The grain size dependence of fracture toughness in an Al-6.0% Zn-2.5% Mg alloy

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The grain size dependence of the fracture toughness (K_{IC}) of an aged Al–6.0% Zn–2.5% Mg alloy was studied experimentally. K_{IC} depended strongly upon grain size (L_G) in two ways. In the small grain size region K_{IC} decreased with increasing average grain size. In contrast, K_{IC} increased with increasing average grain size for large grain sizes. The increase in K_{IC} with increasing grain size arose as a result of the presence of abnormally large grains compared to the average grain size in the large-grained specimens.

1. Introduction

The grain size dependence of yield, flow and fracture stresses in structural materials have been studied by many investigators [1–4]. However, only one investigation on the grain size dependence of the fracture toughness in high strength aluminium alloys has been reported [5]. The purpose of the present study is to measure the grain size dependence of the fracture toughness in a high strength Al–Zn–Mg alloy.

Oates [6] showed that the fracture strength of notched mild steel decreases with increasing grain size at 77K. Then Kanazawa *et al.* [7] showed that the fracture strength of Mn steels was proportional to (grain size)$^{-1/2}$ at -196 and $-150°$ C. Webster [8] studied the plane strain fracture toughness (K_{IC}), the 0.2% yield strength, and the tensile strength of martensitic stainless steels with two different grain sizes (2.3 and 60 μm). The K_{IC} of the fine-grained steel was almost four times that of coarse-grained steel even though specimens with different grain sizes had the same yield stress. In contrast Okabayashi *et al.* [9] reported that the energy for crack propagation in a Ni–Cr–Mo steel decreased with the decrease of austenite grain size at 18, -78 and $-196°$ C. More recently, Kawabe *et al.* [10] showed that the K_{IC} value of an 18% Ni-maraging steel aged at 475 or 550° C did not depend on austenite grain size, though the K_{IC} for the same material with a fine structure which arose from ageing at 400° C increased remarkably with decreasing grain size. Thus, in steels, K_{IC} value ordinarily seems to increase with decreasing grain size, though there are exceptions in which K_{IC} is independent of grain size or even decreases with decreasing grain size.

Hornbogen [5] proposed an expression describing the grain size dependence of K_{IC}, using the relationship between tensile test data and K_{IC} due to Hahn and Rosenfield, [11] in a model polycrystalline material constructed from square grains with a thin lamellar-like soft zone at the grain boundaries. This expression was applied to the experimental results for precipitation-hardened 7075 series aluminium alloys obtained by Thompson *et al.* [12].

It is well known that the fracture of Al–Zn–Mg alloys occurs predominantly at grain boundaries [13–15]. However, the interpretations concerning the cause of intergranular fracture are not clear since two opposing ideas have been proposed. Geisler [16] suggested that intergranular fracture arises from strain concentration in precipitate-free zones (PFZs) along grain boundaries. Alternatively

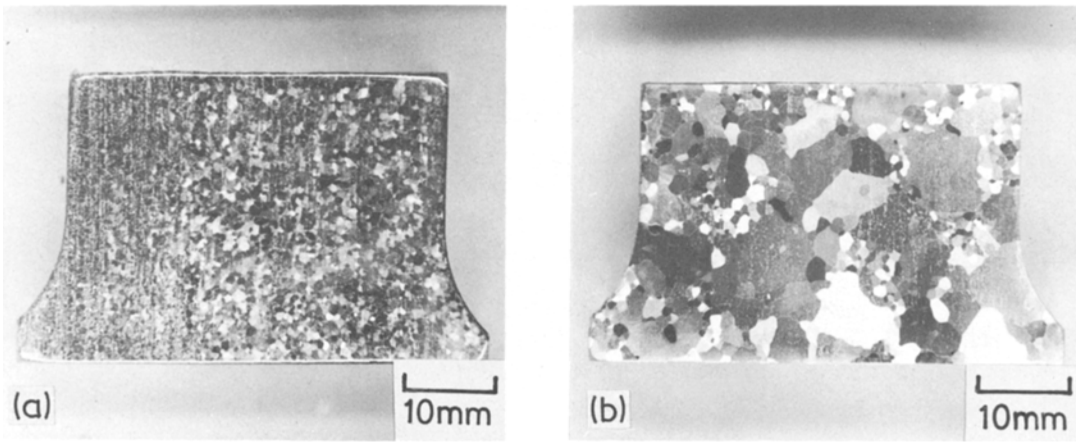

Figure 1 Photographs of structures in specimens with (a) fine and (b) coarse grain.

