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Tear Toughness Evaluation of Aluminum Alloy Castings Using a Small-Size Specimen

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Abstract

The tear toughness of a permanent-mold cast A 356 aluminum alloy was investigated by using standard specimens designated in ASTM B871 and small-size specimens which are about 30% as large in volume as standard one. Unit energies were obtained from load-displacement curves and their dependence on specimen size, specimen thickness and microstructure was examined.

1. Introduction

The fracture toughness of aluminum alloys can be estimated from tear resistance as defined in ASTM B871 [1,2]. In the tear test, a sharp-notched plate specimen is subjected to static tensile loading until a crack develops at the root of the notch and travels across the width of the specimen. Several numerical results can be obtained from the load-displacement curve. Unit crack propagation energy (UEp) is the representative measure of tear toughness and is computed by dividing the measured energy for crack propagation by the net area of the specimen. Recently, Kumai et al. suggested that tear tests provide useful information concerning the effect of solidification structure on toughness, which is available to foundry engineers as a guide for further toughening of aluminum alloy castings [3]. In previous studies, a standard-size specimen has been used. However, the cast product of interest in investigation is not always large enough. Therefore, reduction of the specimen size will be beneficial.

In the present study, the effect of specimen thickness and specimen size on tear toughness was investigated using a permanent-mold cast A356 aluminum alloy. In addition, small-size specimens collected from various parts of the single cast product were tear-tested and correlation between UEp and solidification structure was discussed.

2. Experimental Procedure

Two types of permanent-mold cast products of A356 alloy (cast plates and cast bars) were provided for the test. Before casting, an Al-10mass%Sr alloy was added to the melt for the purpose of eutectic Si modification. The size of the plate was 200×100×20mm. The cast bar was about 30×40×170(mm). Both of them were homogenized at 808K for 14.4ks (4h) and water-quenched. After being maintained at room temperature for 43.2ks (12h), they were artificially aged at 433K for 21.6ks (6h). Standard-size specimens (Figure 1 (a)) with 5 variations in thickness (2, 3.5, 5, 7 and 9mm) were machined from the central part of the cast plate (see Figure 5). Small-size specimens (Figure 1 (b)) with 4 variations in thickness (2, 3.5,5 and 7mm) were sampled from the central part of cast bars. In addition, small-size specimens were machined from several specific parts of the single cast bar. Details of the small-size specimens are given in the following section (3.2).

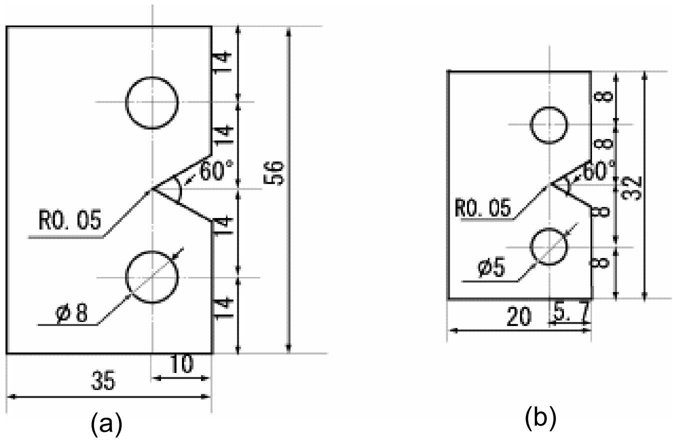

Figure 1: Morphology tear test specimens. (a) standard-size (b) small-size

Tear tests were performed using an Instron-type testing machine. The specimen was subjected to tensile loading at a constant crosshead speed of 8.3×10^{-6}m s^{-1} at room temperature in air.

In the present tests, crosshead displacement was recorded to obtain the load-displacement curve. The present authors performed a number of tear tests for some cast alloys comparable to the present material using the displacement gage in advance. Experience based on a series of experiments has shown the load-displacement curves obtained in the present study are still useful for direct comparison and relative rating of tear toughness of the A356 cast products so long as we use exactly the same testing machine and loading system. The crack initiation at the notch root was detected using an AC potential drop method. Tensile tests were also performed using a rectangular bar specimen with shoulders (gage section: 16×5×4mm) at a constant crosshead speed of 8.3×10^{-6}m s^{-1}

Optical observation of the microstructure was carried out for the polished cross-section of the castings. An image analyzer was employed for quantitative evaluation of dendrite arm spacing (DAS) and size of eutectic Si particles. A polished cross-section was also anodized in a 2% HF solution at a voltage of 25V and a current density of 0.2mA mm^{-2} to reveal the grain structure.

