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Mechanical Surface Treatments of Lightweight Materials—Effects on Fatigue Strength and Near-Surface Microstructures

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Mechanical surface treatments such as shot peening or deep rolling are well-known processes to improve the fatigue strength of metallic components. This is due to favorable microstructural alterations in relatively thin surface layers as a consequence of near-surface inhomogeneous plastic deformations. Typical examples demonstrate the fatigue-strength increase for mechanically surface-treated specimens. Existing possibilities to improve the fatigue strength of welded joints by mechanical surface treatments are also included. In the case of lightweight materials (e. g. magnesium- or aluminum-base alloys), process parameters must be well adapted in individual cases to achieve optimum near-surface material states, taking into account the wide range of mechanical properties attainable as a result of their specific material microstructure.

The effects of process parameters and microstructures on near-surface materials properties resulting from mechanical surface treatments are demonstrated with examples. Depth distributions of macroresidual and microresidual stresses are analyzed together with microstructural observations. An important point for the effectiveness of mechanical surface treatments is the stability of the near-surface material states during loading history. This aspect is treated for the case of fatigue loading.

Keywords aluminum alloy, magnesium alloy, mechanical surface treatment, shot peening, surface rolling

1. Fatigue Strength of Mechanically Surface Treated Components

Figures 1 to 3 are characteristic of the many examples in practice where mechanical surface treatments are used to improve the fatigue strength of components. Figure 1 shows that shot peening of AlMg4.5Mn (5083) increases the bending fatigue strength by about 50% compared with the machined starting condition (Ref 1). The most important process parameters of shot peening are shot size, peening intensity, and coverage, respectively. Details and nomenclature are explained in Ref 2. In the case of welded specimens (Fig. 2) and as a consequence of weld seam geometry and microstructure, only small fatigue strength values are observed. An appropriate shot-peening treatment, however, raises bending fatigue strength of welded specimens up to the respective value of the not-peened base material. In Fig. 3, bending fatigue Woehler curves of milled and additionally shot-peened magnesium alloy AZ31 respectively are compared. In this case, shot peening does not improve fatigue strength. On the contrary, a small decrease of

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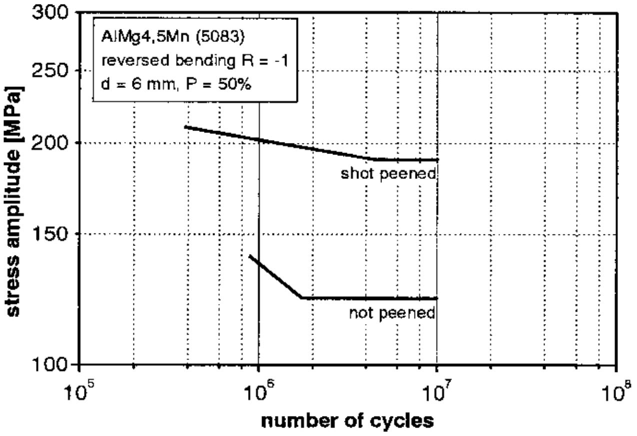


Fig. 1 Comparison between Woehler curves of shot peened (shot size S230; intensity 8A; coverage 200%) and untreated bending fatigue specimens (Ref 1)

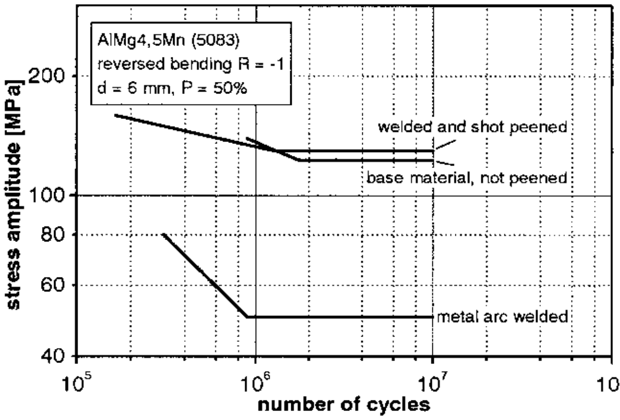


Fig. 2 Influence of shot peening (shot size S230; intensity 8A; coverage 200%) on the bending fatigue strength of welded specimens in comparison with the base material (Ref 1)

fatigue strength is observed. This can be attributed to the fact that the milled surface contained compressive residual stresses comparable to the shot-peened state. In addition, the shot-peened surface revealed small cracks as a consequence of shot-peening induced plastic deformations (Fig. 4).

