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EFFECT OF FRONT NOTCH GEOMETRY AND SPECIMEN DIMENSIONS IN DOUBLE TORSION TESTING OF 2124 - T851 ALUMINUM

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ABSTRACT

Experimental investigation was performed to study the effect of front notch geometry and specimen dimensions in double torsion testing of 2124-T851 aluminum alloy. The results showed that the machined front notch geometry has no appreciable effect on the fracture toughness values, provided that the critical load is read off correctly from the load displacement curve, that is when a stable crack front has been fully developed. The results also showed that the double torsion test can yield valid fracture toughness values in aluminum 2124-T851, provided that the specimen thickness between bottoms of grooves is larger than 4.4 times the plane stress radius of plasticity and the overall thickness of the specimen is sufficient to avoid significant torsional warping.

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INTRODUCTION

The need for a simple and reliable fracture toughness test has been felt in industry for several years, especially for determining the fracture toughness of materials not available in sufficient bulk to satisfy the strict dimensional requirements of standardized techniques. The double torsion testing technique was originally introduced and subsequently developed by Outwater and Gerry |1| to determine the fracture toughness of relatively thin glass sections. The test has since been successfully applied to other brittle metallic, as well as nonmetallic materials, in addition to other materials of limited ductility |2-32|.

However, the analysis of this test had not until recently progressed much beyond its original form. The notable exceptions are the inclusion of kinetic effects in the test analysis |33|, the application of finite element analysis to study the effects of specimen geometry on test results |34,38|, and finally a compliance analysis of the test |39|. An evaluation of the double torsion testing technique has been reported by two of the authors in a previous work |40| in which they reviewed some of the questions concerning the test results which possibly have hindered the adoption of the test as a standard one. The validity of the double torsion test was also studied by one of the authors et al |41|. They reported that the curved profile of the crack front is beneficial to permit material constraint sufficient for maintaining a high degree of plane strain deformation in the vicinity of the the crack tip when the thickness of the specimen reaches a critical value much smaller than the minimum thickness requirement of the ASTM standardized techniques.

In the present work, an experimental investigation was performed to study the effects of initial front notch geometry, and the thickness of the specimen between grooves on the test results of the double torsion test.

EXPERIMENTAL WORK

In the experimental investigation, test specimens of 2124-T851 wrought aluminum alloy were used. The subject materials were received in the form of thick flat plates with the dimensions of 304.8 x 304.8 x 25.4 mm. The specimens were prepared with a geometry that conforms with the finite element model number 4 established by Tseng and Berry |38|, where $\frac{L}{2} = 2$, and $\frac{2t}{W} = \frac{1}{3}$. The specimen dimensions and geometry are shown in Table 1. The general arrangement of the test appears in Fig. 1.

Table 1 Dimensions and Geometry of Double Torsion Test Specimens

Specimen Dimensions (mm)				Geometry of Crack-Front (degree)	Sharpening Condition of Crack-Front
W	L	t	t_c		
61	122	10.2	6.1	0, 45, 90, 135	NFPC**
61	122	10.2	1.3,3.0, 4.6,6.1, 6.6	90	FPC* and NFPC**

* Non-Fatigue Precracked.
** Fatigue Precracked.

A longitudinal Vee groove was milled at mid-width on both faces of each specimen to guide the crack propagation. Various crack starter or front notch designs were machined in order to provide different initial crack front geometries. These are shown in Fig. 2. One of the reasons that notches of this type are recommended is that they circumvent end effects |38|. Certain of the aluminum specimens were directly tested without fatigue precracking, while others were fatigue precracked with a cycling load of about 0.6 of the non-fatigue precracked critical load. The test specimens were then statically tested in a 44,480 N. Instron testing machine using a specially designed test rig. All tests were conducted at a constant crosshead speed of 8.5×10^{-6} m/s and a load displacement curve was plotted.

RESULTS AND DISCUSSION

Determination of the Critical Load P_c:

Typical load-displacement curves are shown in Fig. 3. The figure shows basically that the load-displacement plot of the double torsion test presents four distinct regions, namely, an elastic region, a crack initiation region, a stable crack propagation region and a final failure region.

