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# Comparison of the fatigue behaviour of an Al-Zn-Mg-Cu alloy (7010) in the form of squeeze and chill castings and rolled plate

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The relationship between the fatigue properties and grain size of the commercial 7010 alloy composition in squeeze-cast form has been established and the properties compared to those of rolled plate and gravity-cast 7010 material. The fatigue strength of the squeeze-cast material was found to lie between those of the gravity-cast and the plate material. A decrease in the grain size of the squeeze-cast material considerably improved its fatigue strength. However, the reverse was found to be the case for the fatigue crack propagation resistance. At $\Delta K$ values below $\sim 11$ MPa m$^{-1/2}$, fatigue cracks in plate material grew at a lower rate than in the squeeze-cast material and vice versa at higher $\Delta K$ values. The effects of some of the microstructural differences on the fatigue behaviours of the squeeze-cast, gravity-cast and plate material are discussed.

## 1. Introduction

The aluminium alloy compositions that are considered best suited to the manufacture of castings are of relatively low tensile strength when compared with those aluminium alloys developed for use in the wrought form. Furthermore, conventional casting methods produce material with an inherently low fatigue strength and a characteristically high level of scatter when compared with forgings. Thus, certainly within the aircraft industry, casting as a method of making near net shape forms has, in the past, been seriously disadvantaged with respect to die forging.

There are two things that might redress this balance: (1) the capability of satisfactorily casting higher strength compositions, and (2) the production of castings with improved fatigue properties. There is also a further consideration that might attract designers to castings and that is the continuing problems related to directionality with forgings. Castings have no such anisotropy of properties.

The process of squeeze casting, whereby the metal is solidified under a directly applied pressure, allows the production of gas and shrinkage cavity-free castings [1-4]. Furthermore, by attention to the casting conditions, considerable refinement of microstructure is possible. Williams and Fisher [5] have reported that the mechanical properties of squeeze castings compare favourably with forgings of the same composition, and, furthermore, the fatigue strength of the casting alloy, LM25, widely used for both gravity and low-pressure die castings, can be significantly improved by squeeze casting.

The work reported in this paper has been part of a wider study of the squeeze-casting process on a number of alloys both aluminium and magnesium based [6, 7]. In this work the author has concentrated on the composition of the aluminium alloy 7010, and in agreement with Williams and Fisher's conclusions have found that this high strength alloy can be satisfactorily cast by the squeeze method.

This paper is primarily concerned with the fatigue behaviour of the 7010 composition alloy in squeeze-cast, gravity-cast and the wrought form, and the relationship between properties and microstructure. As might be expected for this alloy composition which was designed to be used in the wrought form, there has been no publication of work on its fatigue characteristics in the cast form.

From the viewpoint of direct applicability the comparison of squeeze-cast material should have been made with die-forged material. However, it was decided to use 7010 plate to represent the wrought form, on the basis that one can be sure of the test-piece flow direction relationships with plate, which is not so with die forgings.

## 2. Experimental details

The $S/N$ data for the various material conditions were obtained using Rolls Royce rotating cantilever plain specimens, i.e. $R$(stress ratio) $= -1$ and a frequency of 80 Hz. Tests were conducted at stress levels between 330 and 120 MPa and two specimens were tested at each stress level: a total of sixteen specimens for each material. The fatigue crack propagation (FCP) rates were measured on notched bend specimens with a stress condition $1.22\sigma_a \pm \sigma_a$, where $\sigma_a$ is the alternating stress, using a Pearson fatigue machine [8]. Crack length was measured with the aid of a travelling microscope.

Rolls Royce specimens were manufactured from a gravity chill casting and three squeeze castings having various grain sizes. These castings were cylindrical in shape with a diameter of 100 mm and a height of

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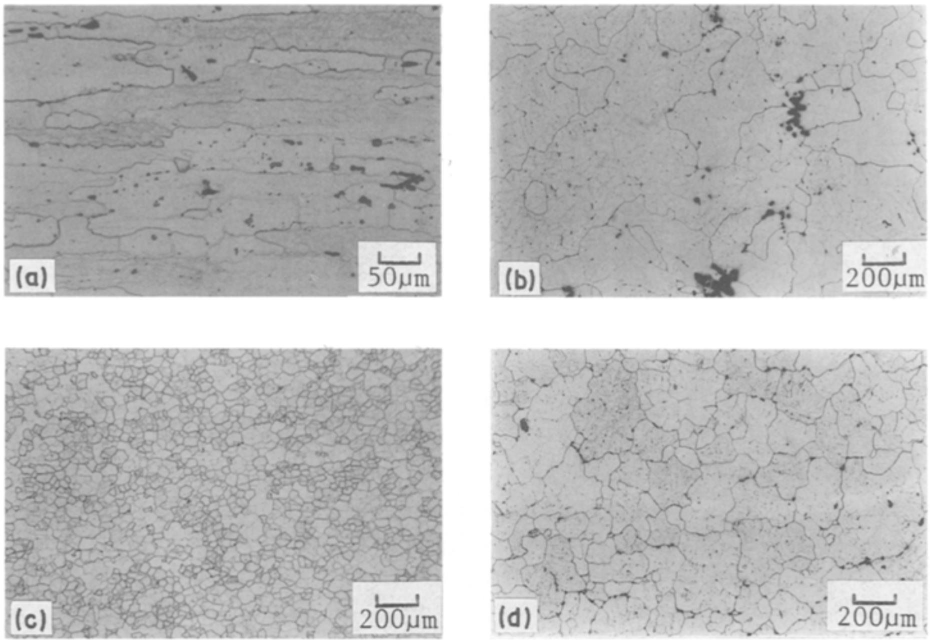


