2002046

Fatigue Strength Improvement of Welded Aluminium Alloys by Different Post Weld Treatment Methods

Thomas Nitschke-Pagel, Helmut Wohlfahrt
Institut für Schweißtechnik, Technische Universität Braunschweig, Braunschweig, Germany

1 Introduction

Special fields where the application of aluminium alloys offer many advantages can be found in the whole field of transportation. Due to strongly increased energy costs the weight factor of transport vehicles like cars, trains and aircrafts has become one of the most important factors because the costs for each vehicle depend directly on its weight. The possibility of substitution of steels by aluminium alloys in fatigue loaded constructions requires the easy applicability of manufacturing techniques where joining processes are a very important part. From steels it is well known that the fatigue strength of a welded construction usually will be very low in comparison with that of the base material. A further problem is, that the notches which are an effect accompanying the welding process will be the more effective the higher the ultimate strength of the base material is. This is the reason because the use of modern high strength steels is not helpful with regard on a weight reduction because the higher potential fatigue strength cannot be found in the welded constructions, if the fabrication procedures are the same.

2 Possibilities of fatigue strength improvement of welded joints

Most of the results of investigations with the aim of a remarkable fatigue strength improvement have been carried out on relatively low strength steels and in some cases also in high strength steels [1,7]. As an example fig.1 shows two different improvement strategies can be used. One way is to use welding procedures which will generate a flat weld seam without sharp notches like TIG-welding or manual-arc-welding (MAW) with special electrodes which may produce a flat weld seam due to a low slag viscosity. The second way is the application of different post weld treatment techniques, where mechanical and thermal treatments can be distinguished. Very effective thermal methods will generate a flat weld toe by remelting this zone with a TIG- or plasma arc without additional use of filler material. Another post weld heat treatment is stress relief annealing which shall reduce high tensile residual stresses. However the results are strongly varying because the initial tensile residual stresses mostly are much lower than assumed and the influence of the residual stresses is probably much lower than the influence of weld defects and notches.

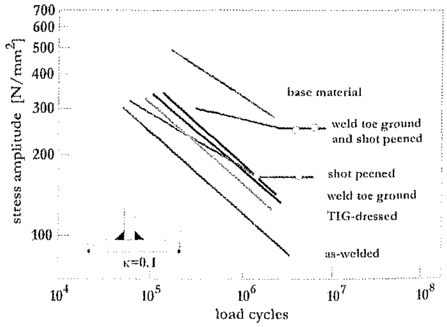
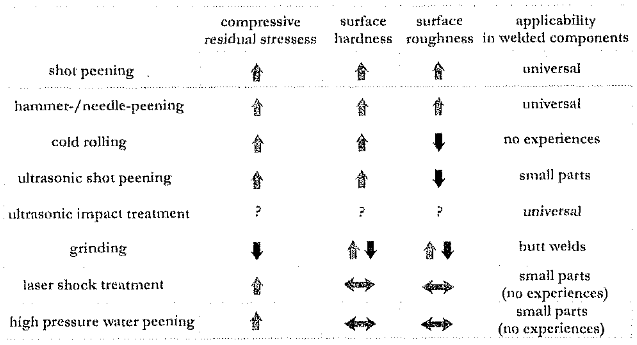


Figure 1: S-N-Curves of welded T-joints after different post weld treatments [2].

Mechanical surface treatment methods which can be applied after welding are methods like grinding (the complete weld seam or only the weld toe), hammer- or needle-peening, shot peening and cold rolling. These methods will reduce the notch effects (grinding) or will increase the resistance against crack initiation by cold working induced surface hardening respectively of the crack propagation by the generation of high compressive residual stresses [6]. Newer methods like the Ultra-sonic-Impact-Treatment (UIT) [8] also enable fatigue strength improvements, but the changes of the micro-structural properties have still to be examined. As the results of a mild steel in fig.1 reveal each improvement method may increase the fatigue strength but it has to be considered, that different features of the surface are affected by the methods summarized in fig.2 in a different way. For example the increase of the surface roughness due to shot peening is a factor, which compensates a part of the fatigue strength improvement achieved by the generation of compressive residuals stresses, an effect which is very important in high strength steels or in high strength aluminium alloys.



	compressive residual stressess	surface hardness	surface roughness	applicability in welded components
shot peening	⇧	⇧	⇧	universal
hammer-/needle-peening	⇧	⇧	⇧	universal
cold rolling	⇧	⇧	⬇	no experiences
ultrasonic shot peening	⇧	⇧	⬇	small parts
ultrasonic impact treatment	?	?	?	universal
grinding	⬇	⇧⬇	⇧⬇	butt welds
laser shock treatment	⇧	⇔	⇔	small parts (no experiences)
high pressure water peening	⇧	⇔	⇔	small parts (no experiences)

Figure 2: Overview of mechanical surface treatment methods for the fatigue strength improvement and affected surface features.