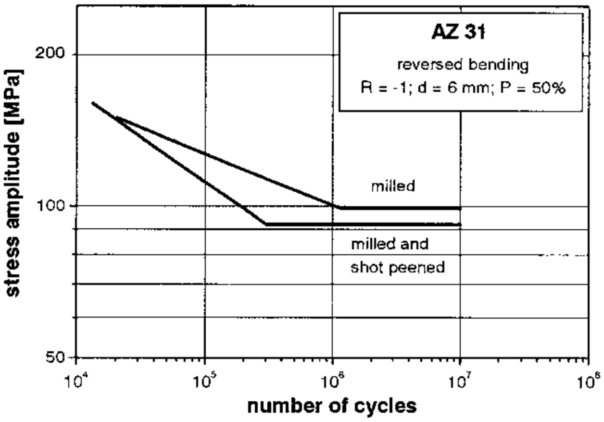
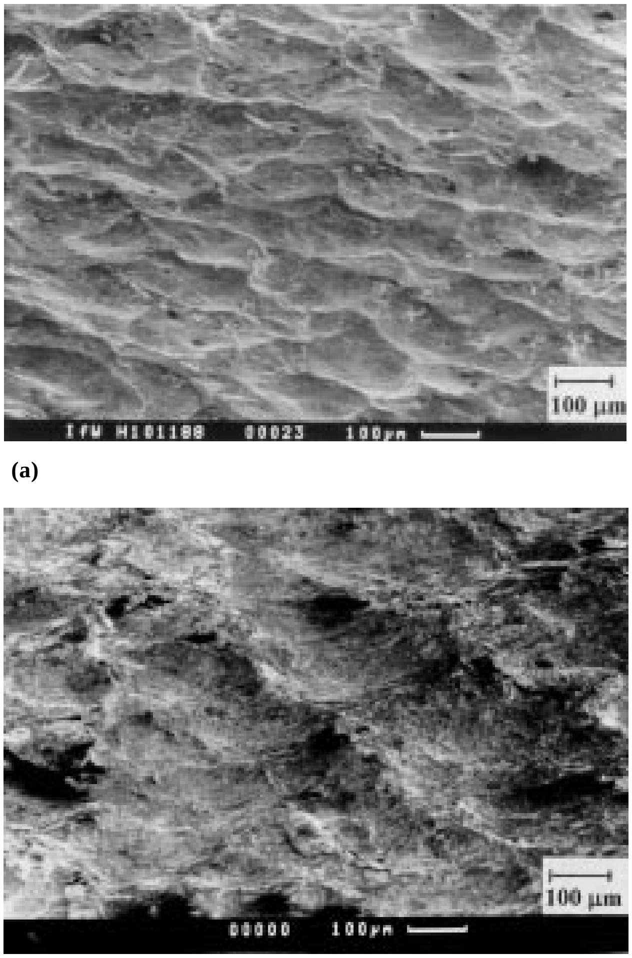


Fig. 3 *S-N* curves of milled and milled-and-shot-peened specimens made of magnesium alloy AZ31



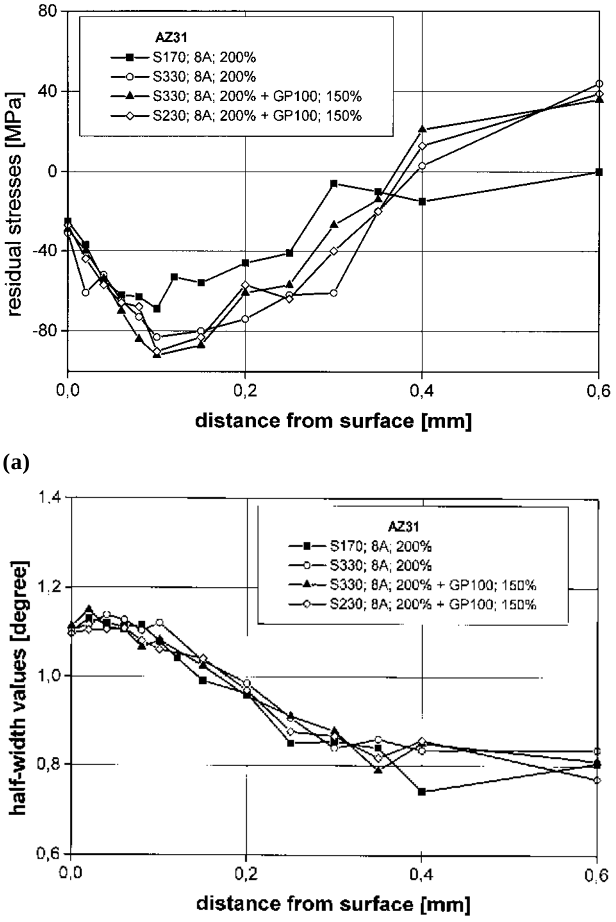
(a)

