Effects of severe shot peening on the surface state of AW 7075 Al alloy

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Abstract

X-ray diffraction methods were used to study the surface layer properties of AW 7075 aluminium alloy before and after application of two different air blast shot peening treatments (similar Almen intensity and different coverage). Results have revealed important information about the strengthened surface layers. An increase of coverage does not result to any increase of the compressive residual stress field in the surface layer. However it plays the determining role in the process of the grain refinement by shot peening. After application of shot peening with 8.3 N/100 % parameters, the surface crystallite size decreased from an initial value of 80 nm to 60 nm. When 9.6 N/650 % parameters were applied, the crystallite size further decreased to a value of 51 nm. The relaxation process of the compressive residual stresses during the cyclic loading was observed; almost half of the residual stresses were lost, but the FWHM parameter, representing the crystallite size and dislocation density, remained more or less unchanged.

K e y   w o r d s: fatigue, severe shot peening, grain refinement, residual stress, X-ray diffraction

1. Introduction

It has been presented by many researchers [1–6] that shot peening and severe shot peening may improve the fatigue behaviour of a material – an increase of the fatigue strength and prolongation of the fatigue life. The fatigue strength increase after the application of conventional shot peening is caused by the compressive residual stresses (CRS) induced in the (sub)surface layers. When using severe shot peening, which differs from conventional shot peening by using unconventional high peening parameters (high intensities and coverage), the grain refinement of the treated surface layer should be also considered. It is proved that severe shot peening, when using optimized parameters, can provide even a higher improvement of the fatigue strength. However, it is still not clear, what part of the improvement is caused by introduction of higher and deeper compressive residual stresses and what part is caused by the surface layer with ultrafine or nano size grains. In order to separate these two effects, surface properties and the fatigue strength of two sets of specimens treated with similar Almen intensity and different coverage will be compared. In this paper, the surface residual stresses after cyclic loading will be measured by X-ray diffraction method and the full width at half maximum of the diffraction peak (FWHM) values will be estimated, which can be considered as a measure of the dislocation density.

2. Material and surface treatments

Specimens from AW 7075 – T6511 commercial aluminium alloy [7] used in this study were machined from extruded bars with a diameter of 15 mm. The

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Table 1. Aspects of surface treatment of fatigue test specimens

Label	Shot type	Almen intensity (0.001 inch)	Coverage (%)	Roughness Ra (μm)	Roughness Rz (μm)
NP	–	–	–	0.125	0.913
SP1	CEZ 100	8.3 N	100	2.614	14.304
SP2	CEZ 100	9.6 N	650	3.493	20.767

tensile properties were obtained at room temperature at a strain rate of $8.3 \times 10^{-4}\,\mathrm{s}^{-1}$ using specimens with a gauge length of 40 mm and a diameter of 5 mm. A high ultimate tensile strength (631 MPa) and low ductility (4.9 %) of the specimens may be attributed to the precipitation strengthening and significant strain hardening by the extrusion process.

Three specimens were treated with conventional shot peening (SP1), three with severe shot peening (SP2) and another three specimens were mechanically polished with metallography diamond emulsions (NP) for providing comparison measurements. The surface treatment parameters are listed in Table 1 together with the resulting surface roughness.

3. Results and discussion

The residual stress distribution was measured by an AST X-stress 3000 X-ray diffractometer (with measurement parameters: Cr Kα radiation, irradiated area of 2 mm^2, evaluated by $\sin^2\psi$ method from 11 measurements and ψ angles were scanned between $-45°$ and $45°$). The peaks of {311} lattice plane were measured at a 2θ value of 139.3°. To obtain the in-depth profile of the residual stress, surface layers were removed step by step by electrochemical polishing.