3 Comparison of weld seam improvement and shot peening

A very popular welding method is the **M**etal-**I**nert-**G**as- (MIG-) welding process which is available in different variations. The process is easy to handle and combines a high productivity with good process stability if a modern welding equipment is used. Unfortunately the weld bead cannot be controlled carefully because high welding speed, current and the speed of the wire are parameters which depend on each other. Therefore the geometry of the weld seam is connected with relatively sharp notches and undercuts at the weld toe which lead to a low fatigue strength o in comparison to the base material.

The **T**ungsten-**I**nert-**G**as- (TIG-) welding process enables very flat weld seams with a strongly reduced notch effect but the productivity of the process is low due to a low welding speed. Investigations on steels have shown

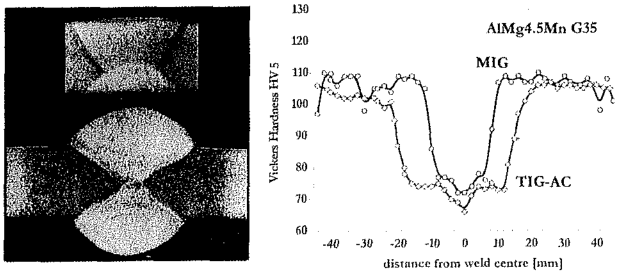


Figure 3: Comparison of the weld seam profile and the hardness distributions of MIG- and TIG-welded joints of a cold worked AlMg4.5Mn G35-alloy (R_m=350 N/mm^2) [3].

that a combination of TIG-and MIG- (MAG) processes also enables an acceptable productivity in combination with an improved fatigue strength. However the applicability of different improvement techniques which are very effective in steels cannot be simply assigned on cold formed or age hardened aluminium alloys, which are very sensitive against an oversized local heat input, because the welding process in combination with a broadened heat affected zone (HAZ) will generate a weld zone with a hardness significantly below the hardness of the base material. Wide softening zones are typical for TIG-welded aluminium alloys. As fig. 3 shows TIG-process enables the generation of a very flat weld seam with a smooth notch geometry at the weld toe in comparison to a conventional MIG-welded joint but with a broadened softened zone in relation to a MIG-welded plate [3].

After TIG-dressing the fatigue cracks frequently will start in the softened transition zone from the HAZ to the base material. The notch effect of the weld toe is reduced but without a strong benefit for the fatigue strength. On the other hand a shot peening process well adjusted on the base material has the same beneficial effect as the combination of weld seam improvement and shot peening in steels. Fig. 4 summarizes S-N-curves obtained on a cold formed AlMg 4.5 Mn-alloy [3]. The combination of a peening process with high enough intensity to produce high compressive residual stresses and surface hardening and an additional surface finishing by peening with glass pearls in order to reduce the surface roughness results in a fatigue strength which is as high as that of the base material. The use of a steel shot whith a size well adjusted on the notch radius at the weld toe surface hardening and compressive residual stresses are combined with an improved notch geometry due to the plastic deformations. Methods like hammer- or needle-peening also induce compressive residual stresses in combination with cold hardening of surface layers. Howeever these processes lead to a higher surface roughness. Therefore newer methods like laser-shock treatment and high-pressure-water peening have been developed with the aim to induce compressive residual stresses without changes of the surface topography. Results of investigations on light-weight alloys reveal that significant compressive residual stresses may be generated however not many results of fatigue test are available.

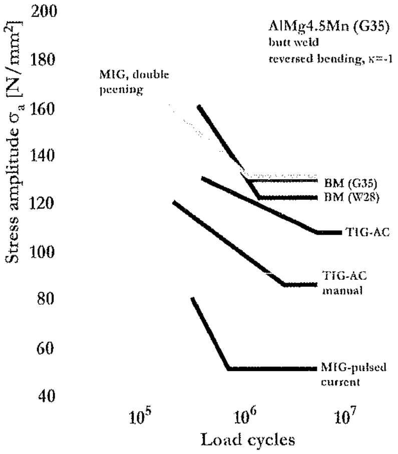


Figure 4: Comparison of the S-N-curves of AlMg4.5Mn G35-alloy welded joints in the as-welded state and after optimised shot peening [3].