(b)

Fig. 4 Surface topographies of (a) AlMg4.5Mn and of (b) AZ31 after shot peening. AlMg4.5Mn: shot size S230, intensity 8A, coverage 200%. AZ31: shot size S170, intensity 8A, coverage 200%

In all cases, the combined effects of near-surface properties resulting from the mechanical surface treatments applied are responsible for the fatigue strength values achieved. Maximum strength levels can only be realized if optimum combinations of near-surface properties are created by the surface treatment processes applied, which is sometimes a challenging task. Among others, the most important influencing parameters that must be taken into account are near-surface strength distributions (that can be specified by hardness distributions), the distributions of microresidual and macroresidual stresses (in most cases detected by x-ray diffraction techniques), and the surface topographies characteristic of the treatments applied (Ref 3).

Nominal or local strength concepts (Ref 4, 5) and the local fatigue strength concept (Ref 6), together with appropriate fracture mechanics concepts, can be used to predict qualitatively or quantitatively the resulting fatigue strengths or lifetimes of the components under consideration. This is possible only if all relevant process parameters and their influence on materials properties in near-surface layers (and ultimately on fatigue behavior) are known. In this article, some important aspects are outlined and discussed.



(a)

(b)

Fig. 5 Depth distributions of (a) residual stress and (b) x-ray interference line half-width values in magnesium alloy AZ31 for the shot-peening treatments indicated

2. Influence of Process Parameters on Near-Surface Properties

Figure 4 shows surface topographies of shot-peened magnesium alloy AZ31 and aluminum alloy AlMg4.5Mn (5083). In the case of AZ31, many small cracks and laminations can be detected (see arrow) that are very detrimental for the mechanical behavior. The surface of AlMg4.5Mn (5083) is also strongly plastically deformed but less damaged than AZ31. In both cases, surface topography clearly shows indentations of the shot-peening medium. From this comparison, it becomes clear that, depending on notch sensivity of the material under investigation, the creation of a smooth and defect-free surface topography is an important prerequisite for an optimized materials state.

Figure 5 shows near-surface residual stress distributions of shot-peened magnesium alloy AZ31 plotted for different shot peening conditions. Specimens were taken from a rolled plate of 15 mm thickness as delivered. For the tensile tests in rolling direction, a yield strength (YS) of 137 MPa and an ultimate tensile strength of 254 MPa were measured. Determination of residual stress was carried out using standard x-ray diffraction techniques. Compressive residual stresses were small and did not exceed 65% of the YS of the material. Maximum values, which always occur well below the surface, were observed for combined treatments with steel shots and glass beads. Such treatments are applied to avoid corrosion damage by steel impurities remaining in the magnesium alloy surface. Amount of cold working can be quantified by interference line half-width values (Ref 7). Depth distributions in the lower part of Fig. 5 show that consequences of shot-peening treatments can be detected up to a surface distance of about 0.4 mm. Near the surface, considerably higher values are measured than in the interior.