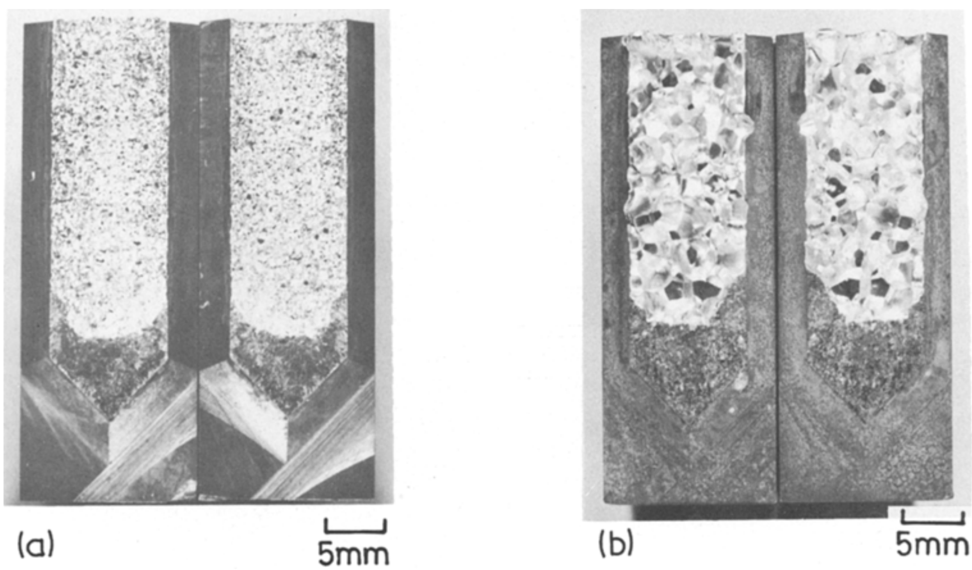

Figure 2 Photographs of fracture surfaces in (a) fine-grained and (b) coarse-grained specimens.

Ryum [17] proposed the PFZs should increase the ductility because they can relax the stress concentration due to dislocation pile-ups extending from the grain interior to the grain boundaries. Most recently, Kawabata and Izumi [15] discussed systematically the relationship between the PFZs, grain boundary precipitates and ductility.

2. Experimental procedure

The composition of the alloy used in the present study is Zn: 6.0 wt%, Mg: 2.5 wt%, and Fe, Si and Cu as impurity elements < 0.01 wt%, respectively. The materials were supplied by the Sumitomo Light Metal Industry, Ltd.

Large single-edge notched tensile specimens with side grooves were tested by the 50 ton Electronic Tube Type Universal Testing Machine. The nominal and notch-reduced sectional areas are 15 mm × 40 mm and 10 mm × ~28 mm, respectively. (The shape and dimensions have been shown elsewhere [18]). Fatigue cracks were introduced at the notch roots by superimposing supersonic vibration on bending stress. The specimens were annealed for various periods (1 to 106 h) at 460° C, in order to vary the grain size, quenched in iced water and then aged at 160° C for 4 h. The grain sizes as measured by the intercept method were L_G = 0.33 to 1.44 mm. The method of Freed and Krafft [21] was used to calculate K_{IC} for the side grooved specimens.

3. Results

3.1. Microstructures and observation of fracture surfaces

Figs. 1a and b show the fine- and coarse-grained structures. The grain size was uniform for annealing periods up to about 25 h. Beyond 25 h large grains which grew abnormally appeared. Figs. 1a and b show the fine- and coarse-grained fine- and coarse-grained specimens. Fig. 3 presents schematically the features of the fracture surfaces. The crack starts from the root of fatigue crack in a direction inclined at about 45° to the tensile axis and runs curving to the plateau in the middle region of the fracture surface. Inevitably, one side of the fracture surface was convex and the opposite side was concave. The deviation of the fracture surface from the plane of the fatigue crack, c, increased with increasing grain size. The crack path connecting back to the root of the fatigue crack was approximately that of the maximum shear stress [19, 20]. The roughness at the plateau region also increased with grain size due to intergranular fracture.

The dark portion at one side of the fracture surface is the fatigue fracture surface which was formed as a crack starter.