In the load-displacement plot of materials exhibiting some ductility, such as the present aluminum alloy (~ 15%), the crack initiation and propagation zones possess some special features. From the typical load-displacement curve of the aluminum alloy shown in Fig. 3, it would seem that once the crack initiates, the crack propagation requires an increase in the load until the specimen finally fractures in a brittle manner. The reason behind the requirement for an increased load for the crack propagation probably arises since the initial crack experiences resistance in the form of local plastic deformation around the crack front. Therefore, it is suggested that the critical load P_c to be utilized in determining the provisional fracture toughness might be generally defined as the load at which cracking initiates. According to this definition, the critical load P_c was marked by witnessing the first audible signs of cracking. It was further observed that the first audible signs of cracking occurred at the load where the load-displacement plot became nonlinear. However, in the case of testing materials that do not show a clear audible crack initiation, acoustic emission sensors may be used for an accurate detection of crack initiation.

Effect of Initial Front Notch Geomtry:

Typical load-displacement plots for non-fatigue precracked 2124-T851 aluminum alloy specimens with different front notch geometries are shown in Fig. 4. The figure shows that the crack initiation occurred at a peak load P_K greater than the load required for stable crack propagation P_c. Moreover, the highest value of P_K occurs when the initial notch front is 0^0 (no starter front notch) followed by 135^0, 90^0, and 45^0. It is clear that 45^0 front notch geometry comes close to the curved stable crack profile and hence would, in practice, require a much lower peak load for crack initiation as compared to 0^0 or unnotched specimens, in which it is necessary to establish a notch. This can be affirmed by looking at load-displacement plots of subsequent loading of a wrought aluminum specimen with 0^0 initial crack front geometry, as shown in Fig. 5. The figure shows that the crack initiation in the first loading of this specimen occurs at a peak load P_K, dropping instantly once the crack front is developed. The figure also shows that by arresting the stable crack propagation and reloading the specimen, the crack initiation occurs at a critical load P_c much lower than that of the initial loading. The subsequent arrest of the crack and reloading showed no further significant change in the critical load P_c. This leads to an important conclusion that a fully developed precrack is essential before conducting the double torsion test on alloys exhibiting moderate ductility to avoid obtaining erroneously high K_Q values. This can be undertaken by fatigue precracking the specimens with a cycling load less than the critical load required for static crack initiation.

Minimum Thickness Requriment in Double Torsion Test:

Fig. 6 shows the relationship between the provisional fracture toughness K_Q and the specimen thickness between grooves t_c for fatigue precracked 2124-T851 aluminum alloy specimens. The figure shows that the value K_Q increases with increasing the thickness between grooves t_c and attains its maximum value at t_c = 4.4 mm.

The feature of Fig. 6 can be explained in terms of the mode of fracture that may exist, as a function of the stable crack front length |41|. Below specimen thickness, t_c = 4.4 mm, the curved length of the crack front formed is relatively small; consequently, the bulk material constraint parallel to the front is low and fracture occurs only by a shear type mode. Assuming that the work done per unit volume of the material that is permanently deformed is roughly constant, the force required to move the crack, as has been defined by Irwin |42|, is proportional to the curved length of crack front. Since the stress intensity factor $\sqrt{K_Q}$ varies as the crack extension force, the value of K_Q should also vary as the square root of the curved length of the crack front for values of t_c below 4.4 mm. When t_c reaches 4.4 mm, the curved length of the crack front approaches a critical value at which level the bulk material parallel to the crack front will fully constrain the plastic deformation at the crack tip and the entire fracture occurs by a normal mode under plane strain conditions at the crack tip. The value of K_Q remains roughly constant for values of t_c larger than 4.4 mm, which is essentially equal to K_{IC} value obtained from independent compact tension tests |21|. Now the radius of plastic zone r_p is given by |43|

$$r_p = \frac{1}{2\pi} \left(\frac{k_{IC}}{\sigma_{ys}}\right)^2$$

For the sample of aluminum-alloy 2124-T851 currently being considered (σ_{ys} ~ 441 MPa), r_p = 1.00 mm and minimum thickness $(t_c)_{min}$ = 4.3 mm. This suggests a ratio of t_c/r_p of the order of 4.3, which is nearly four times less than that of the standardized compact specimen fabricated from the same material.

