Application of shot peening to enhance precipitation hardening effect in aluminium alloys

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Introduction

Positive effect of the severe shot peening (SSP) on the fatigue properties of Aluminum alloys, especially in the very high cycle fatigue region was proved in many studies [1-4]. Improvement of the fatigue properties is achieved by a combination of several factors, however the most significant can be considered to be surface hardening due to the severe plastic deformation. The mechanism which causes the hardening of the material is accumulation of lattice defects by the intensive plastic deformation. Besides the material strength, also other material properties are affected by the number of lattice defects and in case of aluminum alloys, lattice defects play important role in formation of precipitates during age-hardening, thus this arises a question, if the SSP can be used to induce pre-aging plastic deformation to enhance precipitation of strengthening phases.

Al-Cu-Li alloys offer very high mechanical strength while maintaining sufficient ductility. These properties are achieved by the applied age-hardening heat treatment – during which strengthening precipitates are formed in aluminum matrix. The main strengthening phase in advanced Al-Cu-Li alloys is T_1 (Al_2CuLi), whose particles preferentially heterogeneously nucleate on the dislocations. Therefore, to obtain optimal combination of mechanical properties, T8 class heat treatment (plastic deformation applied between solution annealing and aging) is often employed. However, such treatment is hard to apply in case of e. g. welded structures.

In the past, few studies were performed focused on the possibility of precipitation enhancement by the pre-aging severe plastic deformation [5-7]. Increase in the dislocation density resulted in precipitation of denser populated finer particles. Besides that, as a result of dislocation interactions, vacancies are emitted enhancing diffusion rate, thus affecting kinetics of precipitation processes [5,8,9]. On the other hand, excessive severe plastic deformation results in the formation large number of high-angle grain boundaries, which can act as a sink for the solutes and decrease supersaturation of the solid solution [8]. Despite unambiguous precipitation enhancement due to the pre-aging plastic deformation, resulting effects on the mechanical, and especially fatigue properties are questionable. Only a few studies were focused on the fatigue performance of Aluminum alloys with pre-aging severe plastic deformation applied [5]. Application of such surface treatment enhanced precipitation in the affected region, on the other hand, it creates significant surface roughness and can cause creation of various discontinuities on the surface and in subsurface layers. Another aspect is residual stress distribution. In many severe plastic deformation techniques, the residual stresses are the key factor responsible for the improvement of the high cycle fatigue performance. When the pre-aging plastic deformation is applied, the following aging treatment can partially or even fully relieve residual stresses. Increased surface roughness together with relieving of introduced residual stresses can easily outbalance positive effects on enhanced precipitation. This underlines necessity for the careful choice of the pre-aging severe shot peening parameters, to balance plastic deformation intensity and level of surface damage.

In the present study, severe shot peening was applied as a pre-treatment before aging to promote precipitation of the heterogeneously nucleating precipitates. Four series of samples were prepared per Fig. 1. Two different heat treatments were chosen – low and high-temperature regimes. For both heat treatment types, two sample series were prepared. In the first series, the SSP was applied after solution annealing and before aging step. In the second (control) series, the SSP was applied after completed age-hardening. In the low-temperature regime, the strengthening is mostly governed by copper-rich precipitates as GP zones and Θ''. These precipitates are formed homogeneously and therefore their precipitation does not depend on the local dislocation density. On the other hand, the high-temperature heat treatment regime promotes precipitation of T_1 precipitates which are predominantly nucleated on the dislocations [10,11]. High dislocation density formed during SSP treatment can promote precipitation of the denser population of finer precipitates in the affected surface zone. The fatigue properties of all four series in the high cycle region were then examined, to evaluate if application of the SSP before aging can improve fatigue properties. The results were then discussed in the light of the microstructural characterization of the subsurface affected layers and the evaluation of the residual stresses state.