3. Results and Discussion

3.1 The effect of specimen thickness on tear toughness

Microstructural parameters for the A356 cast products are shown in Table1. The Si particle size mentioned here is the average length of the major axis and minor axis of the modified oval-shaped Si particles.

Table 1: Quantitative data of microstructural parameters for the cast plate and the cast bar.

	Grain size (μm)	DAS (μm)	Si particle size (μm)	Aspect ratio of Si
cast plate	420	20.0	1.1	2.3
cast bar	476	26.5	1.8	1.5

Figure 2 shows load - displacement curves of the small-size specimens. Instantaneous load drop, "pop-in", was observed for the specimens with 5mm thickness and more. Small arrows on the load - displacement curves indicate the load where the potential drop change took place. Such a crack initiation load is called "Pi" hereafter. The Pi was also shifted to Pmax with increasing specimen thickness. The pop-in stress was located between Pi and Pmax in thick specimens.

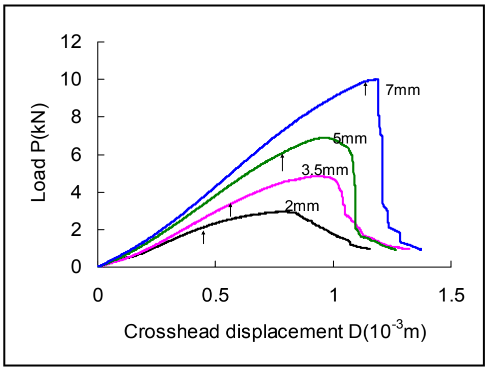

Figure 2: Load - displacement curves in tear tests for the small-size specimens with different thickness. Each arrow on the curve indicates the crack initiation point detected by the AC potential drop method.

Figures 3 (a) and (b) show schematic load-displacement curves in tear tests. Unit initiation energy, UEi, and Unit propagation energy, UEp, are computed by dividing the measured energy by the net area of the specimen. Unit total energy, UEt, is a total of UEi and UEp. On the analogy, true unit energy (UEit, UEpt, UEtt) can be obtained if the load-displacement curve is divided into two segments by the vertical line through the Pi.

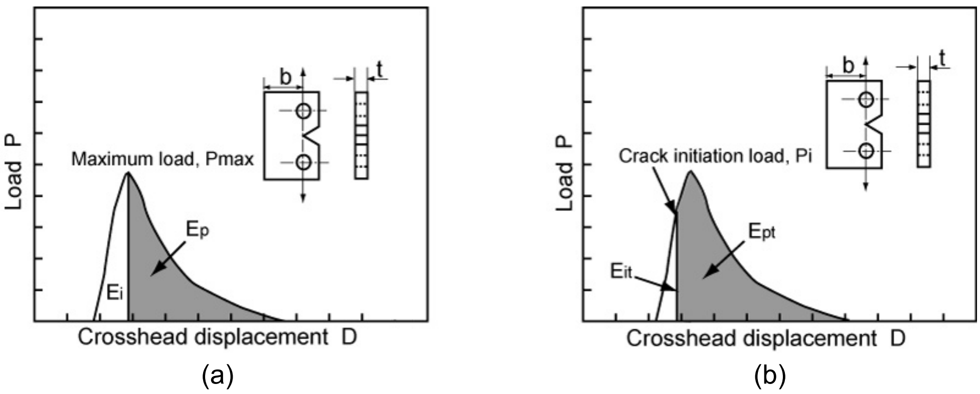

Figure 3: Schematic load - displacement curves in tear tests and definition of energies. (a) UE defined by the maximum load, Pmax (b) UE defined by the crack initiation load, Pi.

Unit energies are plotted as a function of specimen thickness in Figure 4. There is no significant change in UEt at any specimen thickness. In contrast, UEi increases as increasing specimen thickness, while UEp decreases as increasing specimen thickness. Thus, specimen thickness affects quantitative balance between UEi and UEp significantly. Similar specimen-thickness dependency was observed by comparing true unit energies.

Some previous studies treated the effect of specimen thickness on tear toughness. Komura and Taki [4-5] pointed out that the toughness value was hardly influenced by the specimen thickness if it was less than 10mm. Kobayashi et al. [6] found the crack initiation load which was detected by using DC potential method shifted toward the maximum load with increasing specimen thickness and that both UEit and UEpt changed with specimen thickness. However, no explanation was offered. The present study exhibited a clear specimen thickness dependency of UEi and UEp. In particular, UEp decreases monotonically with increase in thickness. This result is consistent with Kaufman's report [7]. He described a general trend for UEp to decrease with increasing specimen thickness.