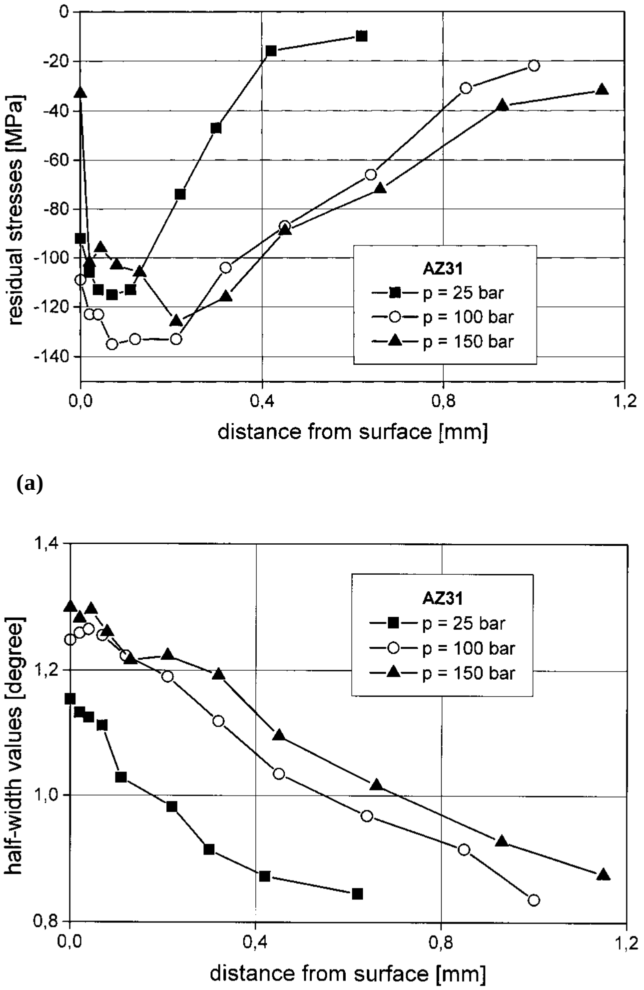


Fig. 6 Depth distributions of (a) residual stress and (b) interference line half-width values for cylindrical specimens made of AZ31 deep rolled with the pressures indicated

For deep-rolled specimens, much thicker surface layers with compressive residual stresses can be achieved than those surfaces achieved with shot peening (Fig. 6). In the case shown, a hydrostatic rolling device and cylindrical specimens were used. Increasing the rolling pressure from 25 to 100 or 150 bars respectively increased maximum amounts of residual stresses as well as layer thickness affected by the process. Residual stress amounts up to the tensile YS of the material investigated were achieved. It is interesting to note that for the highest rolling pressure applied, compressive residual stresses immediately below the surface are small. Depth distributions of interference line half-width values (Fig. 6b) confirmed that with increasing rolling pressure, surface distances of up to approximately 1 mm reveal an increase of microresidual stresses due to rolling-induced plastic deformations.

Also in the case of aluminum-base alloys, the influence of process parameters of mechanical surface treatments on the resulting distributions of strength and residual stresses has been investigated. A typical example is shown in Fig. 7 (Ref 8). The same shot size (S230) but different peening intensities and coverages were used for the treatment of AlZn4.5Mg1 (7020). As shown, the thickness of affected layers can be increased by increasing peening intensity as well as coverage.

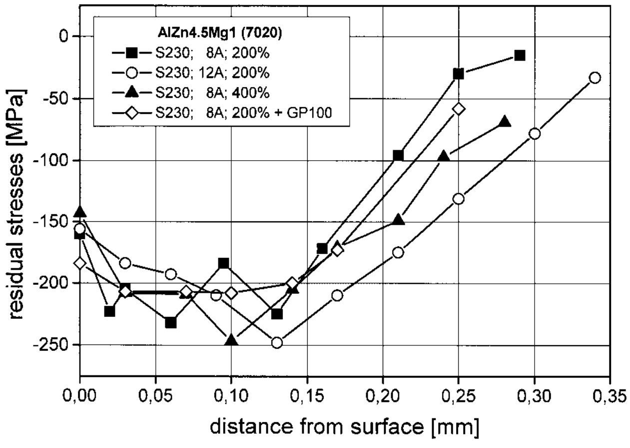
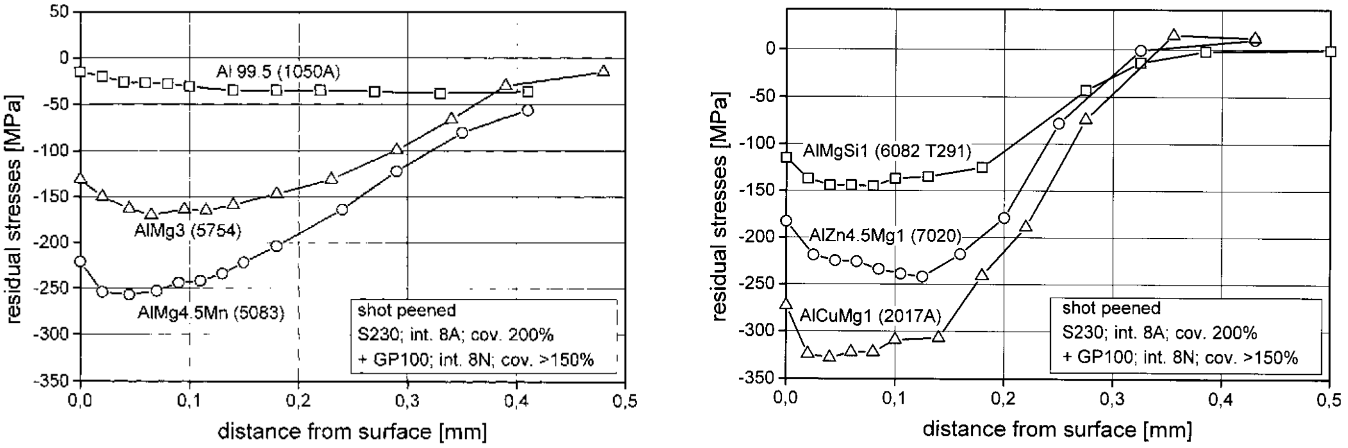
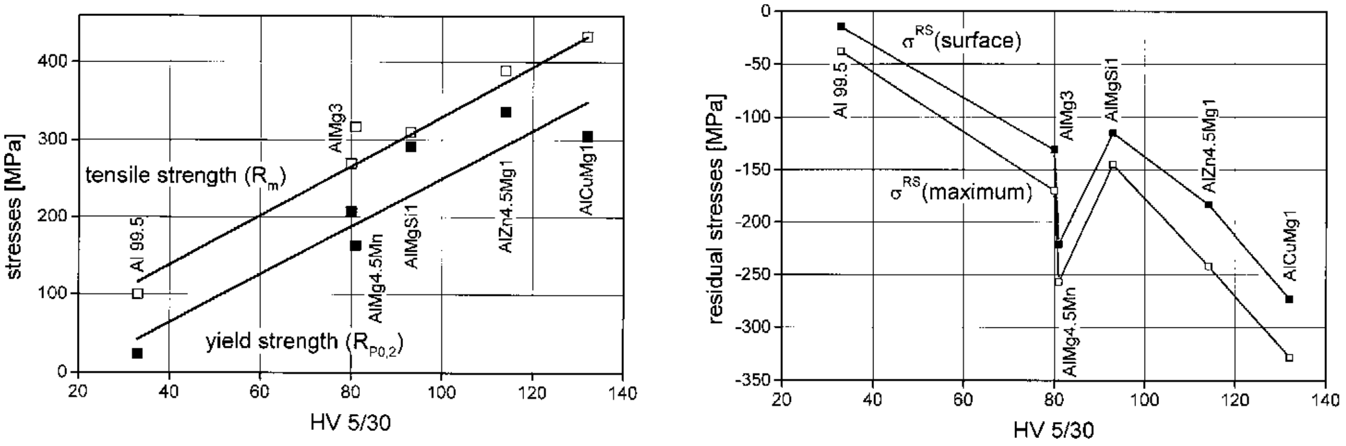