Figure 1a shows the compressive residual stress distribution in AW 7075 specimens without SP treatment (polished specimens) and after two SP treatments with different coverage parameters. It can be seen that increasing the peening coverage from 100 to 650 % did not cause any increase of the residual stress field and its only effect was shifting the residual stress field deeper under the original surface. The area under the curves, which represents the stored energy in the material, is almost identical. This was expected because the Almen intensity is evaluated in the saturation point and in this case the increase of the Almen intensity was very low; in fact it is in the tolerance range of both SP treatments.

During the residual stress measurement the FWHM parameter was also obtained. It is sensitive to various microstructure properties as crystallite size (coherently diffracting areas), not-oriented micro-stress and mainly the dislocation density. A part of the FWHM signal is also related to the instrument in use, however, results obtained on one instrument are
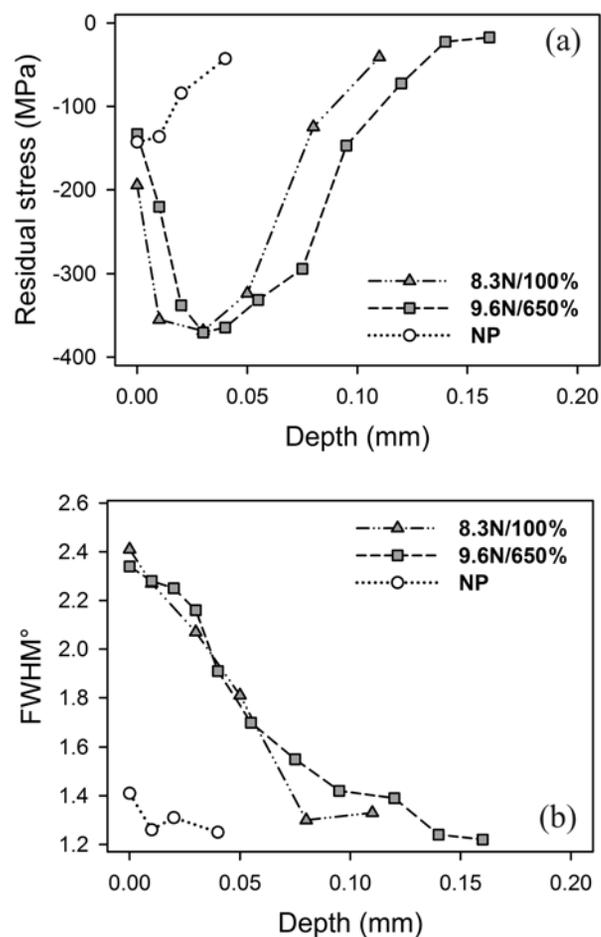

Fig. 1. Residual stress (a) and FWHM (b) profile of not peened and shot peened specimens, AW 7075 aluminium alloy.

comparable. Comparing the FWHM profiles of specimens after two SP treatments (Fig. 1b) reveals that they are almost identical and no differences in the values or position of the curves are present. This indicates that residual stress fields were created approximately by the same dislocation density, which was highest on the surface (Fig. 1b) and then continuously decreased deeper under the material surface. However, when comparing the character of the FWHM profile (Fig. 1a), the highest dislocation density on the surface resulted in a very low value of the compressive residual stresses. This means that the dislocations near

the surface have to be arranged in a substructure with a lower energy.

According to work of Lu and Lu [8], multiple repeating of severe plastic deformation results in arrangement of dislocations to dislocation cells, dislocation tangles and later into the formation of grain and sub-grain boundaries. The highest residual stress is caused by interaction among dislocations in dislocation cells and tangles. When the dislocation structure evolves into creation of grain and sub-grain boundaries the energy of the structure decreases. X'Pert PRO diffractometer (Co radiation, diffraction angles 2θ from $40°$ to $165°$, parallel plate collimator) was used for XRD crystallite size measurements on the specimen's surface. The crystallite size was evaluated using the Rietveld method – the diffraction pattern is compared to a microstructure model, in which the crystallite size is one of the parameters [9]. A crystallite is a main size of coherently diffracting domains in crystals. Therefore, grains may contain several domains separated by a small angle misorientation and these can be considered as the sub-grain boundaries. The crystallite size analysis showed that after the SP applications the crystallite size decreased from 80 nm for NP specimen to 60 nm for 8.3 N/100 % treatment and to 51 nm for 9.6 N/650 % peening parameters, respectively (Fig. 2a). This indicates that the dislocations in the surface layer (penetration of the X-ray beam to measured material is about 20 μm) were aligned to a low energy substructure providing material grain refinement.