4 Fatigue strength improvement of TIG-welded aluminium joints

In [4] 5 mm TIG-welded plates of an AlMg4.5Mn0.7-alloy (AA5083) were examined under reversed bending after application of different surface treatment methods. The primary subject of this investigation was to maximize the welding speed during one-layer TIG-welding with the aim

	current [A]	arc length [mm]	frequency [Hz]	wire speed [m/min]	welding speed [m/min]	shielding gas [l/min]
TIG-AC Ar	450	2	100	1.98	0.90	12 (Ar)
TIG-AC He	290	2	60	2.52	0.83	24 (He)
TIG-AC He/Ar	450	1.5	160	3.42	1.52	29 (He/Ar 90/10)

Table 1: Welding parameters for butt welds of 5 mm AlMg4.5Mn0.7-alloy (AA5083) [4].

to combine a good weld seam quality with an acceptable productivity. In table 1 the parameters are summarized which were used for TIG-welding with alternating current.

Shot peening [1]		High pressure water peening [2]	
Shot material:	S230	Jet pressure:	300 bar
Hardness:	45...55 HRC	Distance from nozzle:	45 mm
Intensity:	0.008" A	Peening time:	2 sec
Coverage:	200 %	Nozzle diameter:	1.5 mm / 20°
Specification:	MI 230 R	Overlap:	1 mm

Table 2: Peening parameters; 1) Metal Improvement Company
2) IWT, Universität Hannover

The macrographs of the TIG-AC- welded plates (fig. 5) reveal the main problem with regard to a fatigue strength improvement which is connected with one-layer weldments. On the top side of the weldments the weld seam geometry shows the typical features well known from TIG-weldments. A flat weld seam with a smooth macroscopic notch geometry. The joint TIG-AC welded under Helium seems to have the smoothest notch geometry and the specimen welded with a high welding speed of 1.52 m/min under Ar/He shows a significant undercut of the weld seam. The notch factors of the different welds calculated with the measured geometry parameters are between 1.28 and 1.53. However the fatigue strength under reversed bending was uniformly between 55 and 57 N/mm^2 and that is to say significantly below the fatigue strength of the base material (118 N/mm^2).

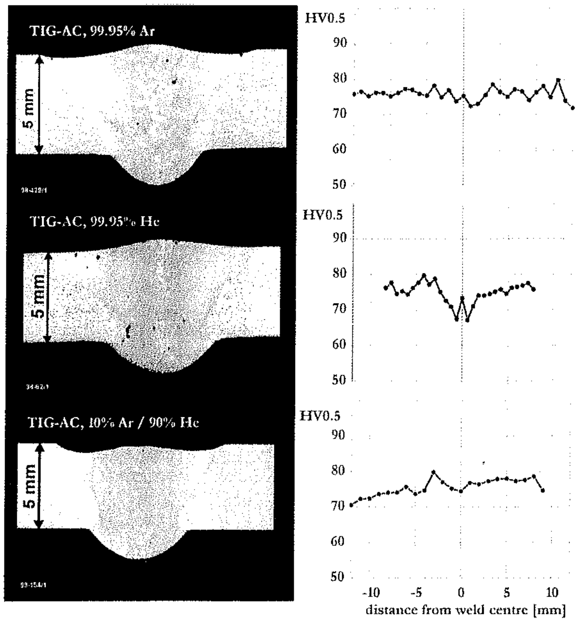


Figure 5: Comparison of the weld seam profile and the hardness distributions of TIG-AC-welded joints of an AlMg 4.5 Mn 0.7-alloy (R_m=253 N/mm^2) [4].

The TIG-AC-Ar- and the TIG-AC-Ar/He-welded joints were additionally examined after different peening procedures (tab. 2). Fig.6 shows the residual stresses measured at the surface by means of X-rays. In the as-welded state slight tensile residual stresses with maximum values of 70 N/mm^2 are found in the weld seam. Both surface treatment methods induce compressive residual stresses in the weld seam and in the base material which are approximately on the same level, the greatest compressive residual stresses (-180 N/mm²) are observed in the weld seam after shot peening. A significant difference between both methods can be characterized by the half width distributions of the diffraction lines. The half widths across the weld after high pressure water peening are almost the same than after welding. On the other side the shot peening process leads to a significant increase of the half widths in the weld seam and in the base material (fig. 6).