Fig. 7 Influence of shot-peening process parameters on resulting depth distributions of residual stresses



(a) (b)

Fig. 8 Depth distributions of residual stresses of (a) strain-hardenable and (b) age-hardenable aluminum alloys for the shot-peening treatment indicated



(a) (b)

Fig. 9 Correlations observed for the materials investigated between (a) hardness, yield strength, and tensile strength and (b) hardness and residual stresses

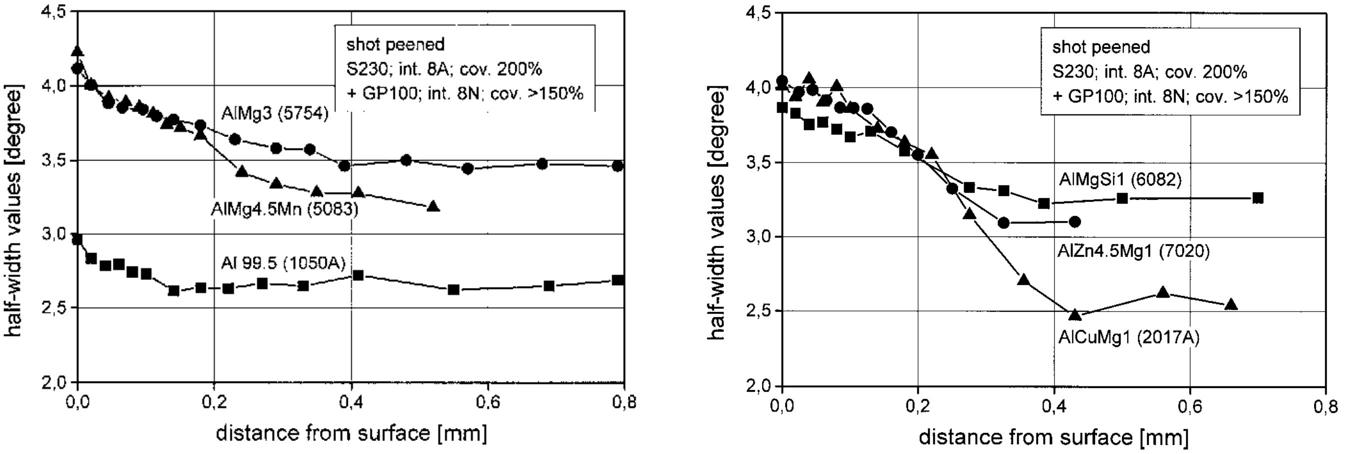


Fig. 10 Depth distributions of x-ray interference line half-width values of different aluminum-base alloys for the shot-peening treatment indicated