Fatigue Precracking Versus Non-Fatigue Precracking:

Although not the primary object of the present investigation, the question of the ratio of fatigue pre-cracked K_Q values to those obtained from non-fatigue pre-cracked double torsion test specimens frequently arises. The results of the tests described earlier in the paper have been collected in tabular form as shown in Table 2. The values of the ratios concerned lie between 0.80 and 0.99. Recent work with electroslag remelted AISI 4340 (H_{RC} 57) revealed values of 0.96 for full-size and 0.95 for small scale 45^0 front notched specimens (non-grooved thicknesses of 9.5 and 5.1 mm respectively). It is interesting to note how the various results compare with the original range of ratios |5| quoted by Outwater et alia (0.81 to 0.89) for 2124-T851 alloy.

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Table 2 Provisional Fracture Toughness, K_Q, Values for Regular Aluminum 2124-T851 Specimens (90 degree notch geometry) With Various t_c With and Without Fatigue Precracking.

t_c (mm)	NFPC - K_Q $MN.m^{-3/2}$ Range of Values	NFPC - K_Q $MN.m^{-3/2}$ Average Value	FPC - K_Q $MN.m^{-3/2}$ Range of Values	FPC - K_Q $MN.m^{-3/2}$ Average Value	Number of (N) Values	(K_Q) FPC / (K_Q) NFPC
1.19	6.55 - 7.45	7.15	4.64 - 6.75	5.71	4	0.80
3.05	23.44 - 28.34	25.80	17.93 - 20.19	19.44	3	0.75
4.42	33.70 - 37.67	35.69	27.72 - 36.10	32.70	3	0.92
4.62	33.78 - 36.33	35.99	30.70 - 35.31	33.60	3	0.93
5.94	32.93 - 34.47	33.90	30.68 - 31.81	31.13	3	0.92
6.88	35.22 - 38.57	33.54	33.54 - 36.89	35.49	3	0.99

CONCLUSIONS

From the present work, the following conclusions may be drawn concerning the effect of front notch geometry and minimum thickness requirement in the double torsion test.

1. In double torsion testing, the critical load, P_c, should be taken as the the load indicated when the first crack initiates (first audible crack sound) in case of moderately ductile materials, rather than peak load P_K.

2. The machined front notch geometry (crack starter) has no appreciable effect on the fracture toughness K_Q values, provided that the critical load P_c is read off correctly from the load-displacement curve, that is, when a stable crack front has been fully developed.

3. The fatigue-precrack fracture toughness, K_Q, values are invariable lower than those obtained from nonfatigue precrack tests.

4. The double torsion test can yield valid fracture toughness values in aluminum 2124-T851, provided that the specimen thickness between grooves, t_c, is larger than about 4.4 times the radius of plasticity, r_p, and the overall thickness, t, is sufficient to avoid significant torsional warping.

