THE EFFECT OF SURFACE RECRYSTALLIZED LAYERS ON PROPERTIES OF EXTRUSIONS AND FORGINGS FROM HIGH STRENGTH ALUMINIUM ALLOYS

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Abstract

Inhomogeneous deformation process occurring during the production of extrusions and forgings results in an inhomogeneous microstructure as well as in remarkable differences in mechanical, fatigue and corrosion properties. This effect can be of great importance especially in loaded constructions made from age-hardenable aluminium alloys. Inhomogeneous deformation together with the forming temperature and the following heat treatment causes very often the occurrence of coarse recrystallized areas. Thus, the areas with a marked structural boundary and a slump of properties are formed in the material volume. The coarse recrystallized areas occur mostly in surface layers that are strongly influenced by the contact with the tool during the deformation process. The present paper deals with the properties of these layers in extrusions and die forgings made from high strength age-hardenable aluminium alloys that are used in aircraft and automobile industry. It was found that the decrease of mechanical properties can reach up to 25 % in the surface layers as compared with the unrecrystallized rest of material. In the case of fatigue properties, the influence of the surface conditions is quite fundamental and the recrystallized structure can decrease the high cycle fatigue lifetime more than by one order.

Key words: age-hardenable aluminium alloys, coarse recrystallized layers, extrusions, forgings, mechanical and fatigue properties

1. INTRODUCTION

Mechanical as well as fatigue properties of products made of age-hardenable Al alloys are influenced by several factors connected with the technology of forming and heat treatment. An inhomogeneous microstructure arising from the inhomogeneous material flow and depending on the heat treatment and forming conditions, leads to the inhomogeneities in restoration and precipitation hardening processes. It results in different level of material softening (recovery, recrystallization), inhomogeneous texture and, last but not at least, in inhomogeneous and anisotropic properties. In the case of inhomogeneous restoration, specific structure defects – coarse recrystallized areas – occur. These coarse recrystallized areas are commonly present in extrusions and forgings of age hardenable Al alloys; in the forgings forged from extrusions, their occurrence is influenced by the structure resulting from the extrusion conditions. Recrystallized areas are mostly observed in the surface layers that are in direct touch with the dies and/or in regions where local changes of plastic deformation take place (e.g. flash area in the die forgings). Typical coarse recrystallized structures in extrusions and die forgings are shown in Fig. 1.1 and 1.2. Recrystallized layers and areas in extrusions and forgings are formed either during the hot deformation and immediately after it, or in the course of final heat treatment. Their negative effect consists in the fact that the boundary between two different structures possessing remarkably different mechanical, fatigue and corrosion properties, is formed. The susceptibility to the formation of those structures depends on forming- and heat treatment parameters and on the alloy type as well. Some of alloys are very susceptible to this. Extrusions
and forgings from some alloys are completely recrystallized after heat treatment and do not contain the boundaries between recrystallized and unrecrystallized structure. Complete recrystallization in the whole material volume causes so called "loss of extrusion effect" [1] which is connected with a decrease of mechanical properties. The causes of the formation and development of surface recrystallized layers have been intensively studied and some theoretical models have been proposed [2, 3]. The present work deals with the recrystallized surface layers in extrusions and die forgings and with their effect on mechanical and fatigue properties.

2. EXPERIMENTAL DETAILS

The assessment of the effect of recrystallized surface layers is not easy owing to the fact that they occupy small volume of material at the surface and they are non-uniform distributed. It is practically impossible to place the test pieces into the products to obtain quantitative information on this effect. In the case of forgings, their effect can be described only by hardness measurements. The situation of extrusions is more favourable as the proper choice of extrusion shape and of extrusion- and heat treatment parameters can assure the growth of recrystallized layers through the whole material volume and, thus, it is possible to obtain the test pieces with fully recrystallized structure.

This work contains the results of investigation of surface recrystallized layers in the forgings of 6082 alloy for automobile industry and two model extrusions of 2124 alloy used in aircraft industry. The examined forging and model Profile 1 and Profile 2 are shown in Fig. 2.1 and 2.2; chemical composition of the alloys is given in Table 2.1. The extrusions were directly extruded with extrusion ratio of \( \lambda = 28 \) from billets 187 mm in diameter. The extrusions were solution treated at 495°C, 2-3% straightened and naturally aged. The extrusions were prepared both with the unrecrystallized structure and with the structure fully recrystallized in the flat parts of profiles. Specimens having unrecrystallized structure were heat treated under common operational conditions to T351 temper. To obtain the fully recrystallized structure in flat parts of model profiles, a lower extrusion temperature and longer solution annealing time were chosen. This heat treatment was carried out under laboratory conditions without the plastic deformation before natural ageing. That is why the state was indicated as T4 temper. The forgings were forged from extruded rod of 43 mm diameter received in as-fabricated F temper. In the case of 6082-T6 alloy, the following heat treatment was applied: solution annealing at 525 °C and artificial ageing 170 °C/6 h.

