Influence of the deformation intensity of different mechanical surface treatments on the fatigue strength

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Abstract

The residual stress condition of post weld treated of welded high strength aluminium alloys is of great interest because it is related often to the fatigue behaviour. Systematic investigations on welded AlMgSi1Mn-joints show the influence of different peening procedures on the near surface residual stresses as those in deeper layers. However under service conditions the initial residual stresses are changed due to plastic deformations. The investigations shall give an answer to the question of the correlation between residual stress relaxation and the consequences for the fatigue performance of such welds.

Keywords: GMA-welding, aluminium, residual stresses, shot peening, hammer peening

Introduction

In the last 10...15 years so called high frequency hammer peening techniques became more interesting for fatigue strength improvement applications in welded joints [1,2,5]. The techniques are used with the aim to produce plastic deformations at the weld toes in order to generate compressive residual stresses in combination with local cold working induced hardening and possibly also a geometrical improvement of the weld toe profile. The techniques are very similar to classic hammer peening [4,5] techniques which are already considered in improved design rules like the IIW-fatigue recommendations for fatigue strength improvement [3]. The principal difference of the new techniques, which are called "HiFit" (high frequency impact treatment), "PIT" (pneumatic impact treatment), "UIT" (ultrasonic impact treatment) or "UP" (ultrasonic peening) to elder techniques is the design of the tools and the tool excitation by means of air pressure or ultrasonics. The resulting higher frequencies of the hammer tools shall enable high deformation intensities and therefore a maximized penetration depth of the compressive residual stresses. Many works are dealing with the retrieval to find out the best application procedure to optimize the residual stress condition of welded steels [6,7,8,11]. Aluminium welds include a high potential for fatigue strength improvement because the FAT (Fatigue) classes of aluminium welds which can be found in the design rules have been rated conservatively so low that aluminium alloys usually cannot be used economically to replace steels in fatigue loaded welds. On the other hand several investigations have shown evidently that the fatigue strength of aluminium alloys may be improved significantly by mechanical surface treatments [8,10]. Here hammer peening techniques are in a challenge with well known improvement techniques like TIG-dressing or shot peening procedures.

As Fig. 1 reveals combined processes like shot peening after a weld toe profile smoothing by TIG-dressing of laser welded joints which has been shown the best performance in steels is less effective than simple shot peening of aluminium welds. The problem is that the relatively high heat input of the TIG-process generates a broad softening zones

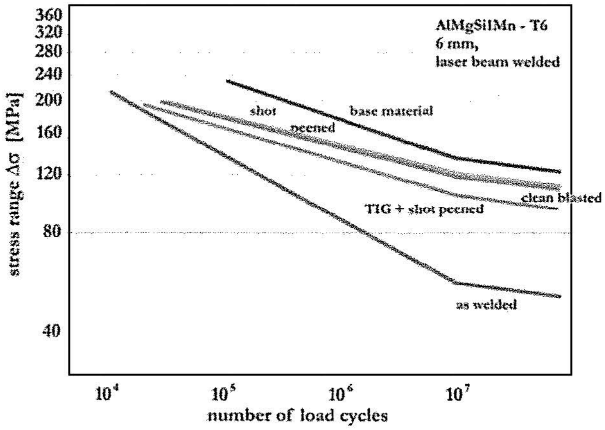

Figure 1. S-N-curves of laser-welded butt joints after different post weld treatments (EN-AW6065)

when applied in cold or precipitation hardened materials. The consequence is that the fatigue cracks doe not start anymore at the weld toe but in the adjacent softened zone and that is to say in a region with a so called structural notch. An additional peening process which generates compressive residual stresses and cold working improves slightly the fatigue strength but is not able to compensate the detrimental effect of the structural notch. On the other hand the comparison of shot peened and high frequency hammer peened samples indicate a higher benefit by shot peening (Fig. 2). This result is not easily to be understood looking on the initial residual stress profiles after the different treatments. The magnitude in the near surface region was nearly the same but the resulting fatigue strength showed a level approximately 20 % lower than in the shot peened condition. The reason for this particular fatigue behaviour is that in the 6 mm thick aluminium welds the high intensity of the hammer peening process generated a local undercut at the weld toe due to the strong plastifications. The result was a loss of finally 15 % of the cross section and that is to say significantly higher local stresses at the same nominal stress amplitude. This example reveals that the maximization of the peening intensity to generate compressive residual stresses as high and as deep as possible is not necessarily the best way to improve the fatigue strength. At least the accurate adjustment of the treatment parameters to the used material enables the highest benefit. That means that the knowledge about the really required intensity and the particular material properties should be taken into account carefully.