*Figure 1* A comparison of the microstructure of the plate, in L-orientation (a), gravity-cast (b) and squeeze-cast fine-grained (c), coarse-grained (d) materials.

140 mm. Their mean grain sizes, after heat treatment, were measured and found to be 450, 70, 380 and 800 $\mu$m. These four different microstructures were designated A0, A1, A2 and A3 respectively. Details of their casting conditions and the features of their as-cast microstructures have been described elsewhere [9]. The plate material under examination was 100 mm thick and was supplied by Alcan Industries, Banbury. Rolls Royce specimens were cut from the plate to test both the longitudinal (L) and the short transverse (ST) directions. Fatigue crack growth rate determinations were only done on the squeeze-cast materials A1 and A2, and only the longitudinal–transverse (LT) direction was tested in the plate.

The compositions of all the materials were within the 7010 specification. A typical composition for these materials is given in Table I. All material was heat treated and tested in the T6 condition (peak hardness). This was obtained by solution heat treatment at 475° C for 24 h followed by quenching into water at 20° C, then age hardening for 24 h at 120° C.

## 3. Results

### 3.1. Microstructures

Fig. 1 shows the microstructures and gives an indication of the grain size and shape in the various product forms tested. The influence of the various features on fatigue behaviour will be discussed in a later section.

### 3.2. Rotating cantilever fatigue tests

The results of the fatigue tests on the cast and wrought material are shown in Fig. 2. The points for material A2 have not been shown in the figure, but they lay between A1 and A3. As might have been predicted, the gravity-cast material showed the lowest fatigue strength and the wrought material the highest.

The scatter band for the ST direction of testing was larger than for the L direction, but the two directions exhibited similar mean fatigue strengths at all stress levels. The fatigue strength of the squeeze-cast material, lay between that of the gravity-cast material and that of the plate. However, there was a significant difference between the different grain sizes of the squeeze-cast material, fatigue strength increasing with decreasing grain size. The fatigue limit increased from 160 to 200 MPa for a grain size change from 800 to 70 $\mu$m.

TABLE I Typical chemical composition (wt %) of the 7010 material

| Zn | Mg | Cu | Zr | Ti | Si | Fe | Mn | Al |
|---|---|---|---|---|---|---|---|---|
| 6.38 | 2.40 | 1.74 | 0.13 | 0.04 | 0.05 | 0.1 | 0.01 | bal. |

### 3.3. Fractography

Some typical fracture surfaces of rotating cantilever test pieces of both plate and squeeze-cast material, at a test stress level of $\pm 250$ MPa, are shown in Figs 3 to 5. The plate material exhibited a totally stage II fracture mode (Fig. 3), whereas the fracture of the coarse grain squeeze-cast material (A3) consisted almost entirely of Stage I facets. A microsection of this specimen also revealed a number of Stage 1 secondary cracks starting from the specimen surface with an orientation of $\sim 45°$ to the tensile stress axis. These cracks frequently changed to the Stage II form when encountering grain boundaries (Fig. 6). The finer grain size material ($\sim 70\,\mu$m) did not exhibit Stage I cracks (Fig. 5).

### 3.4. Surface examination of failed rotating bend fatigue test pieces

Some gravity-cast test pieces were electropolished after fatigue testing and microscopically examined. Fig. 7 shows initiation of fatigue cracks from shrinkage pores. The numerous cracks tended to join one another via the shrinkage pores exposed on the specimen surface.

