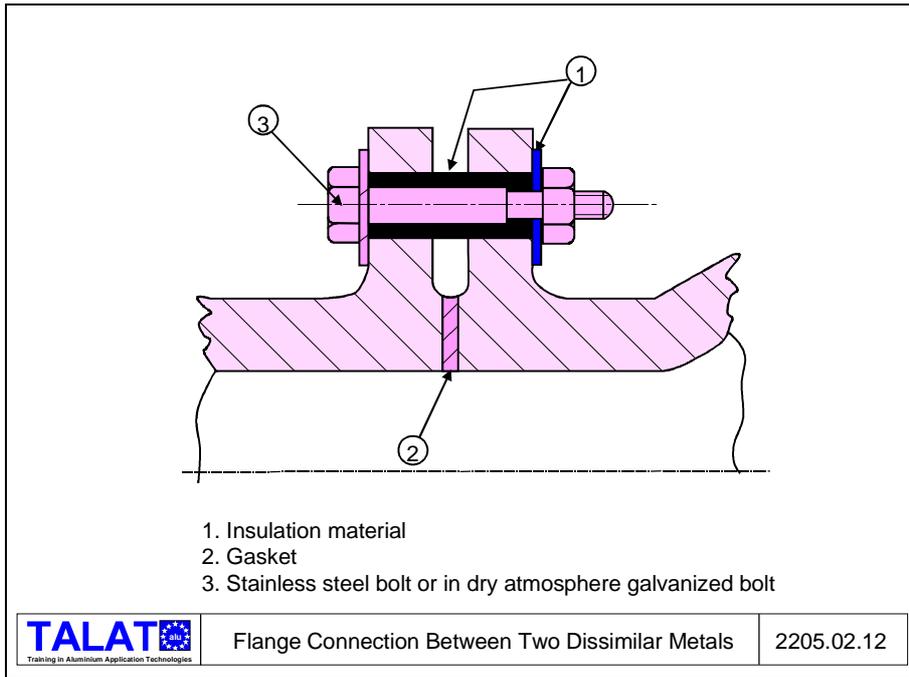
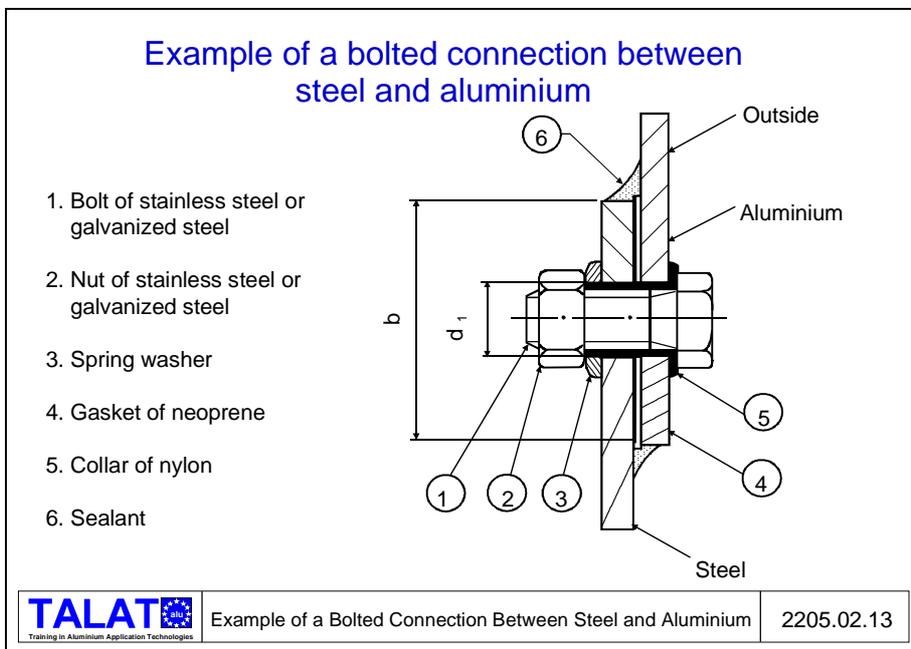


Figure 2205.02.13 gives an example for a corrosion resistant bolted connection between aluminium and steel. It is recommended to seal the flange edges of the connection with an elastic, non conducting sealant. The danger of corrosion is reduced when the distance between neighbouring surfaces of the two dissimilar metals is as large as possible