Material and Experimental methods

In the present study, commercially available AA 2055 alloy was used as experimental material. The alloy was delivered in the form of extruded bars with a diameter of Ø 66 mm. In total, four series of specimens were machined and subjected to the severe shot peening process. In two series, SSP treatment was applied after solution annealing and before aging (one of the specimen series was subjected to low-temperature heat treatment and the second one to the high-temperature heat treatment). In the other two series, the SSP treatment was applied after finished heat treatment (again, one series subjected to the low-temperature heat treatment and the other one subjected to the high-temperature heat treatment). SSP treatment of Almen intensity 8.9N and coverage of 650% was applied in all cases. The SSP parameters were chosen based on our previous studies [1,2], with the aim to induce intensive plastic deformation of the surface layer, while the surface damage (cracks and other discontinuities) was kept as low as possible.

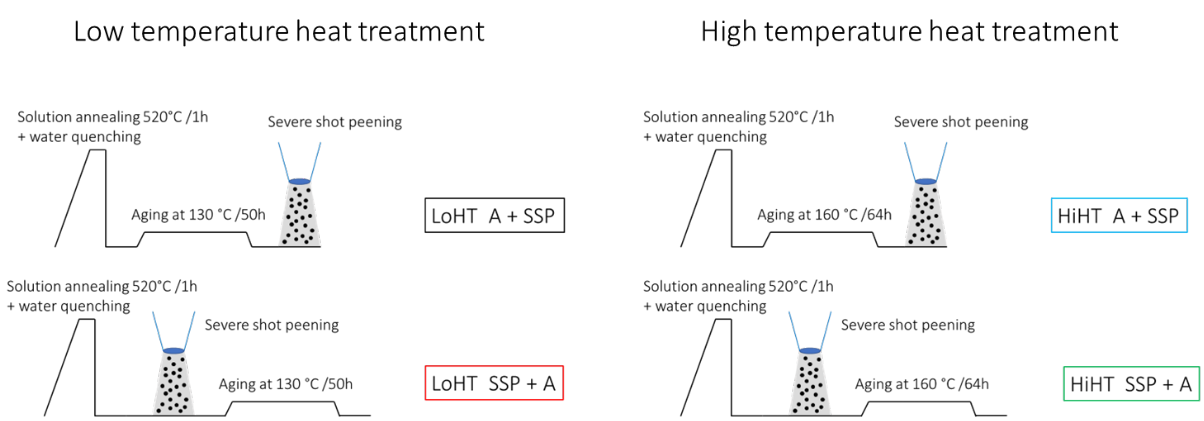

Figure 1. Schematic view of the tested sample series. Four different series were tested, differing in the aging temperature and the application of the shot peening process before/after aging treatment.

Heat treatments were carried out with parameters as follows:

Low temperature (LoHT) - solution annealing at 520°C for 1 hour followed by water quenching, aging at 130°C for 50h.

High-temperature heat treatment (HiHT) - solution annealing at 520°C for 1 hour followed by water quenching, aging at 160°C for 64h.

Residual stress depth profiles were examined using X-ray diffraction. Proto iXRD diffractometer equipped with Cr X-ray source was used and measurements were performed using $\sin^2\psi$ method, with 6 inclinations between ± 40°. Diffraction peaks from {222} planes were collected at 156.9°. In order to reveal residual stress levels at different depths, electrolytic polishing was used for gradual removal of the thin surface layer. Due to the strong crystallographic texture of the base material, the residual stress levels could be measured only in the very thin, heavily deformed layer where the texture was suppressed by the deformation process.

To describe microstructures in subsurface region, lamellas were prepared from all four specimens' series with use of focused ion beam technique (FIB). Approximate dimensions the lamellas were 25×15 μm, and they were oriented in a way, that they were showing microstructural changes from the surface to 25 μm depth below the surface. Microstructure was then observed using Thermofisher Talos F200i transmission electron microscope.

Fatigue tests were carried out on MTS Acumen electrodynamic test system with linear motor. Tests were performed under stress control regime, with fully reversible loading cycle (R = -1). Testing frequency was 30 Hz, and tests were terminated if there was no failure in 10^7 loading cycles.