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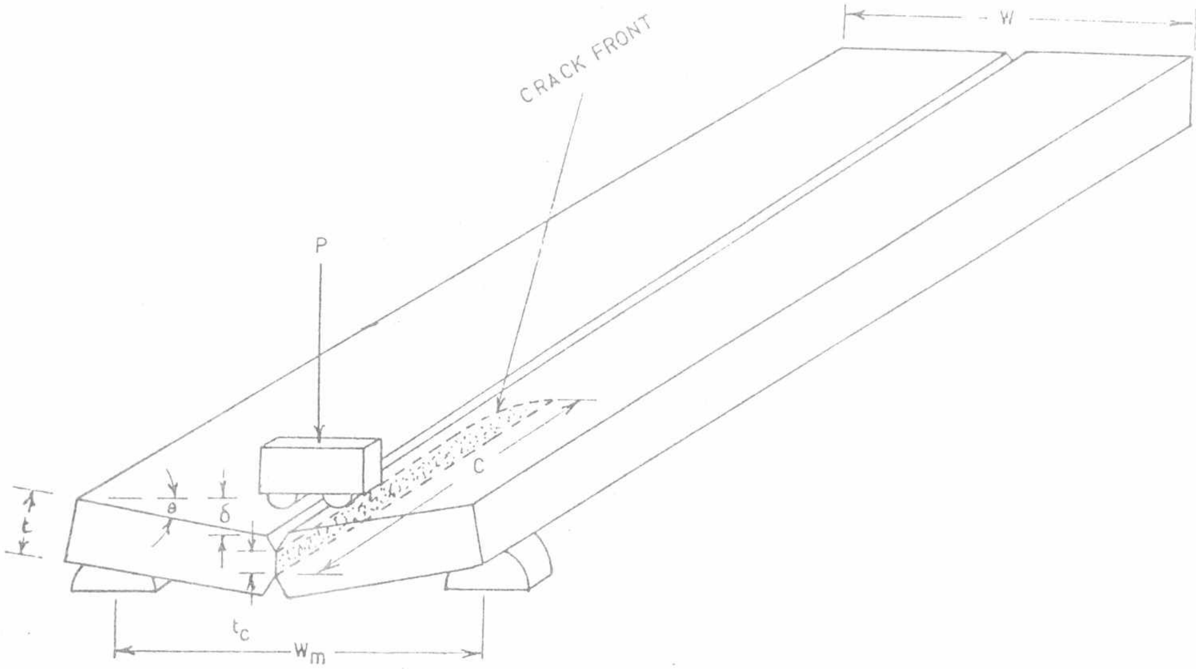

Fig.1 Appearance of a double torsion specimen under loading conditions.

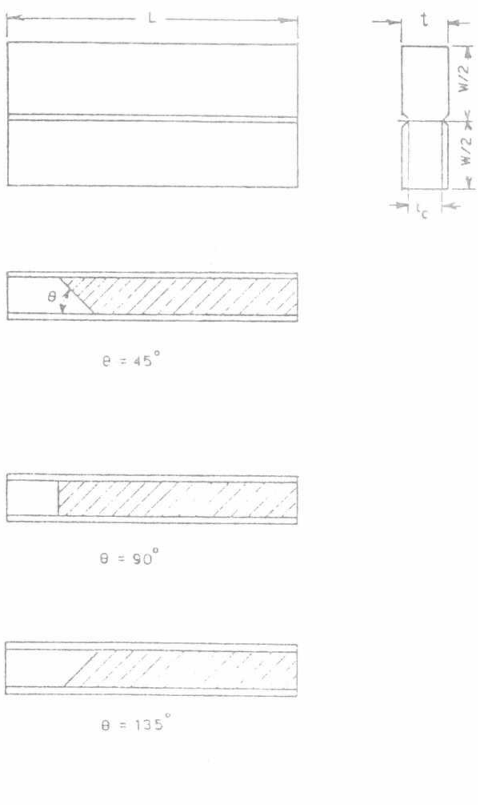

Fig.2 Geometry of test specimens adopted in the tests.

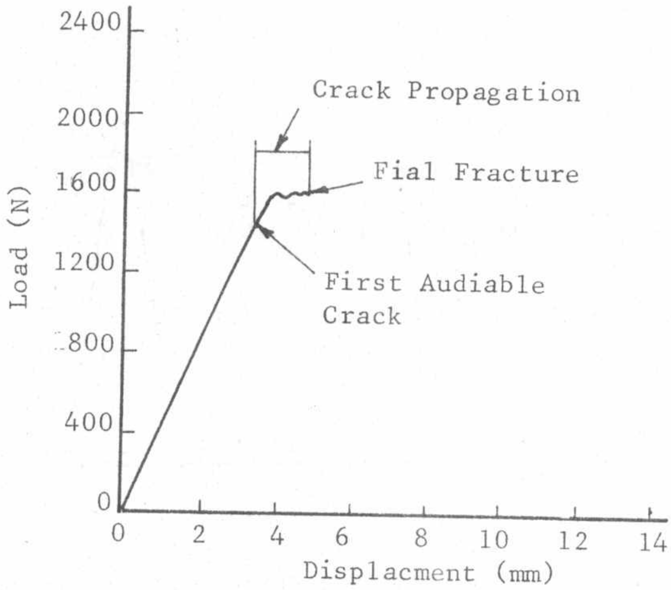

Fig. 3 Typical load displacment record of regular aluminum 2124-T851 fatigue precracked specimen.