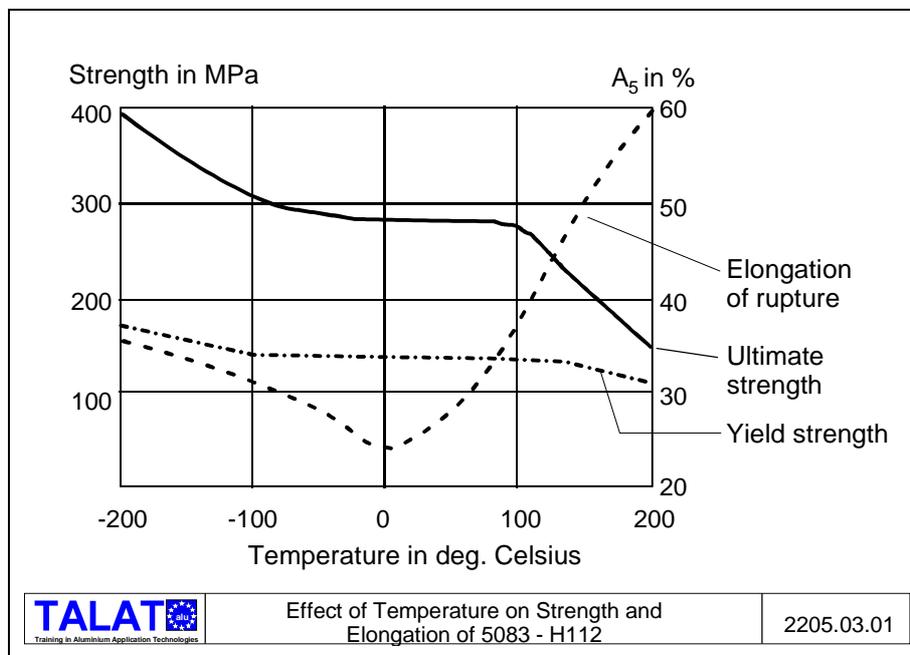


2205.03 Working Temperature

- Mechanical properties
- Aluminium alloy structures exposed to low temperatures
- Aluminium alloy structures exposed to elevated temperatures
- Linear expansion

Mechanical Properties

The strength of aluminium alloys is highest at absolute zero and decreases as the temperature up to the melting point (**Figure 2205.03.01**). The variation of strength depends on the type of alloy and temper. At low temperatures aluminium alloys have no tendency to brittleness which occurs in many steels.



The tables in **Figure 2205.03.02**, **Figure 2205.03.04** and **Figure 2205.03.04** show in percentage the variation of strength, Young's modulus of elasticity and the elongation of rupture (A₅) between - 200 °C and + 200 °C for some alloys.

Aluminium Alloy Structures Exposed to low Temperatures

Low temperatures have the effect of improving the mechanical properties and often also the toughness of aluminum alloys without any tendency to brittleness.

Alloy and temper	Yield strength in % at various temperatures in ° C				
	-200	-100	+25	+100	+200
5052-H34	115	100	100	100	50
5083-H112	120	115	100	95	55
5454-H32	115	105	100	95	70
6061-T6	135	105	100	95	40
6063-T6	115	105	100	95	20
6082-T6	115	105	100	95	40

Source: C. Marsh, Alcan Canada Products Ltd., 1983

	Yield Strength in % for Some Alloys in the Temperature Range From -200 to +200 °C	2205.03.02
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Young's Modulus of Elasticity in % in the temperature range from -200 to +200 °C

	-200	-100	+25	+100	+200
Elastic Modulus	110	105	100	100	90

Source: C. Marsh, Alcan Canada Products Ltd., 1983

	Young's Modulus of Elasticity in % in the Temperature Range From -200 to +200 °C	2205.03.03
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Elongation of Rupture (A_5) in % in the Temperature Range From -200 to +200 °C

Alloy and temper	-200	-100	+25	+100	+200
5052-H34	25	19	14	16	45
5083-H112	36	31	25	36	60
5454-H32	30	22	16	18	45
6061-T6	22	18	17	18	28
6063-T6	21	17	18	19	40
6082-T6	22	18	17	19	40

Source: Aluminium Taschenbuch, 14th Ed. Aluminium-Verlag, 1984

	Elongation of Rupture (A_5) in % in the Temperature Range From -200 to +200 °C	2205.03.04
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The heat affected zone of welded structures will also have an improvement of the mechanical properties, but the elongation of rupture (A_5) will usually be the same as at room temperature.

Structures in aluminium alloys for low temperature conditions can, therefore, be designed according to the codes and regulations applicable to normal, ambient temperatures.

An explanation for the improved mechanical behaviour of aluminium structures at low temperatures is that the difference between the ultimate strength and the yield strength increase when the temperature decreases towards absolute zero. The safety factor against fracture will for that reason increase with decreasing temperature. There is no lower temperature limit for the application of structural aluminium alloys.

Aluminium Alloy Structures Exposed to Elevated Temperatures.

The strength of aluminium alloys decreases when the metal temperature increases beyond room temperature. Most aluminum alloys suffer from considerable strength reduction at temperatures between 120 - 250 °C.