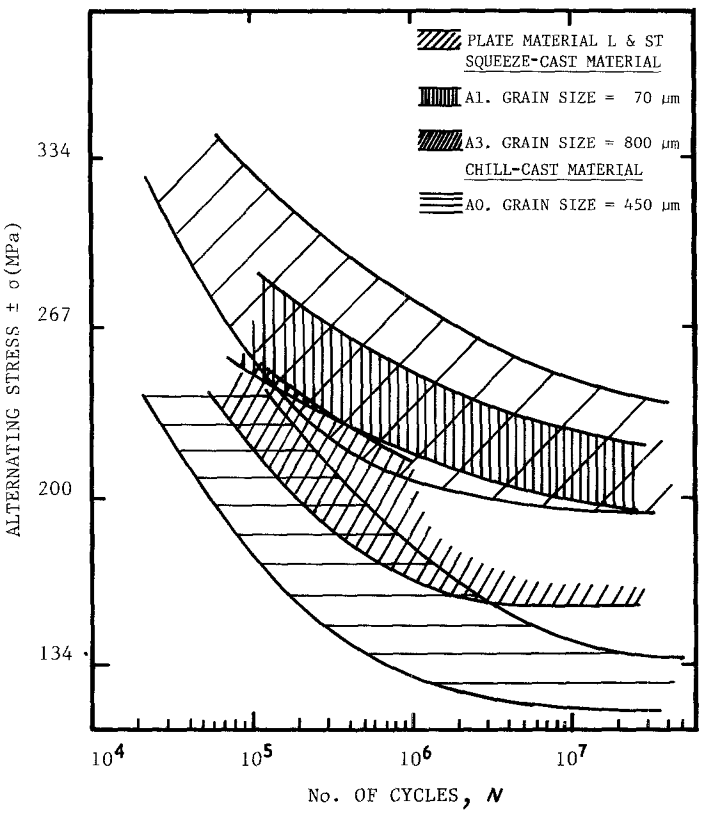


*Figure 2* The *S–N* curves for the plate and cast materials.

## 3.5. Fatigue crack growth rate test results

The graphs of crack length ($a$) against number of fatigue cycles ($N$) for the three batches of test specimens is presented in Fig. 8 and the relationship between crack growth rate, $da/dN$, and stress intensity factor range, $\Delta K$, is given in Fig. 9. The results show that for the squeeze-cast materials the relatively coarse-grain material A2 has a lower crack growth rate than that of the extremely fine-grain material A1. They also show that the wrought material with a small crack less than $\sim 5$ mm, has a lower crack growth rate than the two squeeze-cast materials, and the reverse was found true at greater crack lengths.

## 3.6. Fractography

The plate material, exhibited long, tilted facets that related to the laminated grain structure of the rolled material. An SEM examination of this fracture surface revealed that, near the crack origin, the crack front was divided into many small segments relating to its laminated structure (Fig. 10). However, at a greater distance away from the crack origin the fracture surface became more irregular and the segmented form of fracture became less apparent (Fig. 11). Some lateral grain-boundary delamination was also observed in these regions (Fig. 12).

For both of the squeeze-cast materials A1 and A2, the fracture surfaces were composed entirely of Stage II facets (Figs 13, 14). The size of these facets was directly dependent on the grain size of the material. Quantitive measurements of the topography of the fracture surfaces indicated that for the coarser grain specimen the mean height of the shear cliffs between tilted facets was about 50% greater than that for the fine-grain specimen. The mean cliff heights measured on the coarse- and fine-grain specimens were 46 and 30 $\mu$m, respectively. Both of the squeeze-cast materials frequently exhibited secondary micro-cracks developing from their main fracture surfaces (Fig. 15).

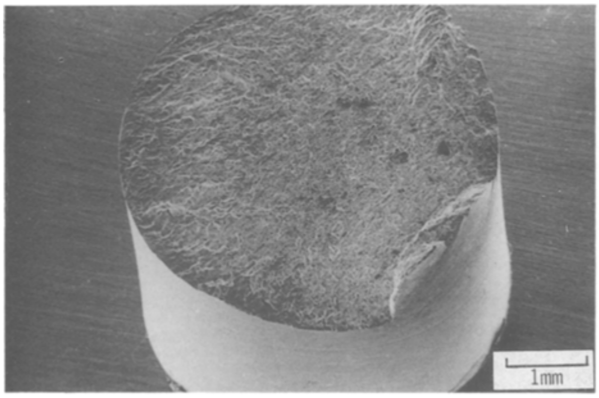


*Figure 3* Fracture surface of a rotating bend fatigue specimen of the plate material.

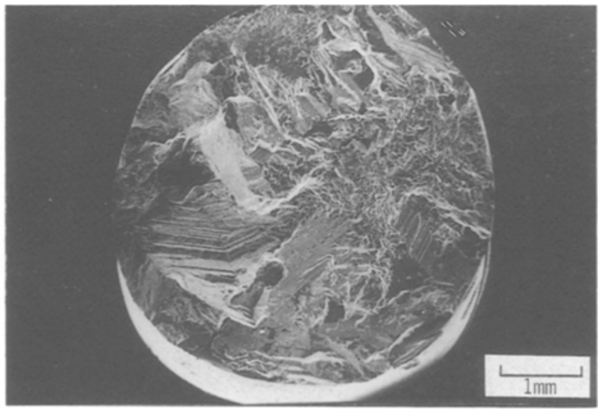


*Figure 4* Fracture surface of a fatigue specimen of the coarse-grained material (A3).