![Fig. 1.1 Coarse recrystallized grains at the surface, extrusion from 2024-T351 alloy](image1)

![Fig. 1.2 Coarse recrystallized grains aligned in the flash, die forging, 6082-T6 alloy](image2)
Fig. 2.1 Die forging from the 6082 alloy used in experiments

Fig. 2.2 Model profiles used for experimental extrusion of the 2124 alloy

Table 2.1 Chemical composition of experimental alloys [wt.%]

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Cu</th>
<th>Mg</th>
<th>Mn</th>
<th>Si</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>2124</td>
<td>4.02</td>
<td>1.36</td>
<td>0.71</td>
<td>0.19</td>
<td>0.21</td>
</tr>
<tr>
<td>6082</td>
<td>0.07</td>
<td>0.98</td>
<td>0.78</td>
<td>1.01</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Tensile tests were performed on the specimens with 6 mm gauge diameter and 40 mm gauge length; to investigate the mechanical properties in the transversal direction, the tests were performed on specimens with short 10 mm gauge length, without the possibility to determine ductility and $R_{p0.2}$ limit. Flat fatigue test specimens with stress concentration factor $K_t = 1.1$ were prepared from Profile 1. All fatigue tests were performed at stress ratio $R = 0$ with a frequency of 80 Hz. Only one stress level, $\sigma_{\text{max}} = 330$ MPa was used. At least 6 specimens were tested at this stress level. Test specimens were sampled parallel to the extrusion direction both in the circular and flat part of the cross section. Fatigue behaviour was characterized by number of cycles to fracture occurring with probability of $P = 50\%$.

3. RESULTS AND DISKUSSION

The structures of 6082 alloy forgings after heat treatment to T6 temper are shown in Fig. 3.1 – 3.4. Fig. 3.1 and 3.2 show the structures after upsetting. The surface recrystallized layers originate in the area under the flat dies and have substantially lower hardness. A distinct boundary between the recrystallized and unrecrystallized structure is shown quite well in Fig. 3.2. It was found that the recrystallized areas in the forging of 6082-T6 alloy have lower hardness by 15 units (Fig. 3.1). The effect of fluctuation of the production technology parameters on the extent of surface recrystallized layers and, consequently, on mechanical properties is given in Fig. 3.3 and 3.4. Recrystallized areas in the forgings are of very irregular shape and their range depends on the forging way and the heat treatment parameters. As the effect of surface recrystallized layers on strength and fatigue properties of die forgings is difficult to describe quantitatively, special attention has been paid to the extrusions.
The advantage of extrusion, regarding from the point of view of the effect of recrystallized structure on properties, is its constant cross section. It enables to choose an appropriate type of the profile, in which the placement and sampling of test specimens in previously determined place of the cross section, is possible. Further substantial advantage in comparison to forgings is the constant deformation along the profile and a relatively easy setting-up parameters of extrusion and heat treatment assuring the required type of structure. It follows from the experimental programme that the production parameters were chosen to obtain both the recrystallized and unrecrystallized structure in the central part of the Profile 1 and in the peripheral parts of the Profile 2. Thus, the effect of coarse recrystallized structure on mechanical and fatigue properties could be investigated in the specimens having this type of structure in the whole volume of the material and not only in somewhat problematically defined surface layer occurring usually in real forgings and extrusions. The results of evaluation of mechanical and fatigue properties are given in Fig. 3.5 – 3.9.