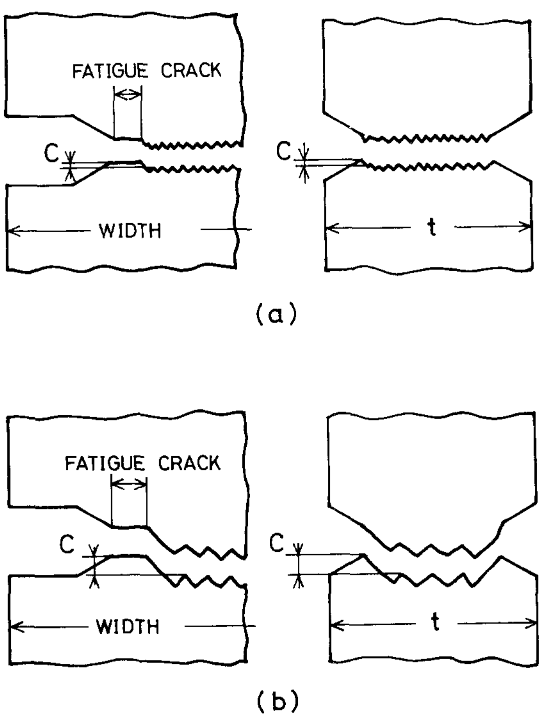

Figure 3 Schematic figures showing the features of fracture surfaces in (a) fine-grained and (b) coarse-grained specimens.

3.2. The shape of load–time curves and the preciseness of measurement of K_{IC}.

Fig. 4 shows an example of load–time curves. In most of the specimens failure occurred suddenly with a large load drop. Some specimens showed "pop-in" behaviour before rapid crack propagation. In general the load–time curve was completely linear. In curve 2 the decrease of inclination with time occurred because the oil hydraulic testing machine used has a characteristic decrease of cross-head speed with increasing load. According to Freed and Krafft [21] the effect of side grooves introduces constraints which allow accurate K_{IC} values to be measured using smaller specimens than are necessary without side grooves.

3.3. Grain size dependence of K_{IC} values.

Fig. 5 shows the variation of K_{IC} values and the mean grain size (L_G) with annealing time at 460° C. Although K_{IC} values, at first, decrease monotonically with increase in annealing time (region I), for periods longer than 50 h they increase with annealing time (region II). The initial decrease of K_{IC} arises from the variation of yield strength with grain size; but increase of K_{IC} for longer annealing periods must arise from some other cause.

Annealing periods of over 25 h produced abnormal growth of some grains and it is considered that this is related to the abnormal increase of K_{IC}.

For annealing times up to 50 h, K_{IC} was proportional to $L_G^{-1/2}$ as shown in Fig. 6.

4. Discussion

4.1. The dependence of K_{IC} on grain size

The strong grain size dependence of K_{IC} arises from the same microstructural factors as determine the dependence of the material properties, such as the ductility and yield strength, on grain size (L_G). The structural parameters which vary with L_G and their effects upon K_{IC} are considered below:

(i) In fractures resulting from the formation of grain boundary ledges (this type of fracture is discussed in a separate paper [22]), the increase of pile-up length of dislocations lowers the fracture stress, resulting in a decrease of K_{IC} values.

(ii) The contribution of the plastic strain from the PFZ to the total plastic strain is small because

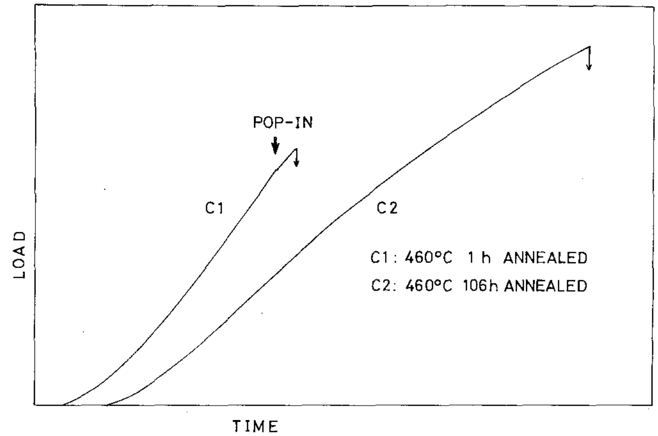

Figure 4 Examples of load–time curves in tensile testing of notched specimens with side grooves.

of the small volume fraction of PFZ. [18] However, concentration of plastic strain in the PFZ is larger than that in the grain interior. Unless other parameters vary with the volume fraction of PFZ (f^V_{PFZ}), the decrease of f^V_{PFZ} results in a small decrease of the total plastic strain to fracture, i.e., a small decrease of K_{IC}. f^V_{PFZ} is expressed as 4.09 (w/L_G) [15], where w is the width of PFZ, therefore, K_{IC} would decrease with increasing L_G.