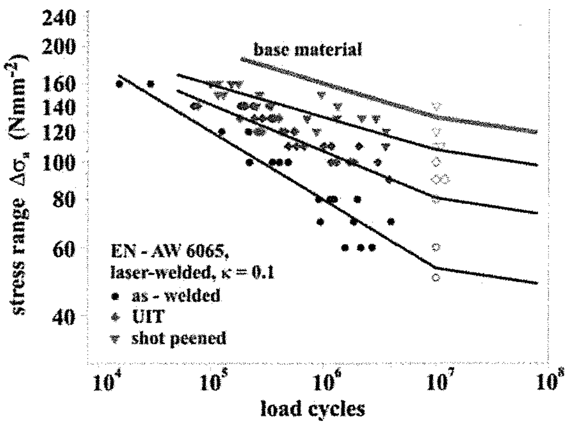

Figure 2. Fatigue test results of laser-welded butt joints after high frequency hammer peening and after shot peening (EN-AW6065) [6].

Aim of the Investigation and experimental program

The goal of the presented work was the investigation of the correlation between the intensity of mechanical surface treatments and the resulting fatigue strength. The experimental works were carried out on butt welds of a precipitation hardened aluminium alloy EN-AW 6082 – T6 (AlMgSi1Mn). All the samples were GMA-welded using an AlMg4.5MnZr filler material. The ultimate strength of the heat treated base material was determined as 341 MPa, the yield strength was 317 MPa. As known the mechanical properties of the precipitation hardened alloy AW6082 may be affected strongly by the heat input due to welding. As the hardness distribution in Figure 3 reveals the entire weld zone and the adjacent heat affected zone (HAZ) show a significant lower hardness than the unaffected base material. As expected the hardness of the weld metal is lower due to the changed chemical composition in combination with the missing precipitation hardening effect. This lower local yield strength is usually not very important for the mechanical behaviour of welds because it is compensated by the higher cross section. However in the HAZ the hardness shows a strong decrease in the transition zone between the HAZ and the base material which is typical for this alloy. The lowered hardness is a consequence of a local recrystallization leading to a local strongly decreased yield strength $Rp_{0.2}$ of 140 MPa.

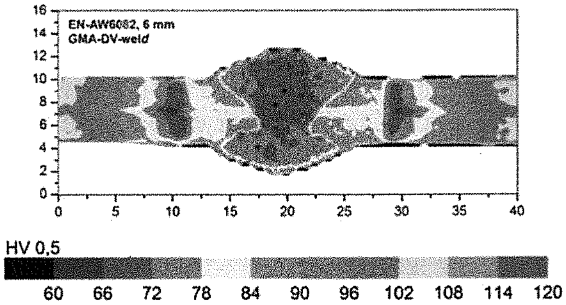

Figure 3. Hardness distribution of a 2-pass GMA-DV-weld of a 6 mm AlMgSi1Mn-alloy (EN-AW6082) in the as-welded condition.

Residual stress measurements were carried out on the fatigue test samples shown in Figure 4 along the marked measurement track transverse to the weld seam in the initial condition before starting the fatigue tests in the as-welded state and at each series of differently treated samples. Additional measurements were performed after different numbers of load cycles in order to determine the relaxation of local residual stresses during fatigue loading. The measurements were performed with a Bragg-Brentano diffractometer (□□-mode) using CoK$_{□}$-radiation. The collimator size was Ø2.5 mm. The {331}-profiles of the Al-matrix were determined at 11 □-positions and the residual stresses were calculated using the sin^2□-method. For the evaluation of the measured residual stresses generally values with regression errors below 10 MPa were considered. Therefore no particular error bars in the residual stress representzations are given. The welded samples were investigated in the as-welded state and after different mechanical surface treatments. The different investigated conditions are described as follows:

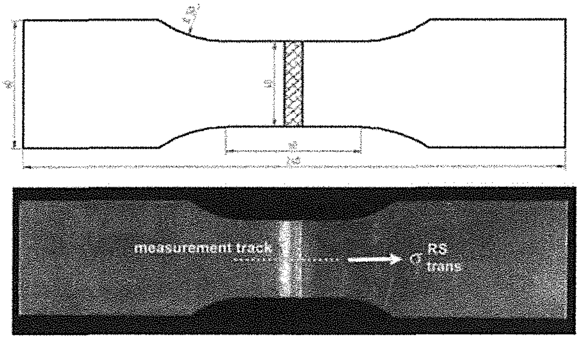

Figure 4. Shape and dimensions of the investigated fatigue test samples.