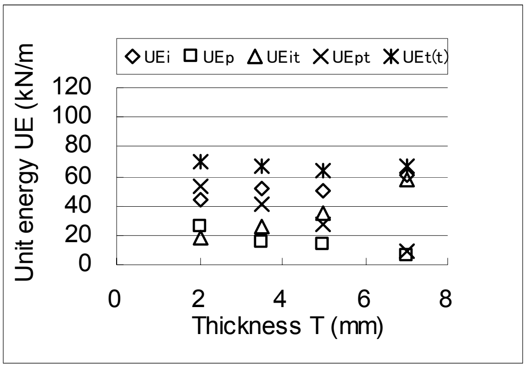

Figure 4: Effects of specimen thickness on unit energies for small-size specimens.

The macroscopic appearance of the crack path is as shown below. For the specimen with 2mm thickness, a slanted crack path was dominant through the specimen ligament. The fracture surface was entirely covered with the slanted crack. In contrast, for the specimen with 7mm thickness, a flat crack path was dominant. The fracture surface was normal to the loading direction through the net section of the specimen. The effect of specimen thickness on fracture toughness for ductile materials was treated by Knott [8]. A fracture mechanics approach also indicated that the slant fracture increases fracture resistance or toughness, and its contribution depends on specimen thickness [9]. Fracture surface observation using SEM revealed that the fracture surface was covered with dimple morphology. The crack growth path was seen to be a mixture of inter-granular and trans-granular since eutectic Si particles dispersed not only along the grain boundaries but also in the grain associated with dendrite structure.

3.2 The effect of solidification structure on UEp

In general, the solidification structure varies within a casting. The outer region of the casting generally exhibits a finer structure compared to that of the middle part. The small-size tear test specimen is so small that we can study such a local microstructure selectively. Several kinds of specimens with different thickness were collected from the single cast bar. Figure 5 shows the location in the cast bar, from which the tear specimens were collected. Microstructures of the cast bar are shown in Figure 6 (a) ~ (f). Alphabetic letters in the picture correspond to the local microstructure at which the specimen was collected. Specimens denoted by “A” have the crack propagating from the notch into a progressively finer structure; in those denoted by “B” propagation is into a coarser microstructure. Labels (s) and (c) refer to the surface and centre of the bar, respectively.

The UEp values are shown in Figure 7 and it is clear that UEp values of “A” specimens are larger than those of “B” specimens. A comparison between (c) and (s) was also made. A(s) and B(s) have larger UEp values than A(c) and B(c). These results are reasonable considering from the relationship between the tensile properties and fineness of the microstructure in the present material as shown in Figure 8. The specimens with finer DAS showed larger UEp. The results shown in Figure 7 suggest that the UEp is a useful measure for evaluating tear toughness of the cast material. It was also demonstrated that the UEp is sensitive to relatively small microstructural difference in the single casting.

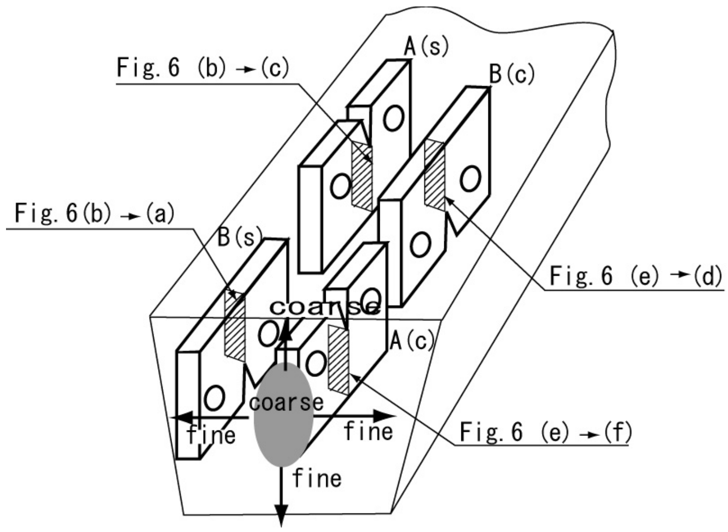

Figure 5: Notation of the collected small-size specimens from various parts of the cast bar product. Microstructure of the shaded area in each specimen corresponds to the picture shown in Figure 6

