THE EFFECT OF GRAIN STRUCTURE ON FATIGUE LIFE OF AGE HARDENING ALUMINIUM ALLOYS

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When using common forming processes like extrusion and forging the grain structure of the final product may vary owing to chemical composition, thermal treatments and deformation procedures.

Testing extruded AlMgSi alloys aged to peak hardness shows that fatigue life is greatly influenced by grain structure, especially at low stress amplitudes. Experiments show that fibrous material may sustain more than a factor of ten cycles more than material having a mixture of fibrous and coarse grains.

INTRODUCTION

It is well known that grain size may influence mechanical properties of metals and alloys. When testing aluminium alloys it has been found that flow stress varies only slightly with grain size (1-3). Ductility, tensile strength and toughness, however, increase when grain size is reduced.(3,4).

The influence of grain size on fatigue properties has received less attention. Lütjering et al (2) have shown that fatigue life increases when grain size is reduced from 200 μm to 30 μm in an AlMgZn alloy in underaged and maximum hardness condition. The same has been found in AlCuMg alloys (5).

The automotive industry has during the last years made considerable efforts to increase fuel economy. One way has been to substitute todays materials, which normally are low alloyed carbon steels, by lighter materials, e.g. aluminium alloys. AlMgSi alloys (AA-6xxx series) are often chosen for these purposes because of good strength and ductility properties combined with high corrosion resistance and good hot and cold formability.

Extrusion and/or forging are common forming methods of alloys from 6xxx-series where the mechanical properties may be somewhat increased when having a fibrous grain structure, the socalled "press-effect". Although aiming at a fibrous grain structure the industrial routines for forming and heat treating may result in an unwanted recrystallized coarse grained surface structure. In

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addition to reducing the mechanical properties if this layer is thick, annodizing properties are reduced and orange peel may arise. If this coarse grain layer covers a small fraction of the total cross section it has a small influence on tensile strength, ductility and toughness and the part may be accepted. The purpose of this paper is to show the influence of such a partly recrystallized grain structure on fatigue properties.

EXPERIMENTAL

The chemical composition of the investigated alloy is given in Table 1 and corresponds to AA 6351.

TABLE 1 - Chemical composition of the investigated alloy (wt%)

Si	Mg	Mn	Fe	Al
1.11	0.66	0.55	0.2	rest

The alloy was industrially DC cast and contained impurities at normal industrial levels. The billets were given a homogenization heat treatment at 793 K (520 °C) for 4 hours before extrusion to sections of 10x100mm^2.

The grain structure of the sections was fibrous, but had a thin surface layer of coarse, recrystallized grains at the rear end, figure 1. When heating the sections to temperatures above ca. 800 K the thickness of the recrystallized surface layer could be increased.

Round fatigue specimens were machined from the front and rear end of the as extruded sections with the length direction parallel to the extrusion direction. The diameter of the heads was 9.8 mm and of the testing area 4.0 mm. The grain structure of the testing area was completely fibrous after machining and paper grinding. After machining and grinding the specimens were solution heat treated at 848 K (575 °C) for 5 minutes, quenching to room temperature and artificially aging at 448K (175 °C). The aging times were 10, 300 and 3400 minutes in order to have the specimens in the underaged, peak or overaged condition, figure 2. Fatigue testing was done at constant load amplitudes at room temperature in a push-pull machine at a frequency of 60 Hz and R = -1. The stress amplitude was triangular.

RESULTS

Grain structure

The solution heat treatment resulted in specimens having different grain structure; some were completely fibrous, others had a surface layer of recrystallized, coarse grains, figure 3, or were coarse grained all over the cross section.

The grain structure had been completely fibrous during machining. There was therefore no detectable difference in roughness over the testing area of the specimen surface, as might have resulted when machining material of a mixed grain structure.