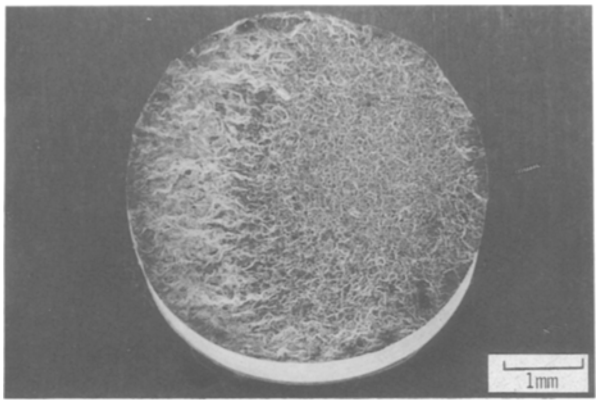


*Figure 5* Fracture surface of a fatigue specimen of the fine-grained material (A1).

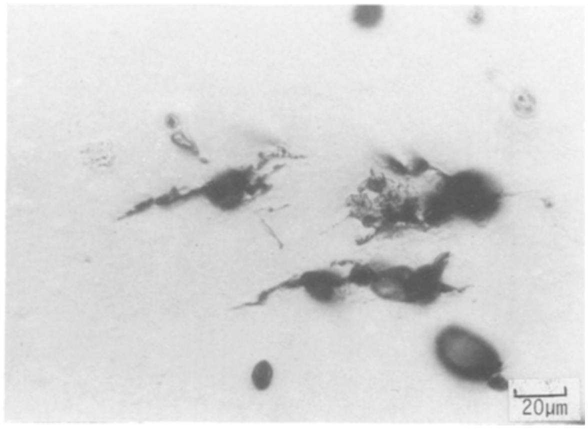


*Figure 7* Fatigue cracks had initiated from shrinkage pores in a gravity-cast (A0) specimen (electropolished).

## 4. Discussion

The results of the rotating bend tests and the FCP tests show that materials of the same 7010 composition produced in different forms and conditions possess different fatigue properties. This appears to be the result of distinct differences in microstructure. The effects of some of these microstructural differences on fatigue crack initiation and on propagation resistance in the plate and case materials will be discussed separately.

On the basis of the present work, it appears that the relatively poor fatigue strength observed for both gravity and coarse-grain squeeze-cast materials is the consequence of easy fatigue crack initiation. In the gravity-cast material, fatigue cracks start readily from shrinkage pores at or near the specimen surfaces. Such pores appear to be very effective stress raisers.

For the coarse-grained squeeze-cast material, Stage I fatigue cracks had grown deep into the test piece before any Stage II cracking developed. Coarse-grained material develops early microcracks (Stage I) which can grow with relative ease, along a slip plane, before they meet the first grain-broundary obstacles. However, for the finer grained material, growing microcracks are hindered earlier and more frequently by grain boundaries.

The relationship between the fatigue strength and grain size for this squeeze-cast material is summarized in Fig. 16. Holzmann *et al.* [10] and Armstrong [11] have shown that something similar to the Hall–Petch grain-size relationship can be used for the fatigue of alloy systems such as steel, brass and monel. However, the results of this present study indicate that at least for this alloy, the Hall–Petch approach is inappropriate, because in the present case there is a change of fracture mode from totally Stage I in the coarse-grained material to Stage II in the extremely fine-grained material.

In the case of the wrought material, there is little difference in the fatigue strength between the L and ST specimens, although the lives of the ST specimens show greater scatter. This could be the result of certain transversely oriented intermetallic stringers encouraging early crack initiation. The small difference observed in the fatigue properties of these two batches of test pieces suggests that crack initiation has not been significantly affected by their differences in grain orientation. Any orientation effect may have been suppressed by the presence of the very fine sub-grain structure observed in both.

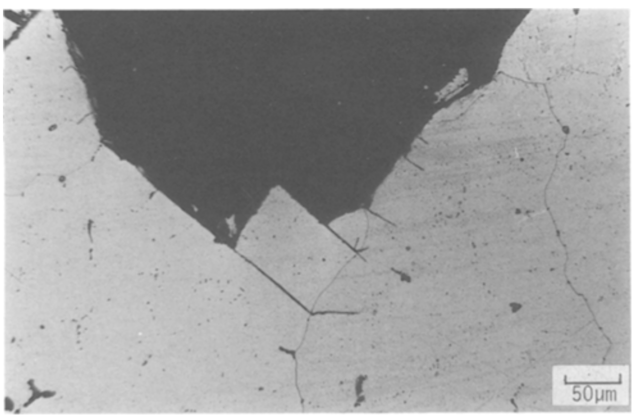


*Figure 6* A microsection of a coarse-grain (A3) specimen, showing Stage I cracks had changed direction when they encountered a grain boundary.