Fig. 3.1 Nonuniform recrystallized structure at the surface in the forging after upsetting and heat treatment, hardness HV30, alloy 6082-T6

Fig. 3.2 Detail of the recrystallized surface region from the Fig. 3.1

Fig. 3.3 Indistinctive or small recrystallized surface layers, die forging, alloy 6082-T6

Fig. 3.4 Distinctive and unacceptable recrystallized surface layers, die forging, alloy 6082-T6
Recrystallized structure in the flat part of model extrusions exhibits, in comparison with the unrecrystallized one, lower values of ultimate strength (approximately by 90 MPa - Fig. 3.5) and higher ductility (by 10% - Fig. 3.6). Owing to the local recrystallization, the anisotropy of mechanical properties changes remarkably in the flat part of the profile. In the case of unrecrystallized structure, the strength values measured in transversal direction are the same or lower than those ones in longitudinal direction (Fig. 3.7), but, on the other hand, they are higher approximately by 70 MPa in transversal direction in case of recrystallized structure (Fig. 3.8). The difference between fatigue resistance of the coarse recrystallized structure and that of the structure with the retained extrusion effect can be seen in Fig. 3.9. Mean fatigue lifetimes are $5.5 \times 10^4$ cycles in the recrystallized structure and $70 \times 10^4$ cycles in the unrecrystallized one. Thus, fatigue resistance of recrystallized structure is approximately 13 times lower than that of the unrecrystallized one. The difference greater than one order demonstrates the danger of surface recrystallized layers in real extrusions. Therefore, it is necessary to take into account this effect, particularly in thin wall profiles, where those layers can occupy greater fraction of the cross section. Fig. 3.9 implies also the difference between fatigue life in the circular part ($180 \times 10^4$ cycles) and in the central flat part ($70 \times 10^4$ cycles) in the case of unrecrystallized structure. More detailed attention to those differences is paid in [4, 5], where the mechanical and fatigue properties of various profiles are compared from the point of view of structure and texture inhomogeneities over the profile cross section.
Fig. 3.7 Heterogeneity and anisotropy of ultimate strength $R_m$ over the cross section of the Profile 2, alloy 2124-T351, $U$ – unrecrystallized, $L$ – longitudinal, $T$ – transverse

Fig. 3.8 Heterogeneity and anisotropy of ultimate strength $R_m$ over the cross section of the Profile 2, alloy 2124-T4, $U$ – unrecrystallized, $R$ – recrystallized, $L$ – longitudinal, $T$ – transverse

Fig. 3.9 Heterogeneity of fatigue properties in two positions of the Profile 1, alloy 2124, $L$ – longitudinal direction, $U$ – unrecrystallized (T351), $R$ – recrystallized (T4)

Our results show the considerable differences in mechanical and fatigue properties of recrystallized and unrecrystallized structure; thus, the occurrence of coarse-grained recrystallized layers is always undesirable. Together with the evaluation of the effect of recrystallized structure on the properties, it must be mentioned that the recrystallized structure resulted from the heat treatment to T4 temper, while the unrecrystallized one was formed during the heat treatment to T351 temper. It can be expected that in the case of T4 temper, in which the profile was not stretched after the solution annealing, a somewhat higher level of mechanical properties could be obtained after carrying out a small plastic deformation.
The results obtained correspond well with those of works [2 - 5] and confirm the idea that the formation of surface recrystallized layers as well as a marked inhomogeneity and anisotropy of mechanical properties are typical for 2xxx, 6xxx, 7xxx and Al-Li alloys.

4. CONCLUSIONS

The impact of coarse recrystallized surface layers on inhomogeneity and anisotropy of mechanical and fatigue properties was studied. The results of the investigation of die forgings and extrusions from 6082 and 2124 age-hardenable Al alloys can be summarised as follows:

1) Distinct boundary between surface recrystallized layers originated during extrusion or forging and the rest of remaining material volume forms at the same time boundary of slump in mechanical and fatigue properties.
2) In the case of 2124 alloy, the strength limit of recrystallized structure in investigated model profiles is lower by 90 MPa than that of unrecrystallized one; ductility is, on the contrary, by 10% higher. Maximum differences in strength of recrystallized and unrecrystallized structure were observed between the circular and flat part of the model Profile 1 ī about 200 MPa.
3) Fatigue properties are lower by one order in the case of recrystallized structure. This result is, however, necessary to correlate with the used parameters of fatigue experiments.
4) Recrystallized layers have ī as compared with the unrecrystallized ones ī a markedly different anisotropy of properties. The values of transversal mechanical properties are higher than those of longitudinal ones. Observed difference in strength values is about 70 MPa.

Our results showed a striking effect of surface recrystallized layers on mechanical and fatigue properties. This effect is particularly important when the layers are present in the product surface used in constructions. Especially in case of thin wall extruded profiles, these layers can importantly deteriorate ī in the dependence on their thickness ī static and fatigue properties of structural parts.

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REFERENCES