Alloys which are age-hardened or strain-hardened will also lose some of their original strength during a temporary period at elevated temperatures between 100 - 150 °C.

Under the prolonged application of a stresses of sufficient magnitude at elevated temperatures, aluminium alloys will creep and may rupture after a period of time. This behaviour does not enter into the design considerations for structures below 100 °C but may require study for high temperature applications.

Maximum working temperatures for an aluminium alloy structure can be set to 100 °C.

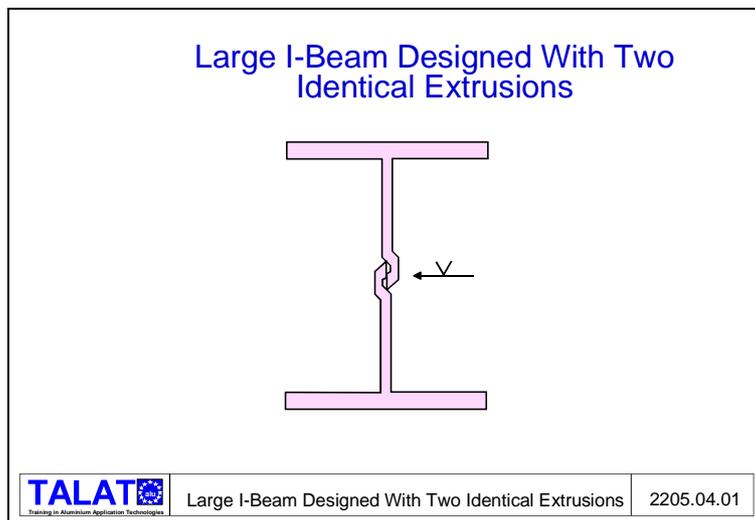
Linear Thermal Expansion.

When aluminium alloy structures are connected to structures made of other material and if they are subjected to larger temperature fluctuations, stresses caused by the differences in linear thermal expansion must be taken into consideration. In the temperature range from - 100 °C to 0°C the coefficient of linear thermal expansion can be taken as $21,5 \cdot 10^{-6} \text{ 1/}^\circ\text{C}$, in the temperature range 0°C to 100°C $23,5 \cdot 10^{-6} \text{ 1/}^\circ\text{C}$ can be used as an average. When the relative difference in linear expansion is known, Hooke's law can be used to find the stress in the structure if the expansion will be within the elastic range.

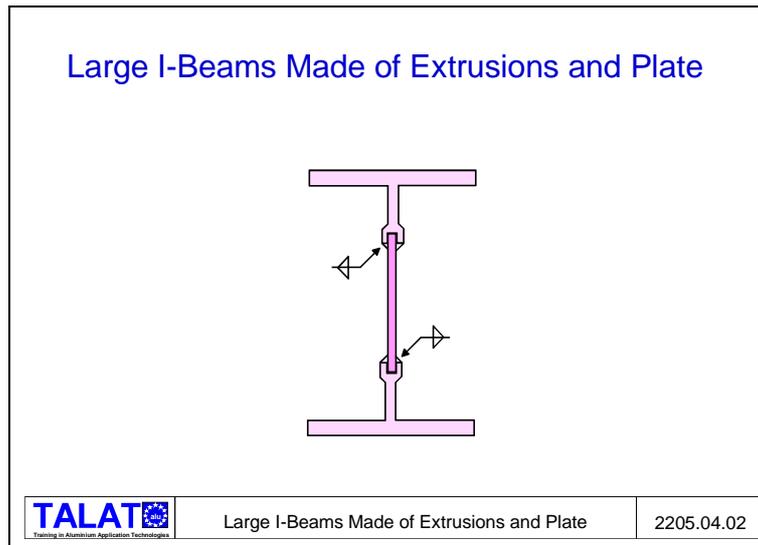
2205.04 Using Extrusions in Design

A great advantage in designing aluminium alloy structures is provided by the possibility of using extruded sections. In **Lecture 2202** some information is given about availability, limitations and costs of extrusions. In **Lecture 2302** "design of joints" a number of examples illustrate the advantageous way of using extrusions in the design of joints.