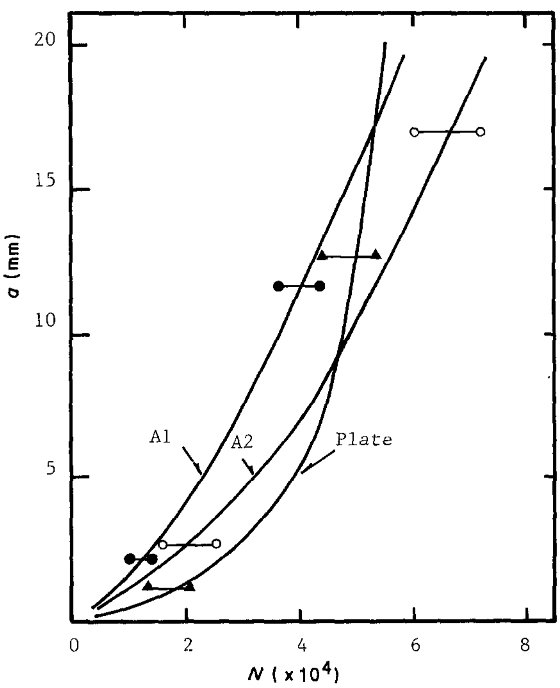


*Figure 8* Crack length ($a$) plotted against number of fatigue cycles ($N$).

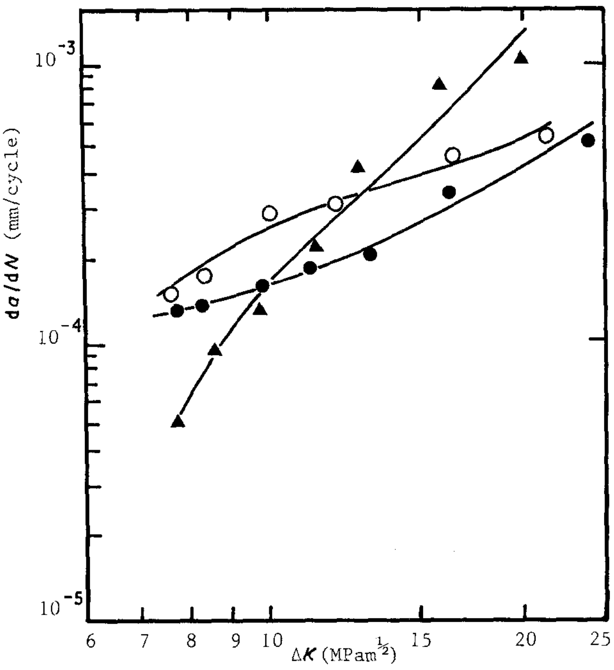


*Figure 9* Fatigue crack growth rate ($da/dN$) plotted against stress intensity factor ($\Delta K$) in 7010-T6 Al-alloy for plate material (▲), and squeeze-cast material (●) A2, 380 $\mu$m, (○) A1, 70 $\mu$m.

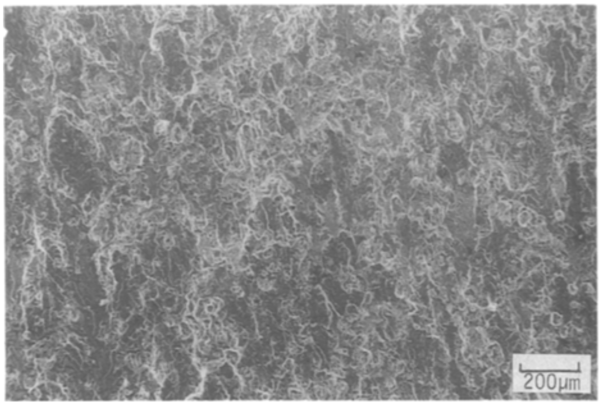


*Figure 11* Same specimen as shown in Fig. 10, showing the irregular fracture surface of the specimen at a distance of 10 mm from the origin.

It has been generally accepted that a finer grain size material should possess better fatigue properties than a coarse-grain size material. The results of the rotating bend tests support this idea. However, in the present work, the results of the FCP tests show that for squeeze-cast material, the coarse-grain microstructure conferred higher FCP resistance than the finer grain one. This indicates that the grain-size requirement for crack initiation resistance is directly opposed to that for crack propagation resistance. In looking more closely for the reasons for this it seems that the more restricted crack deviation from the general fracture plane afforded by the fine-grain size material may be contributory to its inferior crack resistance. In the coarse grained material the larger deviation of the crack path that is observed will result in a reduction of the effective stress intensity at the crack tip, thus reducing the crack growth rate. Also for the coarser grained material the height of the cliffs between the tilted facets was about 50% greater than that of the fine-grained specimen. It is believed that more energy will be required to create the larger shear fracture surfaces between these tilted facets in the coarse-grained material than in the fine-grained material. As a result of this, crack propagation is impeded because additional shear work is necessary to form these steps. At present a direct correlation between the size of the cliff and its effect on FCP rate has not been firmly established, although it has been established for fracture toughness [12].