3. Influence of Material and Materials State on Near-Surface Properties

Of course, besides process and process parameters, the material treated and its microstructural state are important for the resulting properties of near-surface layers. For aluminum-base alloys, typical examples are shown in Fig. 8. Both strain-hardenable as well as age-hardenable alloys have been investigated.

Characteristic properties of the materials used are listed in Table 1. In all cases, the same shot-peening process indicated was applied. Clear differences between the measured depth distributions of residual stresses can be detected.

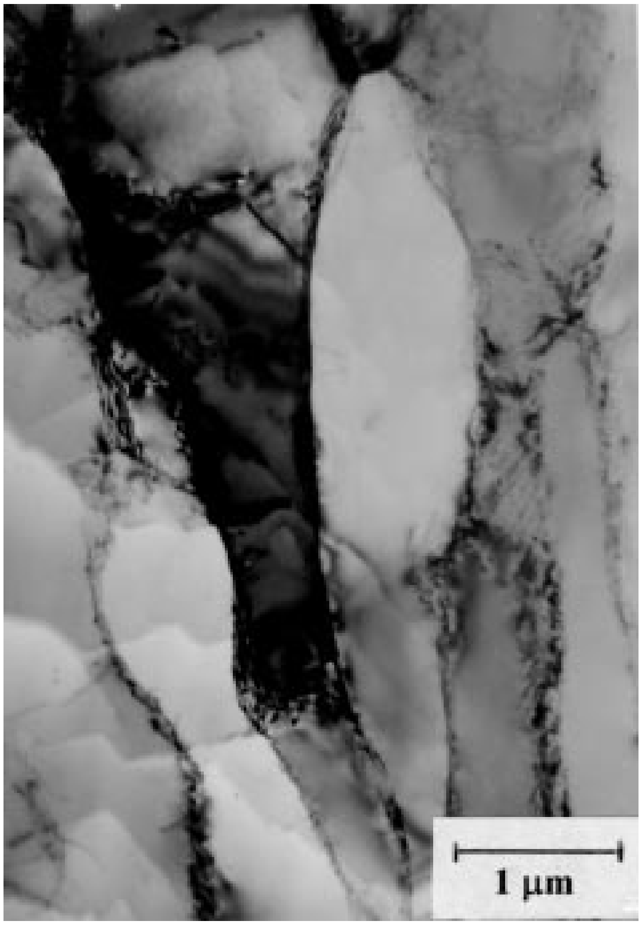


Fig. 11 Near surface (z = 0.12 mm) dislocation distribution in shot-peened AlMg1. Shot size S170, 54-58 HRC, p = 0.24 bar, coverage 98%

Except for Al 99.5 (1050A), residual stress maximums were observed below the surface, but amounts of compressive residual stresses were different for each material. A rough correlation between shot-peening induced residual stresses and materials strength exists, as shown in Fig. 9. The correlation between hardness and YS or tensile strength can be described by approximately parallel straight lines. As shown in Fig. 9(b), hardness also roughly correlates with shot-peening residual stresses at the surface and maximum values below the surface. A clear tendency exists that residual stress values increase with materials hardness. The fact that values for AlMg4.5Mn (5083) are somewhat lower and those for AlMgSi1 (6082) are somewhat higher than the general trend can be explained by the strain-hardening state of both materials. AlMg4.5Mn (5083) is recrystallized with a small YS-to-tensile-strength ratio whereas AlMgSi1 (6082) is highly plastically deformed.

Depth distributions of interference line half-width values, which are shown in Fig. 10, strongly depend on the state of materials treated. It is interesting to note that shot peening-induced changes of half-width values are, for example, in this case much more pronounced for AlCuMg1 (2017A) than for AlMgSi1 (6082). An explanation is that half-width values not only depend on density but also on distribution of dislocations produced during the shot-peening process.

Characteristic examples of near-surface dislocation structures after shot-peening operations are shown in Fig. 11 and 12. After shot peening of AlMg1 (5005A), a dislocation cell structure has developed near the surface (Fig. 11), whereas in the case of AlCuMg1 (2017A) in Fig. 12, a more or less random dislocation structure can be seen with dislocation bundles around the precipitations.

