FATIGUE PROPERTIES OF 7175 ALUMINIUM ALLOY HAND FORGINGS

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Abstract

Al 7175 alloy is one of the high strength heat treatable aluminium alloys. Forgings used in severe operational conditions, especially in aviation, are made of it. Their mechanical and fracture properties are excellent as well as the corrosion resistance in tempers T74 and/or T7452. The content of impurities Fe and Si is controlled and contributes substantially to a very good fatigue resistance. The level and scatter of fatigue properties depend not only on the chemical composition and heat treatment, but also on the forming way and the extent of deformation. In the case of die forgings, which are forged usually from extruded rods, the extent of deformation of as cast structure is high and the fatigue properties do not depend markedly on it. The present paper deals with the effect of deformation on fatigue properties of hand forgings that are produced from cast and homogenized billets. In this case, the amount and way of deformation can influence substantially the fatigue properties and their anisotropy as well.

Key words: Aluminium alloy 7175, hand forging, fatigue properties, homogeneity, anisotropy

1. INTRODUCTION

Final properties of products made of Al alloys are determined by the structural state that is dependent on technological parameters. In addition to chemical composition, deformation type leading to the required shape of the product (extrusions, sheets and plates, forgings) and heat treatment before and after deformation belong also to very important technological parameters. Thus, deformation parameters (temperature, extent and rate of deformation), parameters of homogenization, high temperature annealing and, in the case of age hardened alloys, parameters of solution annealing and artificial ageing are decisive for the final properties. In addition to the required level of mechanical properties, a sufficient fatigue resistance is desirable in the operational conditions of transportation. Fatigue properties are sensitive to the structural state (matrix softening, grain size and their homogeneity) and substructure (size and distribution of primary phases as well as phases precipitating in the course of manufacture). Forming methods are also responsible for anisotropy of properties that is another typical feature of extrusions and forgings. The inhomogeneity and anisotropy of mechanical properties of extrusions and forgings are well-known [1 - 3]. On the other hand, there is relatively few information on fatigue behaviour [4 - 6], particularly in the case of hand forgings. The present paper deals with a high-strength Al-Zn-Mg-Cu alloy widely used in aircraft industry for sheets, plates, extrusions and forgings. Attention is paid to hand forging of DC cast billets. Model hand forging and propeller hub hand forging were performed. The aim of forging experiments was to describe quantitatively the effect of deformation extent of as cast structure to final fatigue properties.

2. EXPERIMENTAL

High-strength Al-Zn-Mg-Cu alloy containing 6% Zn and a low level of Fe and Si impurities was investigated. Its chemical composition is close to that of AA7175 alloy. However, in comparison with AA7175 alloy, the low level of Fe and Si impurities improves fatigue and fracture properties owing to a smaller content of intermetallic phases, especially Al7Cu2Fe, Mg2Si and Al3Fe. In the case of higher Mn and Cr content, further intermetallic phases influencing fatigue properties, e.g. Al12Mg2Cr, Al20Cu2Mn3 and Al12Mn3Si,
occur [7, 8]. Therefore, alloys with a lower Fe and Si content belong to materials of damage tolerant type used in airframes. Chemical composition of the alloy investigated (Tab. 1) shows that Mn content somewhat exceeds the usual concentration of this element in AA7175 alloy. A DC cast billet of 360 mm diameter was made from this material. It followed homogenization annealing at 470 °C for 12 hours.