Results and Discussion

Application of SSP significantly modified microstructure in the near-surface region. All tested series were examined in terms of microstructure evaluation, however only HiHT series are included because of the range limitation. Observation of the LoHT series did not reveal any significant differences neither in the affected zone morphology and the precipitating phase size and distribution. Microstructures of the surface and subsurface regions of both HiHT series are shown in Fig.2. Application of the shot peening on the series after aging (HiHT A+SSP) form heavily refined nanocrystalline zone (zone 1) in depth of 2-3 μm. There were no intragranular precipitates in this zone, what can be explained by the mechanical dissolution due to the strong dislocation activity and the solute segregation on the grain boundaries. Deeper in the material, partially grain refined zone was resolved, with the T_1 particles present. Bended shape of the particles suggests multiple shearing events; however, size of the particles was not affected. The third zone with increased dislocation density but without introduced new grain/subgrain boundaries was present deeper in the structure. There was no sharp interface but rather a continuous transition. In the third zone, average size of the T_1 particles of 122.4 ± 39.4 nm was measured.

Comparison with microstructure of HiHT SSP+A series revealed significant differences. Again, three zones were revealed, however, especially in zone 3, much higher dislocation density appeared. This can be attributed to the absence of strengthening precipitates in initial state (before SSP application), allowing easier dislocation slip within grains. Subsequent aging results in formation of very fine T_1 particles. Particles measurement in the same distance from surface as in the case of HiHT A+SSP series revealed average size of 37.1 ±10.2 nm. Introducing of SSP process before aging thus promotes nucleation of the precipitates resulting in formation of very fine and disperse strengthening particles.

Residual stress distribution in the surface layer of all examined states is shown on Fig. 3. Additional measurement was performed on the sample after solution annealing and SSP, without any following aging treatment. This allowed monitoring of possible relaxation during applied heat treatment. In all examined series, application of SSP process resulted in formation of the compressive residual stresses in the subsurface region. Fig. 3a shows residual stress depth profiles measured on LoHT series. There is no significant difference between LoHT SSP+A, LoHT A+SSP and reference Solution annealed + SSP series. Based on which it can be concluded, that during application of LoHT (series LoHT SSP+A), no significant relaxation occurred. Different behavior was recorded for the HiHT series. In case of the HiHT A+SSP, the maximal residual stress value is similar like in the reference state (solution annealed + SSP) but the affected zone is shallow. It is most likely due to much higher initial hardness of the HiHT A+SSP series. Residual stress profile of the HiHT SSP+A series shows a significant drop compared with the reference ones. It is expected that aging temperature of 160°C is sufficient for partial relaxation of induced residual stresses.