One could expect that similar compressive residual stress fields will provide a similar increase in the fatigue strength. However, the results of tension – compression fatigue tests (ultrasonic loading frequency $f \approx$ 20 kHz, load ratio $R = -1$, temperature $T = 20 \pm 5\,°C$) performed at two stress levels show that the specimen after SP2 (9.6 N/650 % parameters) exhibited a higher fatigue strength increase than after SP1 (8.3 N/100 % parameters) as shown in Fig. 2b. This further increase can be contributed to further grain refinement of the surface layer, because superior mechanical properties of this layer were proven in many recent studies [8, 10–13].

It is interesting to note that in comparison with the compressive residual stress measurements before fatigue test, a significant decrease in the compressive residual stresses of the SP2 specimen (9.6 N/100 % parameters) was observed after $N = 10^9$ loading cycles without fracture (Fig. 3a). On the contrary, the FWHM parameter seems to be much more stable with respect to cyclic loading and only a small decrease in the parameter can be observed (Fig. 3b). This reveals a question: why such a significant decrease of the compressive residual stresses is accompanied with just a small decrease of the dislocation density.

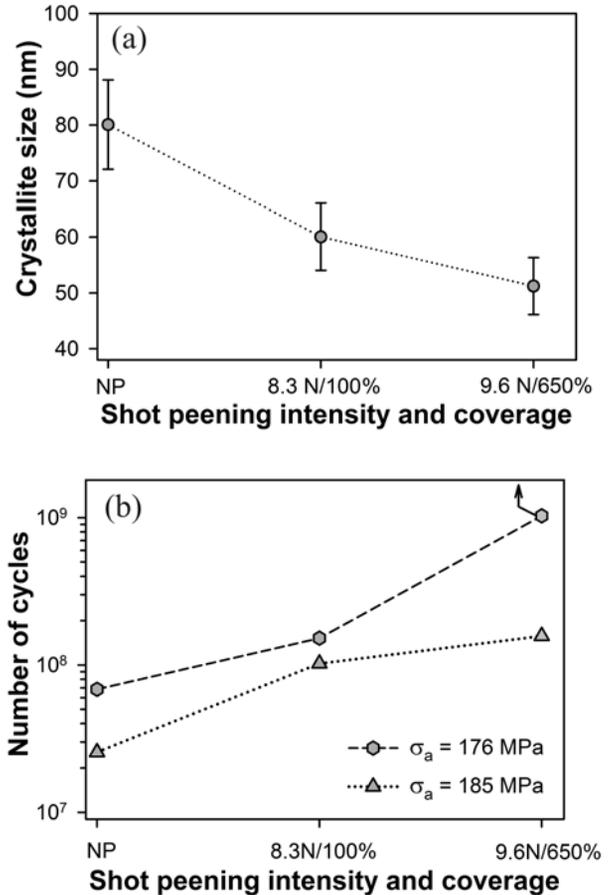A good explanation of the observed behaviour is

Fig. 2. Dependence of crystallite size (a) and fatigue life (b) on shot peening parameters, AW 7075 aluminium alloy.

by connecting it with the process of dislocation evolution to various sub-structures (cells, tangles and sub-grains). The dependence of the dislocation density ρ on plastic deformation ε can be described according to [13] as:

$$\mathrm{d}\rho/\mathrm{d}\varepsilon = K_1 + K_2\rho^{1/2} - K_3\rho - K_4\rho^{3/2}, \qquad (1)$$

where K_1 characterizes the influence of non-dislocation obstacles, K_2 is the coefficient of the interaction among dislocations, K_3 and K_4 are coefficients of dislocation recovery due to the cross slip and dislocation climb, respectively.