- *as – welded condition without any treatment*
- *clean blasted under laboratory and under industrial conditions*
- *shot peened in combination with surface finishing and additionally overloaded*
- *high frequency hammer peening with different procedures and intensities*

The peening procedures were carried out by the companies distributing the particular applications just in process and that is to say that the parameters were not especially optimized for the project but used as commonly suggested for different customers. A special issue was the consideration of different clean blasting procedures. The main difference between a shot peening and a cleaning process is that during cleaning the peening parameters are not controlled precisely. In practice it is used to prepare the surface for different coatings or paintings. This is a commonly used procedure which is not yet established as a fatigue improvement method. Here two procedures where used, one under laboratory conditions and one with help of a railway factory just in process as usual in their production. An additional variation was a series of shot peened and initially overloaded samples. A single tensile load of 160 MPa (e.g. of the magnitude of the yield strength of the recrystallized heat affected zone) should simulate an overloading condition which is expected usually in service and which may reduce the initial compressive residual stresses significantly and therefore the benefit of a shot peening procedure. Fatigue tests were carried out under tension-tension loading with a stress-ratio of R=0.1. The fatigue limit was set to 10^7 load cycles. The fatigue classes (FAT-values) corresponding to the design rules were calculated from the SN-curves for a fatigue strength probability of 95%.

Fatigue test results

The FAT-values of the investigated specimen series are summarised in Fig. 5. The horizontal lines indicate the corresponding values for an untreated DV-weld, which was also determined in the presented tests and the limiting value for the base material "Aluminium" which is FAT 71 (EUROCODE and other design rules [3] generally do not distinguish between different base materials). As the bars for the different treatments reveal a mechanical surface peening treatment generally improves the fatigue strength significantly. With one exception each treatment leads to a fatigue strength above the untreated base material. The highest benefit is reached with the shot peening applications independent on the type of the treatment and that is to say that also a cleaning procedure can generate the same improvement as an optimized process. The fatigue test results of the hammer peened samples are scattering more and the highest intensity not necessarily shows the best benefit. After a single tensile overload the FAT-value is slightly reduced but nevertheless the remaining fatigue strength is very close to the shot peened samples and much higher than the related base material. This result in fact is of great importance for the practical use of the mechanical surface treatments methods. In practice the missing stability of the compressive residual stresses in the case of overloads is usually the main criterion which is used by those institutions which are very critical in accepting these methods for the practical establishment of higher FAT-values for welds which can potentially reached with help of the application of fatigue strength improvement methods like peening procedures. The fundamental reason is the discussable viewpoint that the main view is usually focused on the effect of residual stresses without considering the material properties and the importance of local cold working induced hardening.

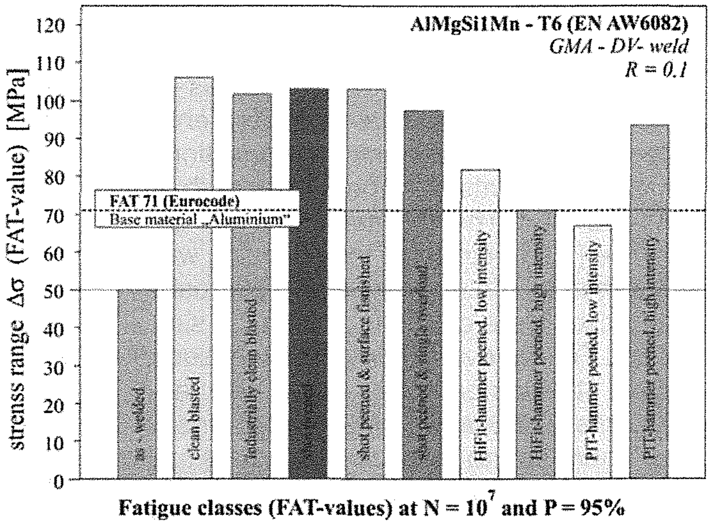

Figure 5: Fatigue test results (FAT-values) of differently peened test samples in comparison to the untreated DV-weld and the base material

Residual stress measurements

The typical result of a residual stress distribution around a GMA DV-weld is given in Fig.6. The profile in the as-welded condition is characterized by very slow tensile or even low compressive values in the load direction (transverse to the weld seam). This is typical for thin walled aluminium welds where due to the thermal properties of the material an equilibrium temperature over the entire thickness at a temperature level of approximately 200°C avoids a high grade of restraint which is the basic condition for the generation of remarkable tensile residual stresses. Thus now results are known where under practical boundary conditions significant high tensile residual stresses were found in aluminium welds. The FWHM-values in Fig.6 indicate the softening in the HAZ of the