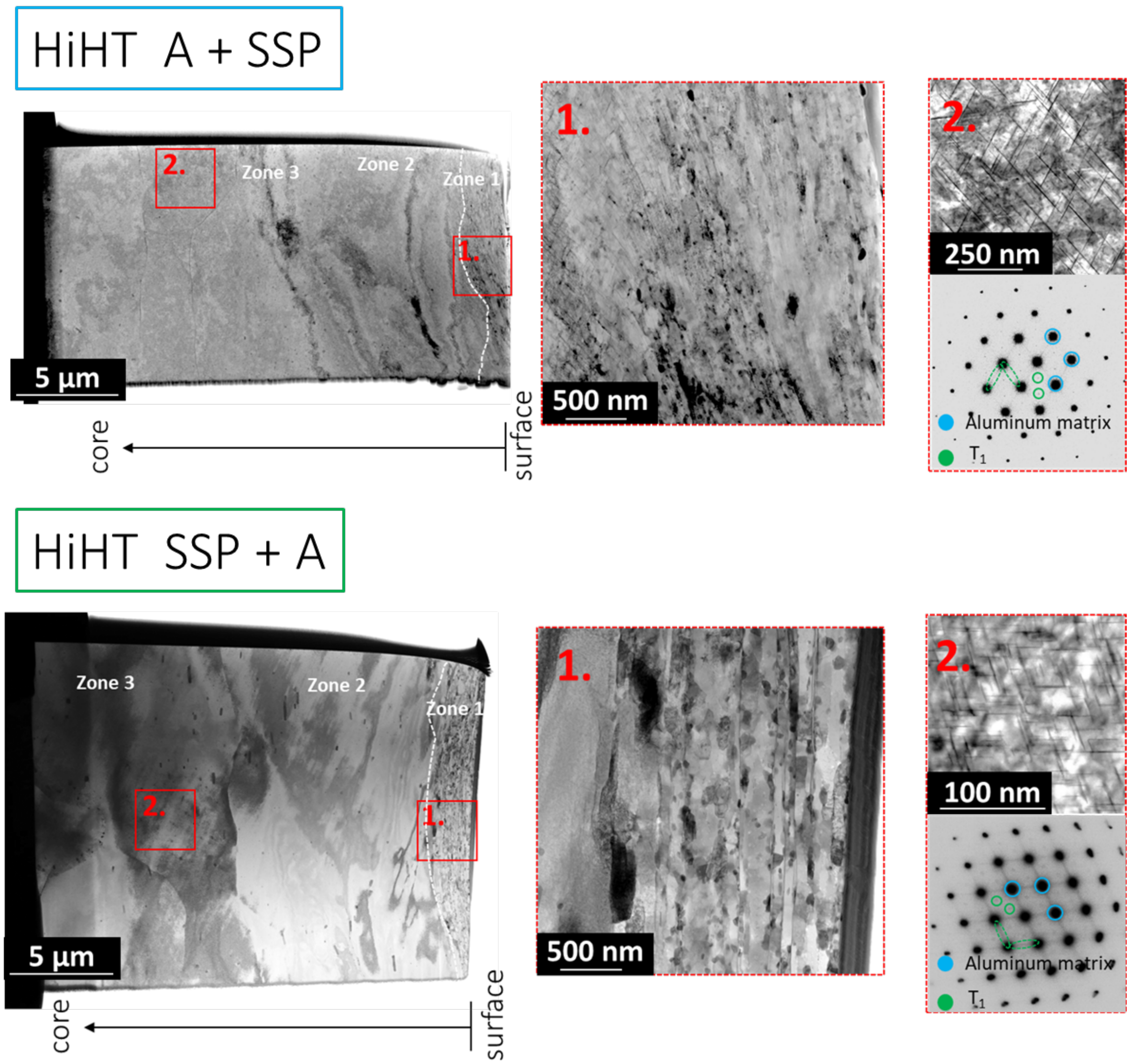

Figure 2. Microstructure of HiHT series (BF-STEM). Images showing overall view on the surface and subsurface region. Images (1) show detailed view on the nanocrystalline layer. Detailed images (2) show T1 plate-like precipitates with corresponding SAED patterns (ZA<110>).

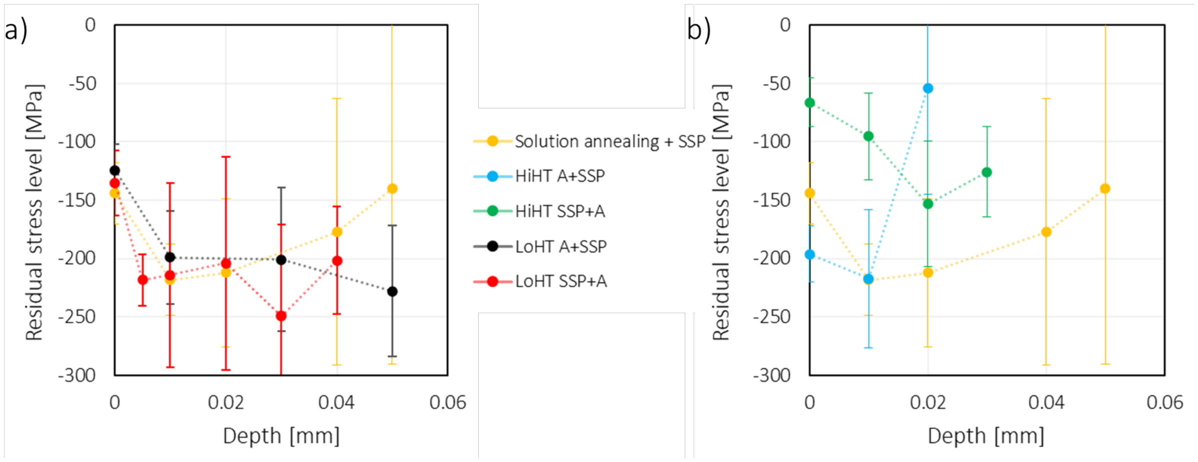

Figure 3. Residual stress depth profiles of all examined series. Compressive residual stresses in the subsurface region induced by SSP process were recorded in all series.