At low values of $\Delta K$ the wrought material had a lower FCP rate ($da/dN$) than the two squeeze-cast materials. An examination of the fracture surface of the wrought material specimen in the low $\Delta K$ range, i.e. near its crack origin, showed that its crack front was divided into many small segments each bounded by the elongated grain boundaries (Fig. 10). Forsyth [13] has suggested that the orientation of plate microstructure with respect to crack growth direction influences the crack front shape and hence crack growth rate. A vertical planar discontinuity will influence crack growth whether that discontinuity is aligned as a crack divider or a crack stopper. Therefore a crack growing in a direction between the L and ST directions in a plate with a laminated grain texture would be subject to both types of discontinuity. Although the effect of the orientation of plate microstructure with respect to crack growth form has been reported, its significance with regard to FCP rate remains unclear, because no detailed comparison of the FCP behaviour of plate and cast material has been made before. Any difference in the FCP behaviour of

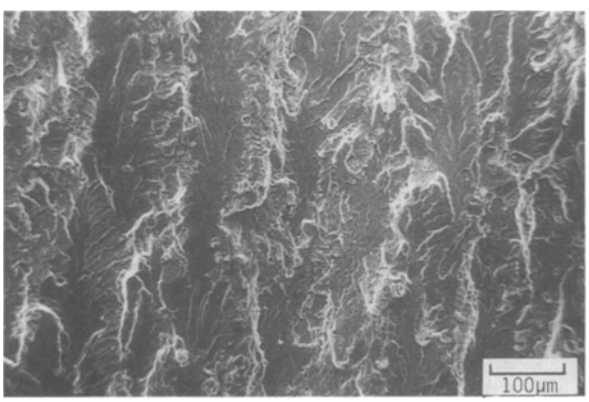


*Figure 10* The hill and valley fracture appearance near the crack origin of a plate material specimen.

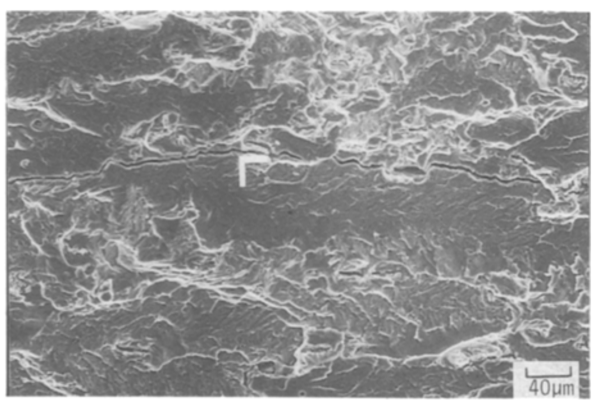


*Figure 12* Lateral grain-boundary delamination observed in a plate material specimen.

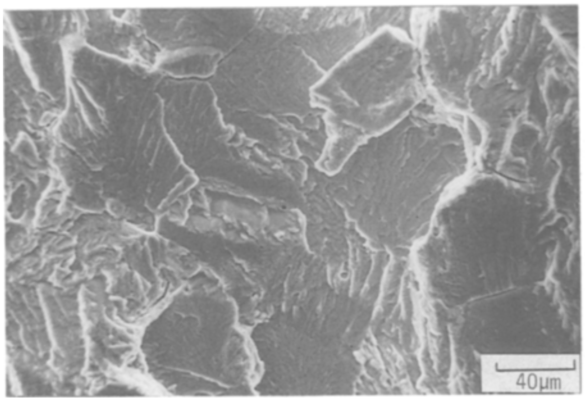


*Figure 13* Fracture surface of a fine-grain squeeze-cast (A1) FCP specimen.

plate and squeeze-cast material that might be revealed in this present work should provide a better understanding of the effect of plate microstructure itself on FCP behaviour.

As mentioned earlier, the fatigue crack front of the plate material specimen, near the crack origin, was divided into many small segments. This was because the orientation of the specimens was such that grain boundaries acted as crack dividers (see Fig. 17). The resulting fracture surface had a hill and valley form. This was caused by crack segments meeting along grain boundaries and the formation, at the boundary itself, of a high disturbed region that took the form of a ridge. Thus the crack no longer advanced in a planar fashion. Furthermore, the crack front lagged behind in the boundary regions. The highly "disturbed" region in the vicinity of the grain boundary suggests that a high-energy absorbing shear process was involved here during the fatigue crack growth process. The segmented cusp-shaped crack fronts increase the crack front length compared with conventionally accepted crack front shape thus reducing the effective stress intensity factor which in turn reduces the FCP rate. Thus, it is evident that a vertical planar discontinuity which causes the crack to divide must slow down the FCP rate, and the reduced FCP rate of the plate compared with that for the squeeze-cast materials at low $\Delta K$ regions is believed to be due to the greater number of these crack dividers in the plate than in the casting. Although the effect of what amounts to a laminated microstructure acting in the

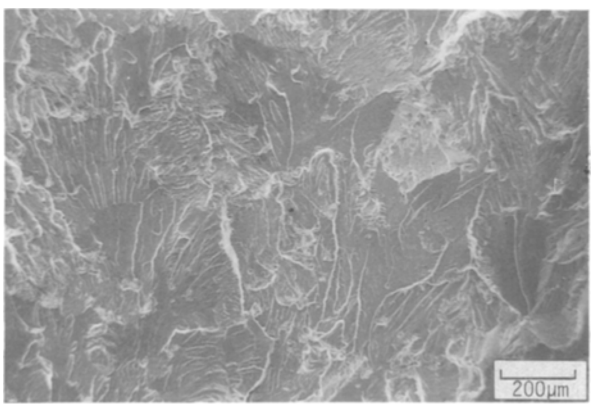


*Figure 14* Fracture surface of a coarse-grain squeeze-cast (A3) FCP specimen.