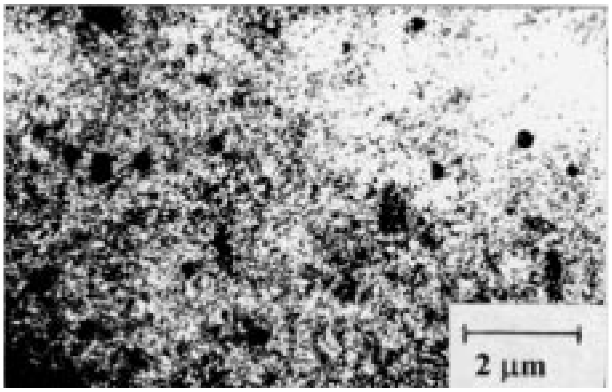


Fig. 12 Near surface (z = 0.05 mm) dislocation distribution in shot-peened AlCuMg1. Shot size S230, intensity 8A, coverage 200% + GP100, 8N, coverage >150%)

Table 1 Mechanical properties and conditions

Alloy	$R_{PO.2}$, MPa	R_m, MPa	Vickers hardness, HV 5	Elongation , %	Processing	Specification
Al 99.5 (1050A)	24	100	33	28	Cold rolled	≈F8
AlMg3 (5754)	207	270	80	14.5	Cold rolled	≈F24
AlMg4.5Mn (5083)	163	317	81	20.4	Recrystallized	W28
AlMgSi1 (6082)	291	310	93	8.5	Hot age-hardened	≈F30
AlZn4.5Mg1 (7020)	336	389	114	13.6	Hot age-hardened	F35
AlCuMg1 (2017A)	305	432	132	23.5	Cold age-hardened	≈F40

$R_{PO.2}$, yield strength; R_m, ultimate tensile strength

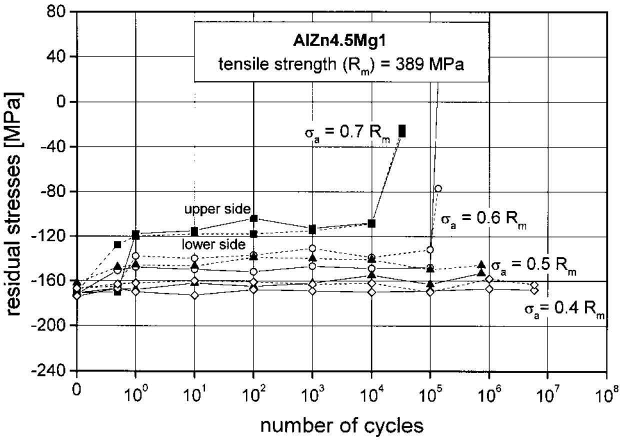


Fig. 13 Stress relaxation in bending fatigue tests of AlZn4.5Mg1

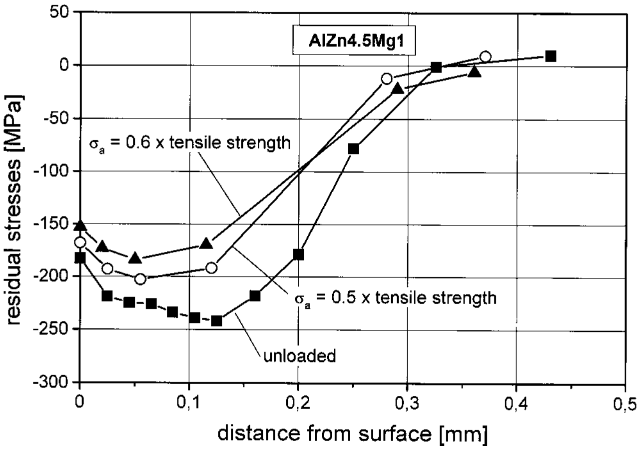


Fig. 15 Depth distribution of residual stresses after fatigue of AlZn4.5Mg1

4. Conclusions

- To assess the consequences of residual stress distributions introduced by mechanical surface treatments, knowledge about their stability during loading history is of importance. A typical example for residual stress relaxation in aluminum-base alloys during fatigue is shown in Fig. 13 for bending fatigue of AlZn4.5Mgl (7020). Relaxation of surface residual stresses is shown. The specimen side denoted "upper side" was always loaded in tension during the first quarter of the first loading cycle. For the stress amplitudes indicated, which are related to the ultimate tensile strength of the materials state investigated, the higher the stress amplitude applied was, the stronger the stress relaxation, as expected.
- A typical observation (made for shot-peened magnesium alloy AZ31 loaded in bending fatigue) is shown in Fig. 14. Here interpretation of results is difficult because of small residual stress amounts at the surface after shot peening. As shown, residual stress values remain almost stable for the loading amplitude indicated.