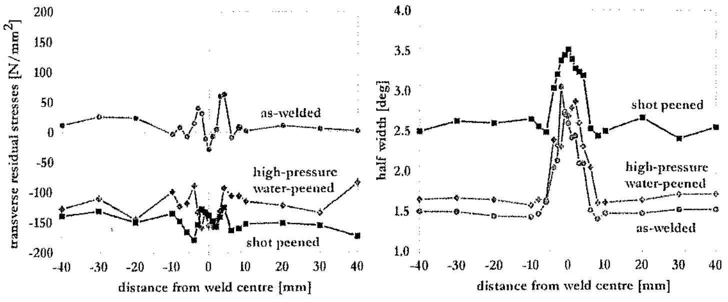


Figure 6: Distributions of the transverse residual stresses and of the half widths after welding, high pressure water peening and after shot peening.

The depth profiles of the residual stresses and of the half widths (fig. 7) obtained after incremental electrochemical polishing evidently show, that the effect of the water peening process is limited on the generation of compressive residual stresses in the surface without any changes of the local strength properties which can be characterized by the half widths. On the other side the penetration of the plastic deformations connected with the shot peening process is much higher. The maximum of the compressive residual stresses can be found in a depth between 0.05 and 0.15 mm, the magnitude of the compressive residual stresses is higher and the depth distribution of the half widths indicates a remarkable cold hardening of the surface layers.

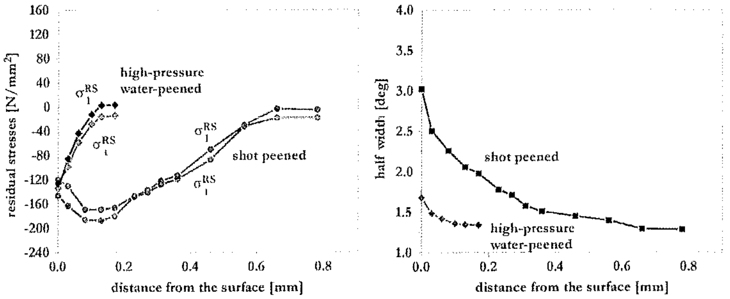


Figure 7: Residual stress depth profiles and half width distributions after high pressure water peening and after shot peening.

The S-N-curves of the different treated specimens determined under reversed bending (fracture probability 50%) are given in fig. 8. In comparison to the base material the fatigue strength decreases significantly as expected to values which are in both cases 50% of the fatigue strength of the base material. The different geometry at the weld toes of the top side of the weld seam which is a consequence of the different welding speeds obviously does not result in a different fatigue behaviour. The fatigue strength is nearly as high as the fatigue strength after conventional MIG-welding. This is caused by the dominating notch effect of the weld toes at the bottom side, where the notch geometry is the same as it can be observed in MIG-welded joints. Because the plates have been welded with one layer a certain control of the weld seam profiles on both sides of the welded plates which is usually possible during TIG-welding due to the separate input of the heat and of the filler material could not be achieved. As fig. 8 reveals both peening procedures which were applied in this investigation lead to an improvement of the fatigue strength. After high pressure water peening at the weld toes the fatigue strength is increased from 57 N/mm² to 75 N/mm². This is equivalent to a percentage of more than 30%, however the fatigue strength value is significantly below the base material After shot peening the fatigue strength is increased from 57 N/mm² to 121 N/mm² and that is to say to the level of the base material. The significant improvement of the fatigue strength due to shot peening is limited on stress amplitudes, which lead to high number of load cycles. With increasing stress amplitude the benefit disappears. This is in agreement with well known results from literature on steels and aluminium alloys.

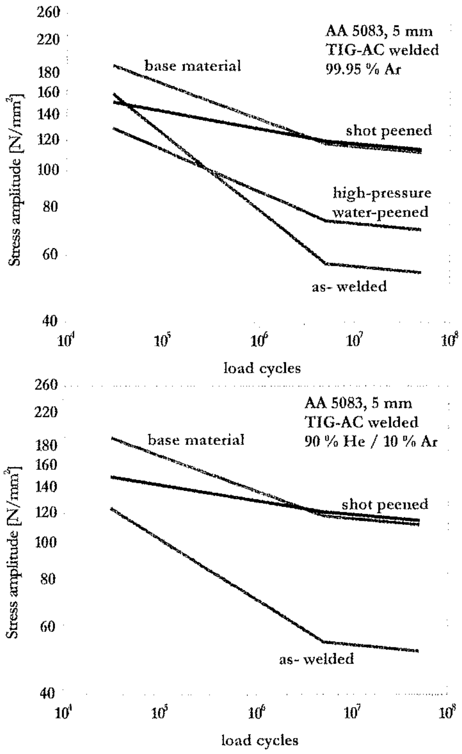


Figure 8 S-N-curves (50% fracture probability) of TIG-AC-Ar- and TIG-AC-He/Ar-welded AlMg 4.5 Mn 0.7-joints in the as-welded state and after a mechanical surface treatment [4].