S-N curves

S-N curves of specimens aged to peak hardness is shown in figure 3. The specimens with a non-recrystallized, fibrous grain structure, as seen to the right in the figure, sustained more cycles before fracture than specimens with a surface layer of recrystallized, coarse grains. Specimens which were coarse grained all over the cross section and an even shorter life. The difference in fatigue life is most pronounced at small stress amplitudes where the number of cycles to fracture may differ by a factor of 10.

The same behaviour is found for specimens in the under- and overaged condition.

Small or no reductions in fatigue life were found when comparing specimens with the same grain structure but different aging treatments.

The experimental scatter in number of cycles to fracture was found to be largest in specimens having a mixed grain structure.

Fractographic investigations

In material with a layer of coarse grains near the surface the fatigue cracks were found to start at the surface in the coarse grains. The fracture appearance is intercrystalline or planar in the coarse grained surface material and changes when passing into the non-recrystallized material.

When investigating the sylindrical surfaces of fractured specimens having a mixed grain structure, there was often found other cracks in addition to the one which resulted in the ultimate failure. These were found to appear in areas having an underlying coarse grain structure.

The rest fracturewas always lying in an area of non-recrystallized grain structure and covers the same area fraction in specimens being fibrous or having mixed grain structure.

DISCUSSION

By reheating the extruded and machined material a mixed grain structure could be obtained in specimens of a form well suitable for fatigue testing. The fraction of recrystallized, coarse grained material over the cross-section varied to some extent, typical values for the specimens used was 20%. The large scatter in number of cycles to fracture in specimens having a mixed grain structure may be due to the variation of fraction recrystallized.

Fatigue is usually divided into four stages; crack initiation, stage I and stage II crack growth and rest fracture. In the tested specimens the rest fracture occurred in the same fibrous grain structure and covered the same area fraction. The rest fracture therefore did not seem to vary from specimens with fibrous grain structure to specimens with mixed grain structure.

As crack growth was not measured it is difficult to be certain whether the better fatigue properties observed for fibrous material is due to crack initiation or crack growth. But fractographic investigations showed that cracks had started in the layer of coarse, recrystallized grains in specimens having a mixed grain structure. And as the layer of recrystallized coarse grains are thin, $\leq 400\mu m$, the main length of stage II crack growth must therefore take place in material having a fibrous grain structure, also in specimens with a mixed grain structure. The conditions for stage II crack growth should therefore be much the same in materials of both grain structures. The observed difference in number of cycles to failure is therefore most likely due to easier crack initiation and stage I crack growth in specimens having a thin surface layer of coarse recrystallized grains.

Compared with other investigations it has been found that crack initiation in specimens having a coarse grain structure is easier than in specimens of fine grain structure (2,5). This supports the above conclusions.

When comparing effects of microstructure on fatigue properties experiments should be carried out on specimens having the same yield and tensile strength. In material with a mixture of microstructures this condition may not be fullfilled. When tensile testing peak aged material having recrystallized, coarse grains throughout the volume the "press effect" is lost and the yield and tensile strength is found to be about 15% lower than for fibrous material. In material of mixed grain structure the coarse grained surface layer constitute a small area fraction of the cross section and therefore the reduction in average strength due to loss of "press effect" may be small, 2-3% in the present case. This change is so small that in industrial practice it is normally accepted to be within the limits of experimental scatter without further investigations being done.

When fatigue testing material of mixed grain structure the ratio of cyclic stress to yield stress may locally be higher in the coarse surface grains than in fibrous structure. This favours crack initiation in the coarse grain layer.

Other reasons for easier crack initiation in the coarse, recrystallized grains than in fibrous grain structure may be due to the morphologie of hardening particles in age hardening aluminium alloys. In these alloys a precipitate free zone, PFZ, is present adjacent to grain boundaries. This zone has therefore a lower strength than the grain interiour and deforms at a lower stress.

If the hardening particles are shearable strain may be localized to bands of increased slip activity, PSB, in the grain interiour.