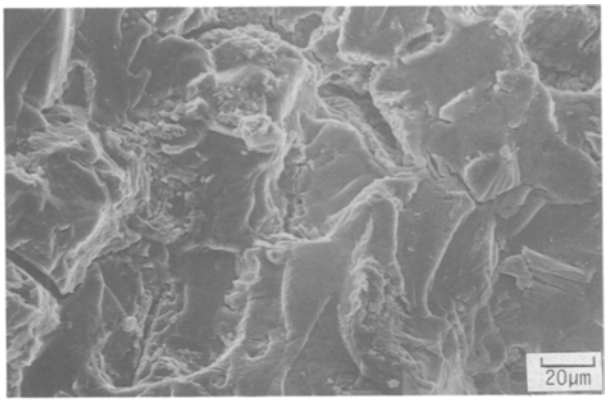


*Figure 15* Microcrack branching in a fine-grain squeeze-cast (A1) FCP specimen.

crack stopping mode (as opposed to the crack dividing mode) has not been studied, it might be expected to be even more effective in slowing down the FCP rate.

At high $\Delta K$ values, above $\sim 11\ \mathrm{MPa\,m^{1/2}}$, the FCP rate of the plate material was found to be higher than that of the two squeeze-cast materials. Although at present, a complete explanation for this cannot be given, observations on the fracture surface and microsections of the FCP fracture specimens provide some insight into this phenomenon. At a few millimetres away from the fracture origin of the plate specimen, the fracture surface topography changed and the hill and valley fracture texture characteristic of low $\Delta K$ became less apparent. It is believed that the stress at the crack front was now raised to such a value that the grain boundaries lost their pinning effect. Based on these observations a schematic illustration of the cracking sequence in peak-aged 7010 aluminium alloy tested in the LT direction is proposed and is shown in Fig. 18.

The noticeably wavy crack path of the two squeeze-cast materials is considered to be responsible for their higher FCP resistance in the higher $\Delta K$ regime. Apart from the "cliff" edges on the fracture the crack tilting itself results in an effective decrease in stress intensity

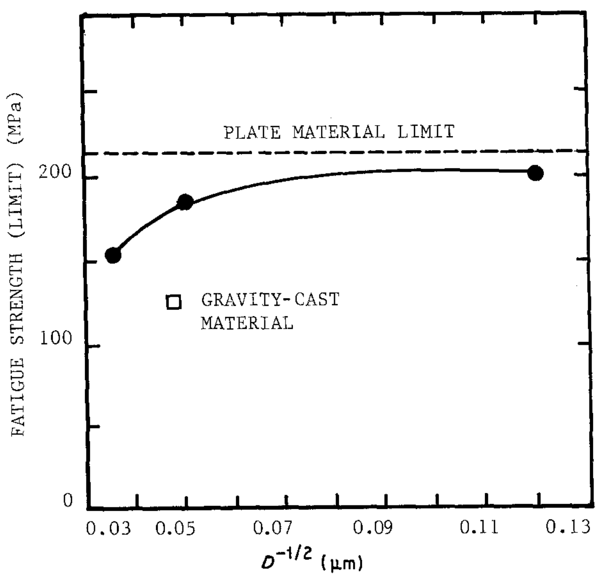


*Figure 16* The fatigue strength of squeeze cast 7010 - T6 material (●) plotted against grain size ($D^{-1/2}$).

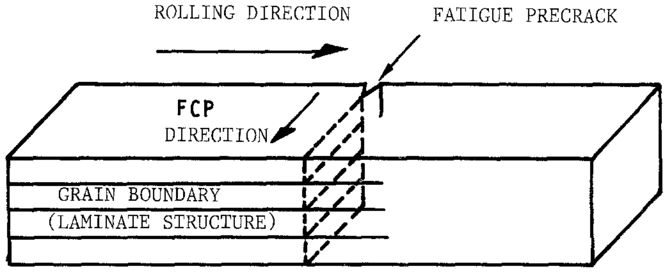


*Figure 17* The orientation of plate microstructure with respect to the fatigue crack propagation (FCP) direction.

factor at the crack tip. Secondary microcrack branching, as is frequently observed in the two squeeze-cast materials, would also contribute to the effect of reducing the local stress and thus increasing the FCP resistance. Pitcher and Forsyth [14] have found that the fatigue crack growth rates of some cast alloys were significantly lower than those of high-strength wrought alloys and microcrack branching was considered to be one of the major factors in causing the low FCP rate in the cast materials.

The presently established result that fatigue crack initiation seems to be more difficult in fine-grain material is in keeping with other workers findings, and what has now become firmly established knowledge. The fact that fatigue crack propagation resistance seems to be higher in coarse-grain material is less well established for fatigue, although well established with regard to tensile crack resistance, i.e. fracture toughness.