As summarized in fig. 2 the mechanical surface treatment methods affect three parameters which are important for the fatigue behaviour, the residual stresses, hardness of surface layers and surface roughness. Due to shot peening beneficial compressive residual stresses are induced and the surface hardness increases. On the other side the surface roughness increases as well which may have a negative effect for the fatigue strength. The magnitude and the distribution of the induced compressive residual stresses will be the more important the higher the ultimate strength of the material is. This is caused by the effect, that in low strength materials the residual stresses will be reduced strongly during the first cycles because the fatigue strength is very close to the yield strength respectively to the cyclic yield strength. With increasing ultimate strength the cyclic yield strength increases stronger than the fatigue strength with consequence of more stable residual stresses. On the other hand the surface hardening effect becomes less important but the surface roughness has to be considered. Therefore in weldments, which are mostly built by relatively low strength metals, the more important factor for the fatigue strength improvement due to mechanical surface treatments is the cold working induced surface hardening. The compressive residual stresses are also effective but they will be reduced strongly at higher load amplitudes. Thus the fatigue strength improvement due to high pressure water peening is much lower than due to shot peening because the surface hardness is not changed significantly. This results frequently in a flat slope of the S-N-curve with the consequence that the fatigue limits at high load amplitudes are as high as in untreated joints. In aluminium alloys the surface roughness is an additional very important parameter because the effectiveness of small notches – and the higher surface roughness can be interpreted as a notch factor – can be much higher than in low strength steels.

5 Conclusions

Different methods for the fatigue strength improvements are available which can be applied on welded joints of steels and light weight alloys. However the recommended way first to improve the weld seam profile and then to apply a mechanical surface treatment only in steels will result in a fatigue strength which is equivalent to the base material. In high strength aluminium alloys the improvement of the weld seam profile will only result in a significantly better fatigue strength, if the weld seam improvement is not connected with a strong softening in the weld seam and in the HAZ due to high local heat input. In welded joints with one-layer welds or in constructions which cannot be welded from both sides the improvement of the weld seam geometry for example with help of TIG-dressing will not result necessarily in an improved fatigue strength.

A mechanical surface treatment as demonstrated with shot peening can result in a fatigue strength improvement, where the fatigue strength of the weldments may reach the value of thebase material. This can achieved without an especially optimised welding process. However the avoidance of a broad softening zone is required because results of experiments after a combined treatment (e.g. TIG-dressing and shot peening [4]) have shown, that the softening effects cannot be compensated by the mechanical surface treatments. Several other improvement methods are available, but their principles have to be clarified respectively it has to be examined, in which cases these methods my be applicable under consideration of economical boundary conditions. However the success of each fatigue strength improvement method depends on the possibilities to affect all points of a weldment, where the probability of a crack initiation high. This is also valid for methods like shot peening. If places with sharp notches as the root of fillet welds or the bottom side of one-layer butt welds cannot be affected, an application of a post weld treatment method will result only in a shift of the crack initiation sites without a significant improvement of the fatigue strength.

6 References

[1] Heeschen, J.: Dissertation Universität Kassel (1986).

[2] Haagensen, F.; Dragen, A.; Slind, T.; Orjasaeter, 0.: In: „Steel in Marine Structures", Proc. 3nd Int. ECSC Offshore Conf. (SIMS '87), Delft, The Netherlands, June 15-18, 1987, S. 689 - 698, Elsevier Science Publishers B.V., Ed. C. Nordhoek and J. de Back

[3] Zinn, W.: Dissertation Universität Kassel (1989)

[4] Krull, P.: Dissertation TU Braunschweig (2000).

[5] Haagensen, P. J.: IIW-Doc.XIII-WG2-30. August 1994

[6] Wohlfahrt, H., Krull, P. (Hrsg.): Mechanische Oberflächenbehandlungen: Grundlagen – Bauteileigenschaften – Anwendungen. WILEY-VCH-Verlag Weinheim 2000.

[7] Haagensen, P. J.: IIW-Doc.XIII-1748-98.