During tensile or fatigue testing plastic strain may therefore be concentrated to PFZ or PSB and lead to undersirable stress concentrations and earlier crack initiation (2.6).
The larger the grain size the more pronounced is this effect. In the specimens with a mixed grain structure the surface grain size is typical more than 100 μm compared to subgrain sizes of less than 10 μm in the fibrous materials. It is therefore reasonable to expect easier crack initiation in material having a mixed grain structure than in fibrous material. A reduction of strength in the coarse grained surface layer or slip localization due to precipitate distribution may therefore lead to easier crack nucleation and stage I crack growth as observed.

The reductions in hardness or yield strength in the under- and overaged conditions were about 25%. It is difficult to understand that this reduction had a negligible influence on fatigue life. Fatigue experiments using constant strain amplitudes are now being set up to investigate these topics further.

The resistance to corrosion of AlMgSi-alloys is generally good. However, due to small differences in electrochemical potentials between recrystallized and unrecrystallized material galvanic corrosion may occur along interfaces where recrystallized material meets unrecrystallized material. When specimens of mixed structure is fatigued in corrosive environments these localized corrosive attacks may reduce total life because of easier crack initiation.

When using age hardening aluminium alloys for purposes where fatigue and corrosion properties are of importance, the grain structure of the material may therefore be of importance even though no influence is found when testing strength, ductility and toughness.

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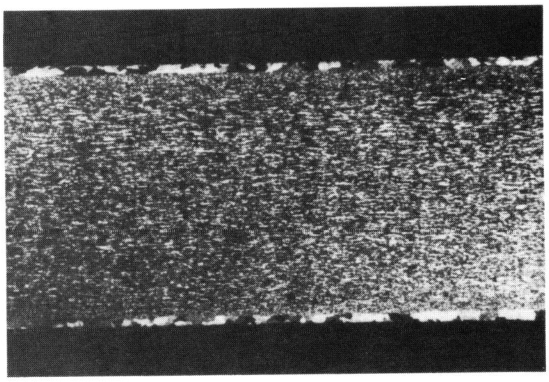

Figure 1 The grain structure of the extruded $10x100mm^2$ profil, Cross section.

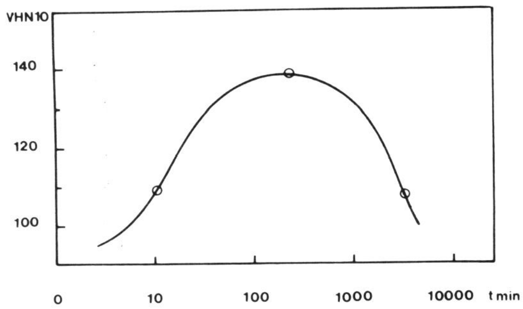

Figure 2 Hardness curve showing the aging condition of the specimens, under and over aged conditions and peak hardness

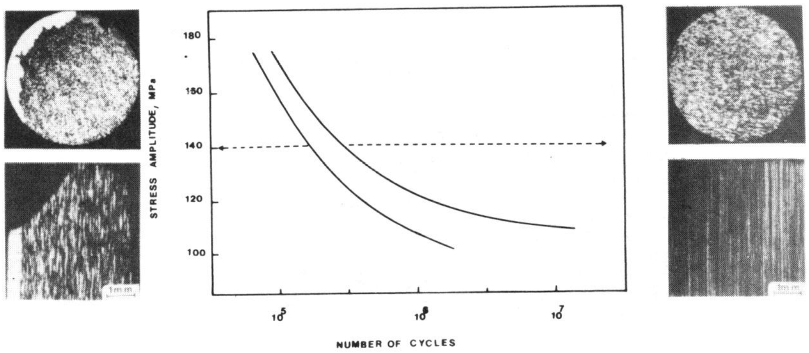

Figure 3 S-N curves of specimens aged to peak hardness. The upper curve showing S-N curve for specimens with fibrous grain structure and the lower curve showing S-N curve for specimens with mixed grain structure