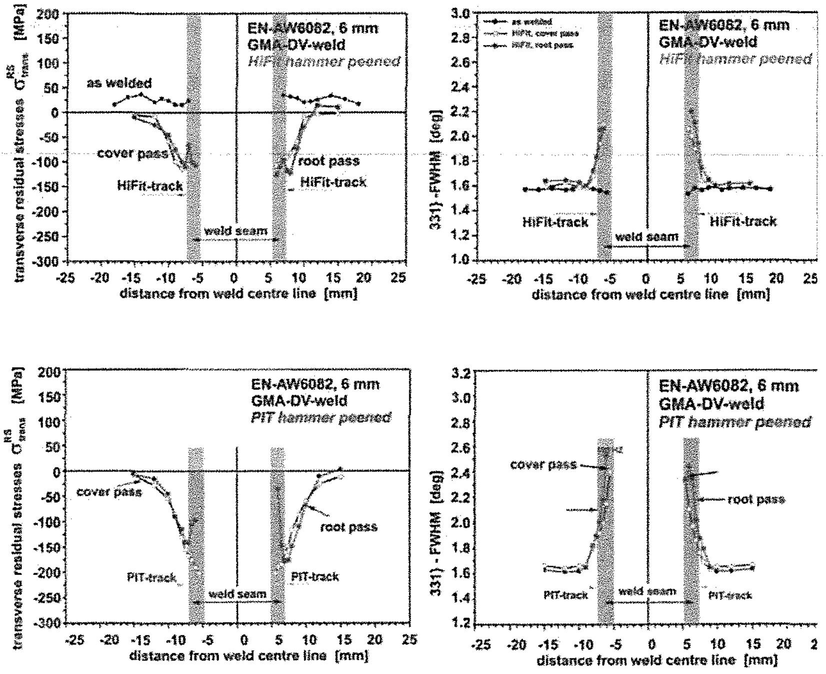

Figure 6 and 7. Transverse residual stresses in the as-welded condition and after a local hammer peening at the weld toe and FWHM of the {331} diffraction lines of DV-welds.

weld due to the thermal cycle. A local hammer peening at the weld toe (HiFit) generates remarkable compressive residual stresses in the treated zone and in the neighbourhood as well as the distribution of the FWHM-values reveals the significant increase of the local strength due to the cold working effect in the treated surface. The same distribution can be found after a comparative hammer peening (PIT) in Fig. 7.

A detailed view of the near surface condition of differently treated samples is given by the residual stress depth profiles shown in Fig.8. As expected the generated maximum compressive residual stresses which can be found generally below the surface are not significantly different for the applied techniques but the depth profile are varying. While the different shot peening procedures show now no remarkable differences the higher intensity of the hammer peening process generates a broader maximum below the surface but the slope of the increasing residual stresses to the equilibrium tensile residual stresses is significantly steeper. The tensile range is reached here after 0.9 mm while the residual stresses after a hammer peening with lower intensity after 1.4 mm below the surface the residual stresses are still compressive. Fig.9 shows distributions of the micro hardness determined with a micro indenter in the weld toe region of differently treated samples. The hardness distributions evidently show, that the high intensity of the hammer peening procedures lead to a strong increasing local hardness. An additional effect of the high intensity of the hammer peening process is the strong deformation of the weld toe region (see Fig.10). The local deformation changes the weld toe profile and leads toe smoothing of the toe radius. The resulting radius corresponds with the tip radius of the used tools. A remarkable effect is that in the thin walled aluminium alloys the strong deformation reduces the cross section the more the higher the intensity is.

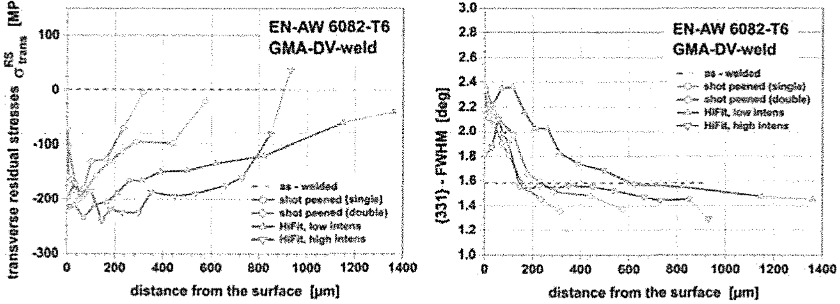

Figure 8. Residual stress depth distributions and FWHMvalues of shot peened and hammer peened samples at the weld toe.