**Tab. 1** Chemical composition of experimental material and the AA7175 alloy [wt. %]

<table>
<thead>
<tr>
<th></th>
<th>Cu</th>
<th>Mg</th>
<th>Si</th>
<th>Mn</th>
<th>Zn</th>
<th>Fe</th>
<th>Cr</th>
</tr>
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<tbody>
<tr>
<td>AA7175</td>
<td>1.2</td>
<td>2.1</td>
<td>0.15</td>
<td>2.9</td>
<td>0.15</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>Cast billet</td>
<td>1.5</td>
<td>1.9</td>
<td>0.11</td>
<td>0.28</td>
<td>5.9</td>
<td>0.14</td>
<td>0.13</td>
</tr>
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The effect of deformation extent of as cast structure on final properties and structure of intermetallic phases was examined by model tests carried out on DC cast billets of 360 mm diameter and by forging of propeller hub. The scheme of model hand forging of cast billets to investigate the extent of deformation is shown in Fig. 1. Reductions were carried out by progressive open die forging with the decreasing diameter from the starting cross-section S₀ to the final cross-section S₁; the values of rate k = S₀/S₁ were 1.8; 3.2; 5.6 and 10.0. The propeller hub was forged from extruded billet of 280 mm diameter from DC cast billet of 360 mm diameter (extrusion ratio λ=1.7). The extruded billet was alternately upset and cogged down from the starting length 820 mm to final height 290 mm and final diameter 480 mm by upsetting and progressive die forging. Eventually, the pin of 210 mm was pierced into its centre. The schema of the hub blank is given in Fig. 2. Forging temperature of the model forging and propeller hub forging was held between 410 °C and 440 °C. Forged pieces cut to smaller parts were heat treated under laboratory conditions to T74 state in the following way: solution treatment 470 °C/45 min, natural ageing 1 day, artificial ageing 115 °C/5 h + 175 °C/10 h. Solution treatment was carried out in the salt bath, cooling from the solution annealing temperature was carried out in 60 °C water.

For the fatigue tests, notched test rods with M16x1 threaded heads were used. Fatigue tests were performed at chosen levels of loading with cycle asymmetry of R = 0 and loading frequency 100 Hz. At each loading level, minimally 5 specimens were tested. The tests of fatigue crack growth rate (FCGR) were carried out on CT test pieces of L-T orientation to material flow, width W = 50 mm and thickness B = 7.5 mm. Cycle asymmetry R = 0.5 and various amplitudes of stress intensity factor ΔK = const. were used. The ΔK levels were chosen from the range of Paris law validity. Attention was paid also to the anisotropy of fatigue properties. Together with the investigation of the effect of deformation extent on the fatigue properties, the metallographic study of this effect on the morphology of intermetallic phases was carried out.
3. RESULTS AND THEIR DISCUSSION

Typical dispersion and morphology of phases in as cast state is shown in Fig. 3. Fatigue lives at various loading levels are represented graphically in terms of the distribution functions plotted in log-normal probability scale (Fig. 4 – 7). Fatigue properties improve with the increasing deformation extent at all loading levels. During the progressive die forging the deformation flow proceeds in the same direction and this way of deformation contributes also to the anisotropy of fatigue properties. In comparison with the fatigue lives of specimens parallel to the pin axis, those of specimens oriented perpendicularly to the pin axis are less sensitive to the deformation extent and systematically lower (compare Fig. 4 – 6 with Fig. 7). The effect of deformation extent on the mean fatigue lives, characterized by the failure probability $P = 50\%$, increases with the decreasing loading (Fig. 9).

Our results suggest that the fatigue resistance is strongly dependent on deformation extent of as cast structure and show that even a relatively high degree of deformation ($k = 5.6$) is not sufficient to remove its lower fatigue resistance.

Fig. 10 enables to compare the fatigue lives distribution of model hand forging and that of the propeller hub forging at the same loading level 225 MPa. As upsetting and progressive die forging are used during the hand forging of the propeller hub, this comparison comprises in the case of the model forging both perpendicular and parallel test rods. Further, owing to a certain degree of deformation of the propeller hub, the results of deformation of the model forging with $k \geq 3.2$ were only used for the comparison and the results of low deformation extent ($k = 1.8$) were not considered. Orientation of test pieces cut from the propeller hub forging, with respect to the direction of deformation flow, was not determined. Fatigue lives distributions suggest that the fatigue properties of both forgings are comparable inside the region of minimum and mean values. Different courses of distribution curves in the region of higher fatigue lives can be attributed to a greater number of test pieces of the model forging having the parallel orientation to the direction of deformation flow.

**Fig. 3** Intermetallic phases in as cast state

**Fig. 4** Fatigue lives distribution for specimens cut parallel to deformation direction, $\sigma_{\text{max}}=275$ MPa; model hand forging

**Fig. 5** Fatigue lives distribution for specimens cut parallel to deformation direction, $\sigma_{\text{max}}=250$ MPa; model hand forging
The effect of deformation on the fatigue properties is apparent also in case of FCGR. Results given in Tab. 2 and Fig. 11 are in compliance with fatigue lives i.e. they confirm the striking effect of deformation extent on the decrease of the FCGR. The scatter of fatigue crack growth rate values measured at the constant stress intensity factor range $\Delta K$ decreases with the increasing deformation extent as well.