(iii) It has frequently been observed that the Al–Zn–Mg alloy fractures at grain boundaries (or in the PFZ) on which sliding occurs [15, 22]. Grain boundary sliding is therefore an important mechanism leading to grain boundary fracture. The sliding displacement on one side of the boundary increases with the length of the grain side, and the degree of formation of defects leading up to fracture is also proportional to the sliding displacement. That is, if the sliding reaches a critical value the grain boundary would be fractured. Therefore, the larger the value of L_G, the smaller the overall strain to fracture. As a result, increasing L_G leads to a decrease in the overall fracture energy.

4.2. The increase of K_{IC} arising from the presence of grains of much greater than average size.

As shown in Fig. 5 K_{IC} increases with annealing

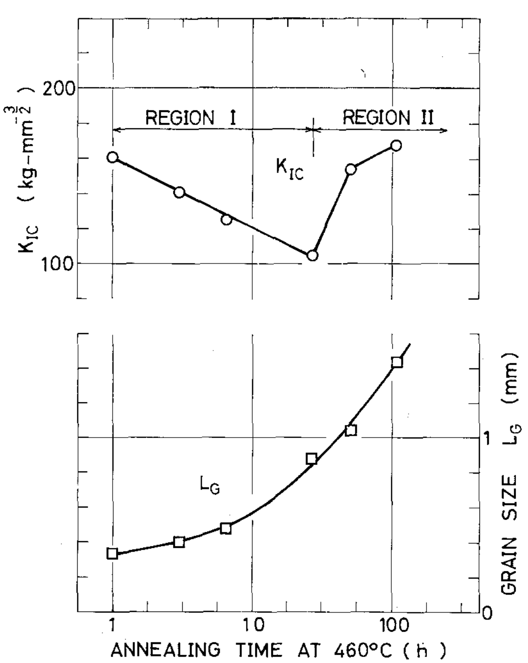

Figure 5 The variation of K_{IC} and L_G with annealing time at 460° C in an Al–6.0% Zn–2.5% Mg alloy.

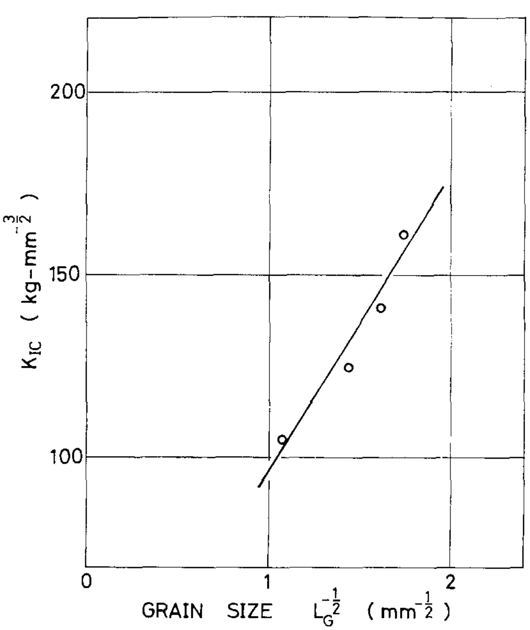

Figure 6 Tentative representation of K_{IC} versus (grain size)$^{-1/2}$ in an Al–6.0% Zn–2.5% Mg alloy.