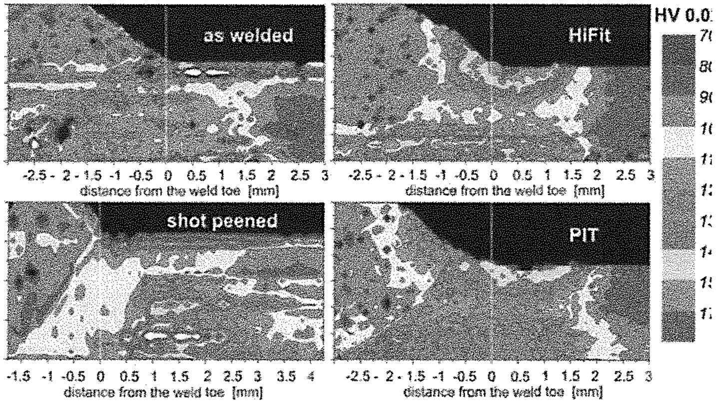

Figure 9. Microhardness distributions in the weld toe region of differently treated samples.

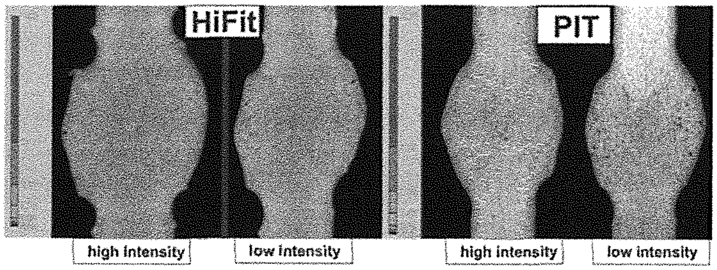

Figure 10.: Shape of the cross section of hammer peened samples and porosity distributions (computertomography).

The residual stresses generated by the peening process are relaxed due to a static tensile load above 100 MPa continuously while compressive loads do not change the residual stress condition

(Fig.11). This typical behaviour can be related to the Bauschinger effect which is present in case of reversed load direction after plastic deformation. After a tensile load close or slightly above the local yield strength of the recrystallized material the initial compressive residual stresses are reduced strongly. Nevertheless the tests have shown that the over-load does not reduce the fatigue strength improvement significantly. This indicates that the local hardening obviously is more important for the fatigue performance of mechanically treated aluminium welds than a particular residual stress condition

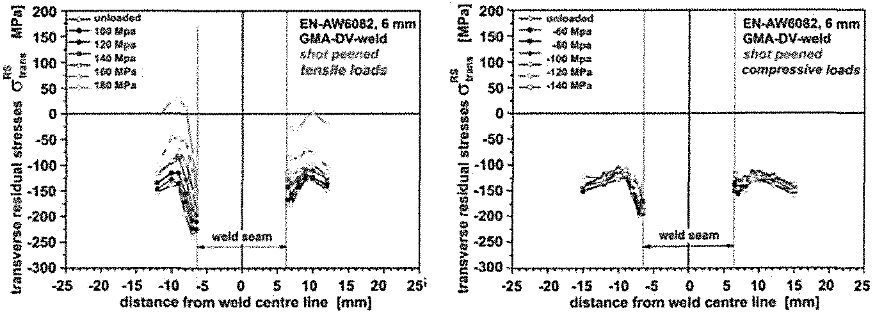

Figure 11. Residual stress distributions in a shot peened samples after different tensional (left hand side) and compressive (right hand side) overloads.

Summary

The fatigue strength of welded aluminium joints can be improved significantly with help of different mechanical post weld treatment methods. It depends on the shape of the weld, the applicability of the methods under service conditions and on the loading conditions, if an improvement of the weld seam geometry or a mechanical surface treatment will give the better results. The best fatigue performance is not necessarily guaranteed with help of a maximization of the peening intensity with regard to the highest amount and penetration depth of the generated compressive residual stress. In weak materials like welded aluminium alloys or low strength steels obviously the cold hardening which is accompanied by the plastic deformations of the surface is more important for the benefit. This leads also to the conclusion that under usual load conditions the risk of a load induced loss of the beneficial effect of such treatments is relatively low. Furthermore the results reveal that shot peening as an improvement technique is a comparative technique.

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