**Tab. 2** FCGR of the model hand forging for different extent of deformation and different stress intensity factor range $\Delta K$; cycle asymmetry $R=0.5$, L-T orientation

<table>
<thead>
<tr>
<th>$\Delta K$ [MPa.m$^{1/2}$]</th>
<th>8</th>
<th>10</th>
<th>12</th>
<th>15</th>
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<tbody>
<tr>
<td>k [1]</td>
<td>$\sigma_{\text{max}}$</td>
<td>$\sigma_{\text{max}}$</td>
<td>$\sigma_{\text{max}}$</td>
<td>$\sigma_{\text{max}}$</td>
</tr>
<tr>
<td>1.8</td>
<td>89</td>
<td>19</td>
<td>162</td>
<td>24</td>
</tr>
<tr>
<td>10</td>
<td>-</td>
<td>-</td>
<td>162</td>
<td>18</td>
</tr>
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</table>
The results of evaluation of intermetallic phases correspond with the measured fatigue lives. Their morphology and arrangement were investigated on metallographic samples by means of image analysis in both as cast and deformed states and the following structural parameters were determined: volume fraction $V_v$, particle number per area unit $N_A$, particle dimension $D_{MAX}$ and particle cross-section area $S$. Intermetallic phases and their arrangement in the cast structure are shown in Fig. 3. In as cast state, the values of volume fraction of intermetallic phases and particle number per area unit are $V_v = 1.74 \pm 0.55\%$ and $N_A = 690 \text{ mm}^2$, respectively. After the model forging with high degree of deformation ($k = 10$), particle number per area unit increased to the value $N_A = 1082 \text{ mm}^2$. The changes of particle dimensions and their cross section area are shown in Fig. 12 and 13, where their distributions are given. Intermetallic phases disintegrate with the increasing deformation, particle number per area unit increases, their dimension and cross section area decrease. Substantial change of structural parameters is observed as early as after deformation of as cast state at the value of $k = 1.8$. 

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**Fig. 10** Fatigue lives distribution for propeller hub and model hand forgings, $\sigma_{max}=225 \text{ MPa}$

**Fig. 11** Influence of the deformation extent on FCGR; model hand forging

**Fig. 12** Distribution of area cross section $S$ of intermetallic phases in as cast state and after different extent of deformation; model hand forging

**Fig. 13** Distribution of maximum diameter $D_{max}$ of intermetallic phases in as cast state and after different extent of deformation; model hand forging
The favourable effect of deformation during forging on fatigue resistance is connected with the disintegration of phases and deformation of as cast grains. Thus, the plastic deformation during forging contributes to breaking up of as cast grains as well as to the refinement of intermetallic phases precipitating in the course of crystallization. From the point of view of deformation resistance, the high temperature annealing carried out before the forging (homogenization of chemical composition, changes of the chemical composition of phases) contributes to its substantial decrease.

4. CONCLUSION

The results of investigation of AA7175 alloy hand forgings can be summarized as follows:

1) Deformation extent and the direction of deformation flow influence markedly level and scatter of fatigue properties of hand forgings.

2) Fatigue live as well as its scatter increase with the increasing deformation. The effect of the deformation extent, on the mean fatigue live, increases with the decreasing stress. The direction of deformation flow influences fatigue live in the whole region of stresses investigated.

3) Mean fatigue live of test pieces with parallel orientation to the deformation flow at deformation degree \( k = 3.2 \) is almost three times longer than that of specimens oriented perpendicularly. Fatigue lives of test specimens oriented perpendicularly to the direction of deformation flow are less sensitive to the deformation extent.

4) Mean value and scatter of fatigue crack growth rate in L-T oriented test specimens decrease with the increasing deformation extent.

5) Morphology of intermetallic phases changes with the increasing deformation extent. Deformation causes the disintegration of brittle phases; their number per area unit increases, while the size and cross section area decrease. In this way, deformation contributes to improvement of fatigue properties.

6) It was found that the deformation extent characterized by the values of parameter \( k = S_0/S_1 \) higher than 5.6 leads to the improvement of fatigue properties. Therefore, a sufficient deformation of hand forgings seems to be quite necessary.

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