There is no doubt that fatigue crack initiation resistance, as represented by test lives under the conventional *S/N* type testing, is strongly influenced by the presence of defects. Where crack initiation at defects occurs, then direct Stage II growth ensues with no evidence of a Stage I period. Nevertheless, in the absence of such effect stress raisers, some Stage I activity develops and preceeds to the Stage II stage. Thus the grain size effect *per se* seems to be one of control of Stage I behaviour. Such a limitation of single slip generation that this implies is in keeping with our presently accepted understanding of grain size effects on plastic deformation and would fit in with a Hall–Petch approach to flow strength.

With regard to crack growth resistance, whether fatigue or tensile, the usual explanation for a grain size effect is that grain size, like other microstructural features that affect crack path, does so by making it more or less tortuous. The large grain size is more effective in this respect than small grain size, even though, in both large and fine grain size material the fracture path was faceted i.e. had some crystallographic tendency rather than being intergranular.

## 5. Conclusions

1. The fatigue strength of the squeeze cast 7010 composition material when aged to the T6 condition, lies between that of the gravity cast and wrought material in the same precipitation hardened state.

2. Decreasing the grain size of the squeeze cast 7010 composition material considerably improved fatigue strength. The fatigue strength (as defined by the *S–N* curve) of the finest grained material (70 $\mu$m) lay within but at the lower end of the scatter band of the wrought material. This improvement is believed to be due to the higher fatigue crack initiation resistance when compared with the larger grain size material.

3. Conversely, the lower fatigue strength of the larger grain size squeeze-cast material was due to its lower resistance to crack initiation and easy transition to a coherent fatigue crack.

4. The inferior fatigue properties of the gravity-cast

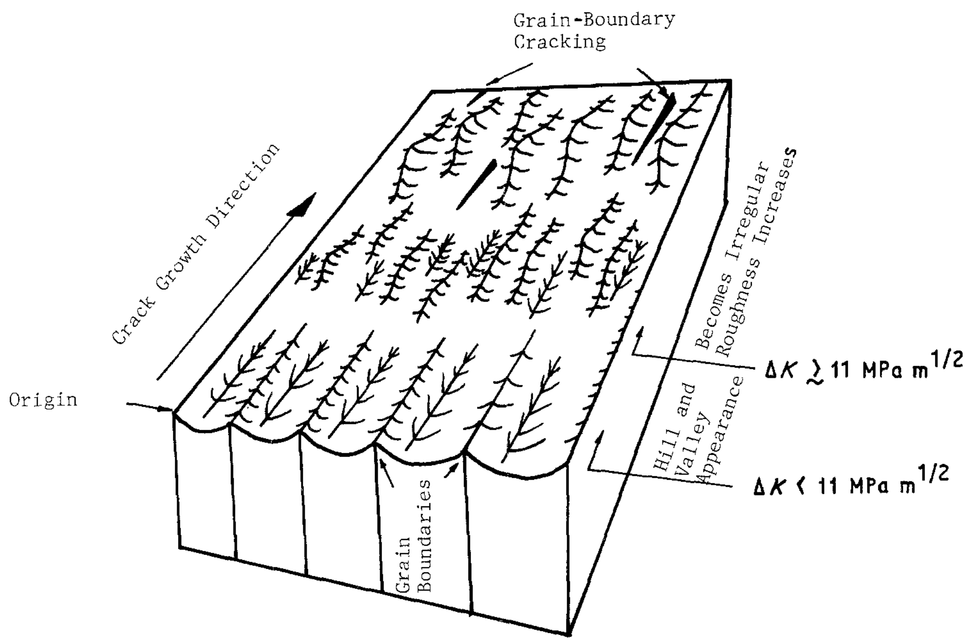


*Figure 18* A schematic illustration of the fatigue crack growth model in the 7010 - T6 plate material tested in the LT direction.

material was the result of early crack initiation at shrinkage pores exposed on the specimen surface.

5. The fatigue crack propagation rate of the large-grain squeeze-cast material was found to be lower than that of the small-grained material over the whole $\Delta K$ range tested. This was attributed to the more irregular crack paths that developed in the large-grain specimen. Both crack tilting and the height of the shear "cliffs" contributed to this irregularity.

6. At low $\Delta K$ values below $\sim 11$ MPa m$^{1/2}$, cracks in the plate material grew at a lower rate than in the two squeeze-cast materials. The superior fatigue crack propagation resistance of the plate material appeared to result from laminar microstructure dividing the extending crack front.

7. In the high $\Delta K$ regime, above $\sim 11$ MPa m$^{1/2}$, the cracks on the plate material grew faster than in the squeeze-cast materials because the grain boundaries lost their special pinning effect on the crack front. In the squeeze-cast materials the continuing tortuous nature of the crack path, and the feature of micro-crack branching seems to have been responsible for their relatively low fatigue crack propagation rates in the high $\Delta K$ regime.

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