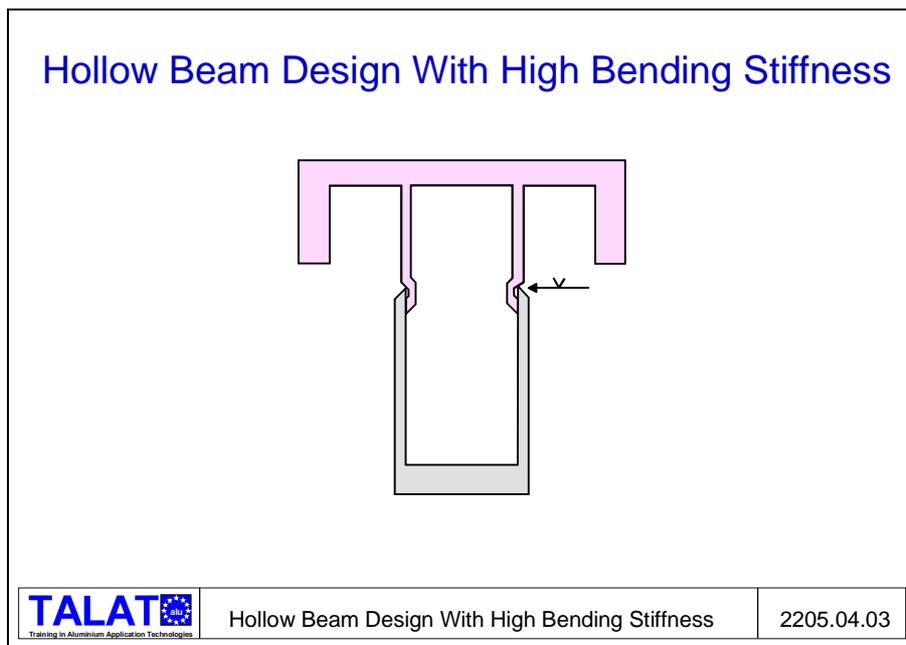
Structural applications sometimes require large members. If these members cannot be produced from single extrusions, welding together smaller extrusions can be a good solution. The welds can then be located in places where the heat affected zones do not reduce the bearing capacity of the member. **Figure 2205.04.01** shows an I-beam made of two identical extrusions, welded together with two butt welds in the middle of the web. The extrusions are produced ready for welding with the groove and backing already attached in the extrusion process.



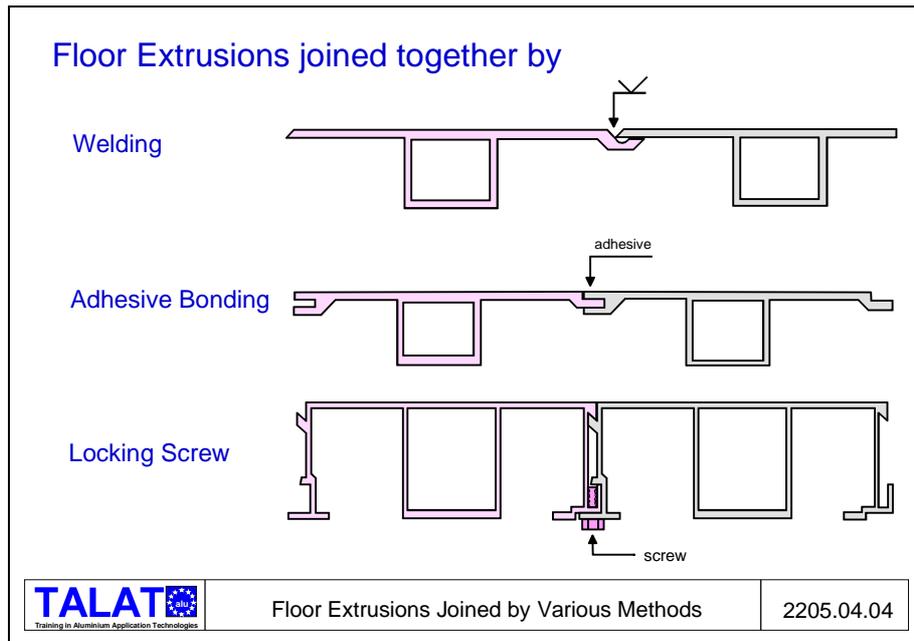
Another way of making I-beams is shown in **Figure 2205.04.02**. The flanges are made of extrusions and the web is a plate or an extruded flatbar. In such a way the same flange extrusion can be used to make I-beams of different heights. This beam is welded together with four fillet welds.



An example from a special case: A member must have bending stiffness horizontal in the upper flange and vertical for the whole member. This is solved by using two extrusions welded together with two butt welds. **Figure 2205.04.03** shows the solution.



In floor structures the extrusion technique can be used by extruding both the floor plate and the stiffener in one extrusion. The extrusions can be put together in several ways: welding, screwing, adhesive bonding or with snap connections, see **Figure 2205.04.04**.



2205.05 References

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- [3] SINTEF Korrosjonssenteret: Korrosjonshåndbok for aluminium. STF 34 A87116 (In Norwegian). 1987.
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2505.06 List of Figures

Figure No.	Figure Title (Overhead)
2205.01.01	Example of Residual Stresses in a Welded T-Profile
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