When dislocations create new sub-grain boundaries, a large part of plastic deformation is reflected in the K_1 coefficient. The presence of the compressive residual stresses is mainly caused by the interaction among dislocations (for example anchoring of dislocations in dislocation tangles), represented by the K_2 coefficient. During cyclic loading, the external load causes not only dislocation slip but also cross slip and climbing of dislocations, and many of them may anni-
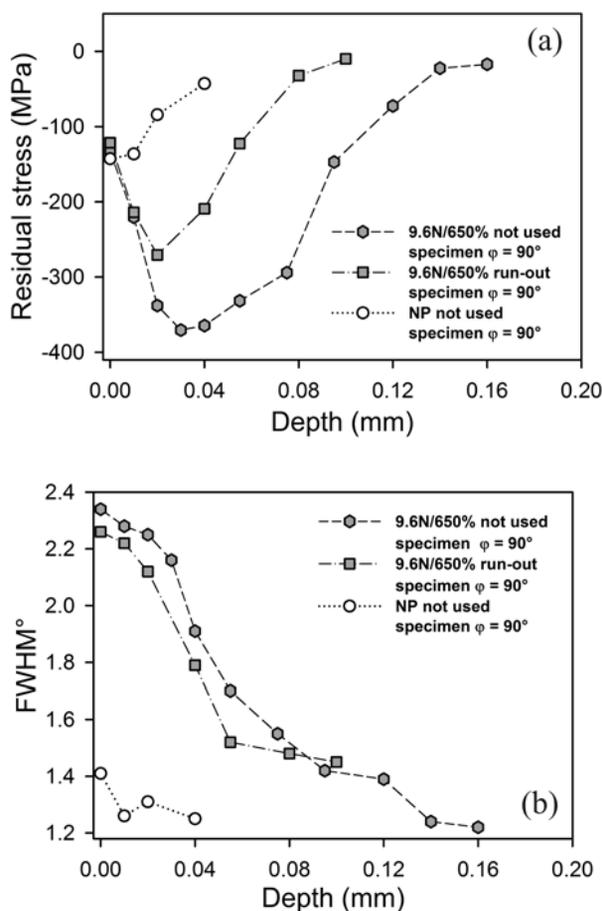
Fig. 3. Comparison of residual stress (a) and FWHM (b) profile before and after a fatigue test with a run-out result ($\sigma_\mathrm{a} = 176$ MPa, $N = 10^9$ cycles).

hilate. This causes a decrease in the dislocation density (K_2 decreases and the third and fourth terms in Eq. (1) cause a decrease in ρ). So, in general, the cyclic loading causes a decrease of the dislocation density at the specimen surface and, consequently, of the values of residual stress. However, the deformation "stored" by the grain refinement is kept constant. Because FWHM parameter reflects crystallite size together with the dislocation density, its decrease reflects only a decrease in dislocations which were not aligned in grain and sub-grain boundaries.

4. Conclusion

Increasing shot peening coverage does not create higher compressive residual stresses, but provides further grain refinement of the surface layer. Even when similar fatigue improvement can be expected due to the identical residual stress profiles of specimens treated with 8.3 N/100 % and 9.6 N/650 % shot peening parameters, or even lower fatigue strength

of 9.6 N/650 % specimens due to the surface roughness increase, the fatigue strength improvement of 9.6 N/650 % is significantly higher. The only difference in the surface character of the specimens after different shot peening treatments was smaller surface crystallite size after treatment with higher coverage. This means that not all benefit of shot peening to the fatigue strength can be credited to the compressive residual stresses created by the treatment. This is also supported by the fact that fatigue loading causes significant residual stress relaxation; however, the relaxation is accompanied with just minor changes in the FWHM parameter. Dislocations arranged in sub-grain boundaries are not so influenced by the mechanical deformation during the fatigue loading and they present a constant fraction of the FWHM value.

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