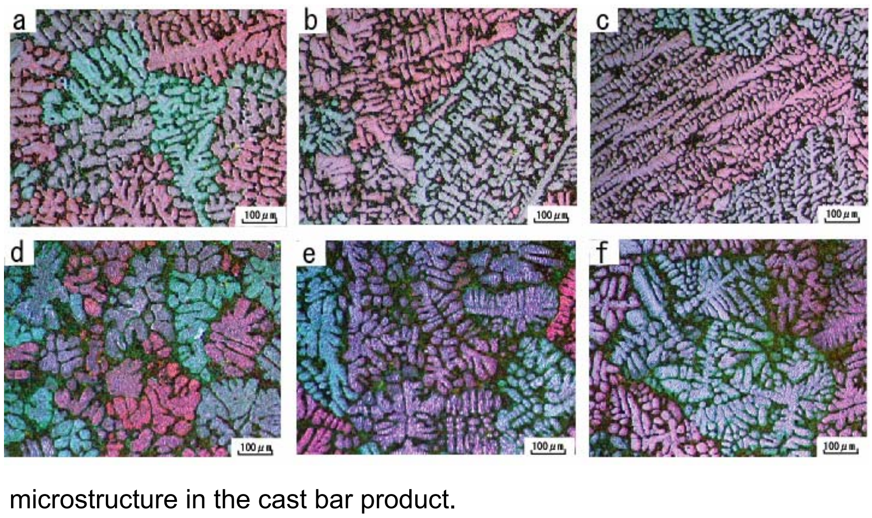

Figure 6: Local microstructure in the cast bar product.

(a) Top-surface (b) Middle-surface (c) Bottom-surface (d) Top-central (e) Middle-central (f) Bottom-central

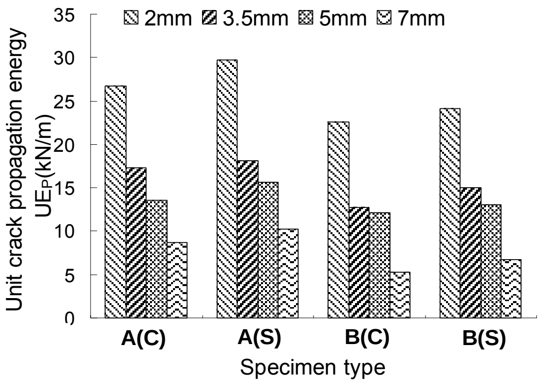

Figure 7: Effects of specimen thickness and local microstructure on UEp.

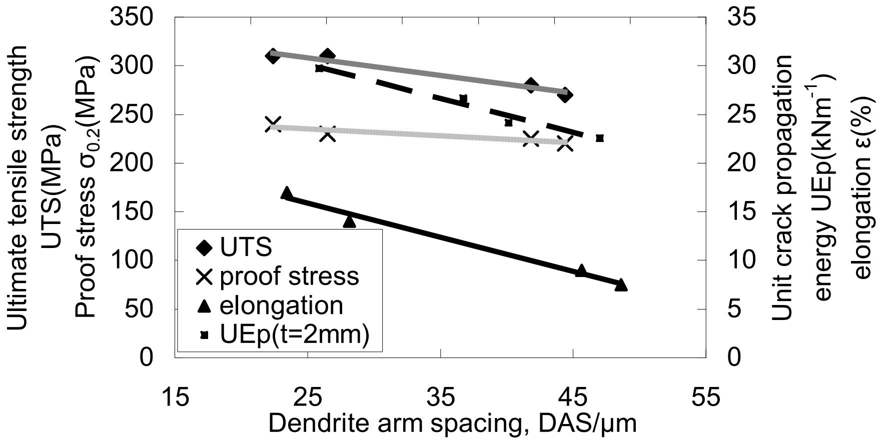

Figure 8 Effects of DAS on the tensile properties and tear toughness

4. Conclusions

Tear toughness evaluation was performed on permanent-mold cast A356 alloys. Unit energies for crack initiation and propagation were examined and their specimen size, thickness, and microstructure dependency were discussed.

Unit crack initiation energy (UEi) increased with increase in specimen thickness. Unit crack propagation energy (UEp) monotonically decreased in accordance with increase in specimen thickness. Small-size tear test specimens were collected from the various parts in the single cast product. The tear specimen with finer DAS showed larger UEp. These findings suggest that the tear test using a small-size specimen is useful for toughness evaluation of the cast aluminum alloys even though it is still one of the comparative tests.

Acknowledgments

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