Results of the fatigue tests are shown in Fig. 4. Both series of LoHT exhibited similar behavior at the short and medium fatigue lifetimes. However, at longer fatigue lifetimes, series with SSP process conventionally applied after completed age-hardening show superior fatigue properties than series with the SSP applied before aging. Based on this, it can be stated, that in case of LoHT, there is no beneficial effect of application of severe plastic deformation before aging treatment. Different behavior was recorded for HiHT series. In this case, series with SSP applied before aging shows superior fatigue properties at short and medium fatigue lifetimes. At long fatigue lifetimes, the differences between both HiHT series are diminished. Application of SSP before aging in case of HiHT is therefore beneficial at least in certain regions of the fatigue lifetimes.

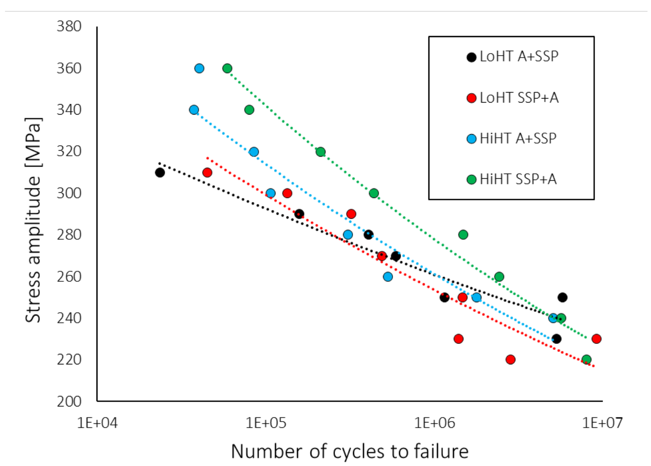

Figure 4. Results of the fatigue test in form of S-N curves. There can be seen, while in case of LoHT, no beneficial effect of introducing SSP process before aging is visible, for the HiHT series

Microstructural observations did not reveal any notable differences between two series after LoHT. Similarly, residual stress depth profiles of both states were comparable. Possible explanation of the worse fatigue properties of LoHT SSP+A series could be the lower initial hardness, which typically result in the higher surface roughness. Such measurements, however, were not included in the study and at this point, the statement cannot be confirmed.

In case of the HiHT series were recorded major microstructural differences. The high dislocation density induced by SSP process result in the precipitation of the very fine T_1 particles in HiHT SSP+A series. Average size of the particles was 37.1 ±10.2 nm at distance of 15 µm from the surface. In the same area, the average size of T_1 particles in HiHT A+SSP series was 122.4 ± 39.4 nm. Significant refinement of the strengthening particles could be beneficial in terms of the strength of particular zones. Another important aspect affecting the fatigue properties is the residual stress distribution. Compressive residual stresses suppress crack initiation and have positive effect especially in the area of long fatigue lifetimes. Partial residual stress relaxation in the HiHT SSP+A series could outbalance the positive effect of the refined T_1 particles, explain equalizing properties of HiHT SSP+A and HiHT A+SSP series at long fatigue lifetimes.

Conclusions

Application of the severe shot peening process as a pre-treatment before aging can be beneficial for the fatigue properties, when optimal combination of the shot peening process parameters and the aging conditions are chosen. Application of SSP before aging results in formation of the finer and denser population of T_1 strengthening particles, in case of high-temperature heat treatment regime. In contrary, no beneficial effect regarding particle distribution was recorded in case of low-temperature heat treatment.

Series of specimens with SSP process applied before aging show superior fatigue resistance in short and medium fatigue lifetimes, compared to the series with shot peening conventionally applied after finished age-hardening. At long fatigue lifetimes, superiority of shot peened + aged samples diminished, and both series exhibited similar properties.

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