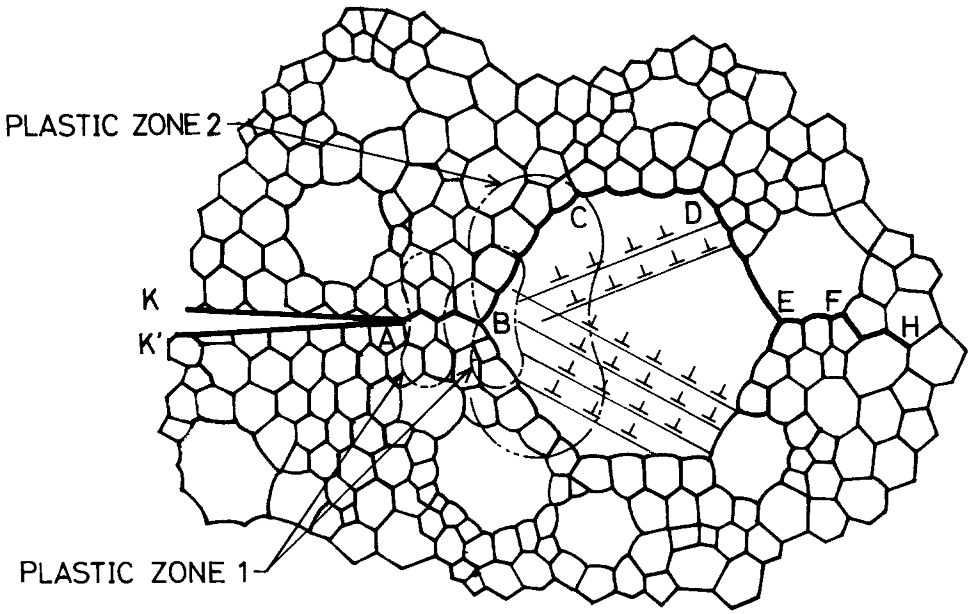

Figure 7 Schematic figure showing the effect of large grain size on K_{IC}.

time for periods in excess of 50 h. The average grain sizes varied from 1.03 to 1.44 mm for 50 and 106 h, respectively.

The specimens showing this abnormal behaviour had mixed microstructures with grain sizes generally in the range 1 to 1.4 mm, but with occasional grains of 5 to 8 mm in diameter. Observation of the fracture surfaces showed that the grain boundary planes of those large grains appeared on the fracture surfaces, and the roughness of the fracture surface was remarkably large compared with that of specimens having an approximately equi-axed small grain size.

From the above, it is speculated that the large grains act as obstacles on a plane where the crack propagated, resulting in an increase of K_{IC} due to the increase of fracture energy associated with the large deviation of the course of the crack and the increase of plastic zone size. A schematic figure illustrating this mechanism is shown in Fig. 7. As the applied stress increases, a plastic zone is formed in front of a crack KAK′. When the stress and the strain at the crack front are large enough to start grain boundary fracture, the crack will advance to point B. In order to propagate from the point B the crack must proceed along a course BCDEFH. The crack is envisaged to stop at B for a short time until the plastic zone grows large enough to propagate the crack along the boundary BCD of the large grain. In order to advance the crack to beyond the large grain, the size of the plastic zone must become considerably larger than that of the crack propagating among the small grains.

Furthermore, the plastic zone size shown as 1 in Fig. 7 should be large enough to propagate the crack to the point B. While the crack is stopped, the size of plastic zone increases gradually to that of zone 2. If the stress level within zone 2 is raised so that dislocations can move, and if a slip plane in the large grain exists in a direction close to that of the maximum shear stress, slip bands will pass through the large grain because the leading dislocation is pushed by following pile-ups formed within zone 2. That is, even if the region in which dislocations are moveable is limited only within zone 2 and occupies only a portion of the large grain, the area of the plastic zone will tend to be enlarged to the whole of the large grain. This phenomenon results in an additional increase in plastic work which contributes to the increase of K_{IC}.

The ratio of large grains to small ones increased with the average grain size. Therefore, the increase in K_{IC} with L_G arises for two reasons, i.e. the increase in the ratio of large grains and the additional plastic work required by the size of the large grains.

5. Conclusions

The grain size dependence of fracture toughness (K_{IC}) in an aged Al–6.0% Zn–2.5% Mg alloy depends strongly upon the grain size (L_G) in two ways. In the regime of smaller grain size K_{IC} decreases monotonically as the grain size increases; in contrast K_{IC} rises with increase in average grain size for a regime of large grain size. The plot of K_{IC} values versus $L_G^{-1/2}$ in region I showed an approximately linear relationship. The phenomenon in region II is explained by (i) the enlargement of the plastic zone due to the existence of the large grains mixed in with the small ones and (ii) the increase of the ratio of large grains to small grains with increase of the average grain size.

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