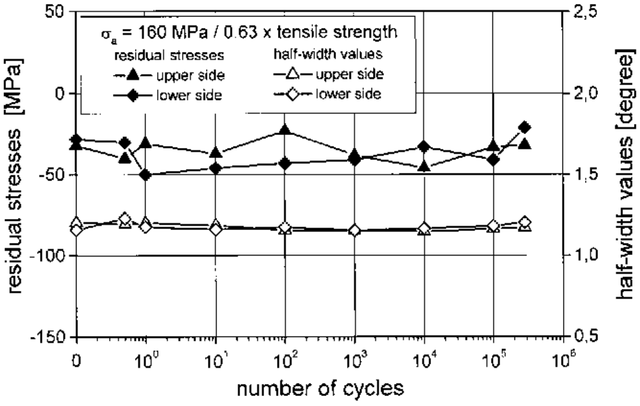


Fig. 14 Stress relaxation in a bending fatigue test of AZ31 at a stress amplitude of 160 MPa = 0.63 R_m (R_m, ultimate tensile strength)

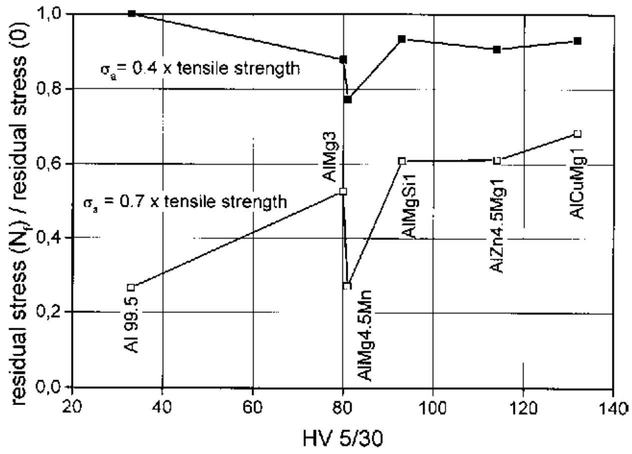


Fig. 16 Surface residual stress relaxation vs. Vickers hardness HV 5/30

- A characteristic observation for aluminum-base alloys is that stress relaxation is the most pronounced during the first loading cycle. Then, stress values remain almost constant or decrease only slightly. The relaxation behavior of residual stresses immediately at the surface can be quite different compared to the subsurface residual stresses. An example is shown in Fig. 15. As shown, stresses near the maximum relax somewhat faster than stresses at the surface.
- To a first approximation, surface residual-stress relaxation can be correlated to hardness or strength of the materials investigated (Fig.16). Stress values measured before fracture or for 10^7 loading cycles respectively are plotted as a function of hardness for different aluminum-base alloys investigated, cyclically loaded with the stress amplitude indicated. There exists a clear tendency that the higher the materials hardness is, the more stable the residual stresses.

References

1. W. Zinn, *Investigations about Bending Fatigue Strength of Butt-Welded Aluminum Alloys AlMg3 and AlMg4.5Mn,* 1990 (in German)
2. MIL-S-13165B

3. B. Scholtes, *Residual Stresses in Mechanically Surface Treated Materials,* DGM Informationsgesellschaft Verlag, Oberursel, 1990 (in German)
4. D. Radaj, *Fatigue Strength,* Springer-Verlag, Berlin and New York, 1995 (in German)
5. H. Zenner, Lebensdauerkonzepte, Beschreibung-Kritik-Entwicklungen, in *Fatigue Life Concepts, Description—Review—Developments,* DVM-Berichte 800, 1997 (in German)
6. P. Starker, H. Wohlfahrt, and E. Macherauch, Subsurface Crack Initiation during Fatigue as a Result of Residual Stresses, *Fatigue Eng. Mater. Struct.,* Vol 1, 1979, p 3-9
7. V. Hauk, *Structural and Residual Stress Analyses by Nondestructive Methods,* Elsevier, Amsterdam, 1997
8. W. Zinn and B. Scholtes, Generation and Stability of Shot Peening Residual Stresses in Different Aluminum Base Alloys, *Proc. of the Fourth European Conference on Residual Stresses,* S. Denis, J.-L. Lebrun, B. Bourniquel, M. Barral, and J.-F. Flavenot, Ed., Cluny, 1996