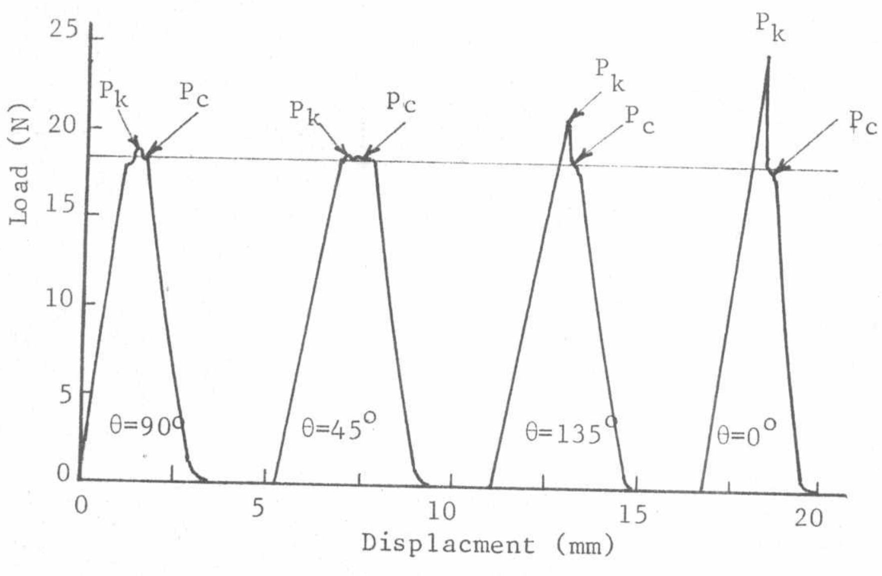

Fig.4 Typical load displacment plots for non-fatigue recracked (NFPC) 2124-T851 aluminum alloy double torsion specimens with different initial front notch geometries.

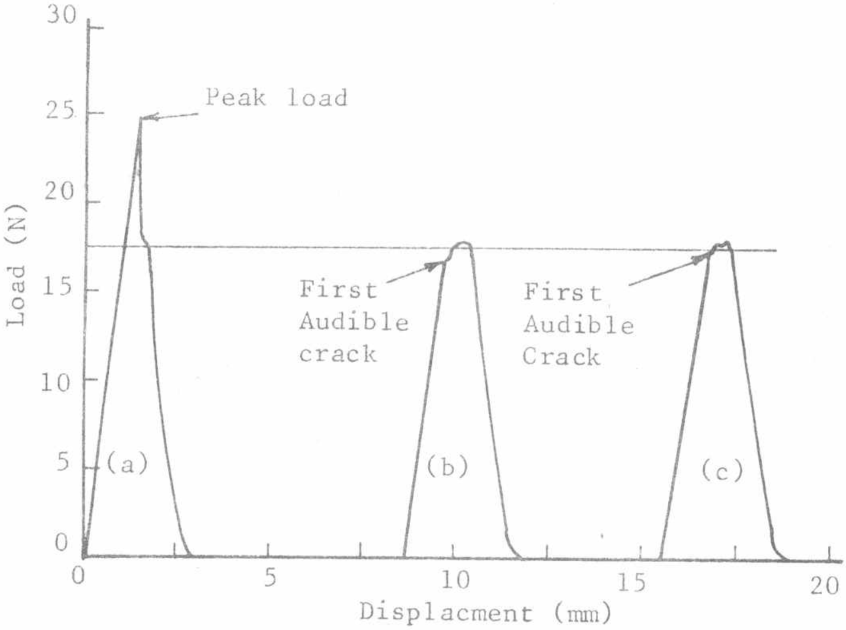

Fig.5 Typical consecutive load-displacment plots of non-fatigue precracked (NFPC) 2124-T851 aluminum alloy specimens with 0^{o} initial crack front: (a) First loading; (b) Second loading; (c) Third loading.

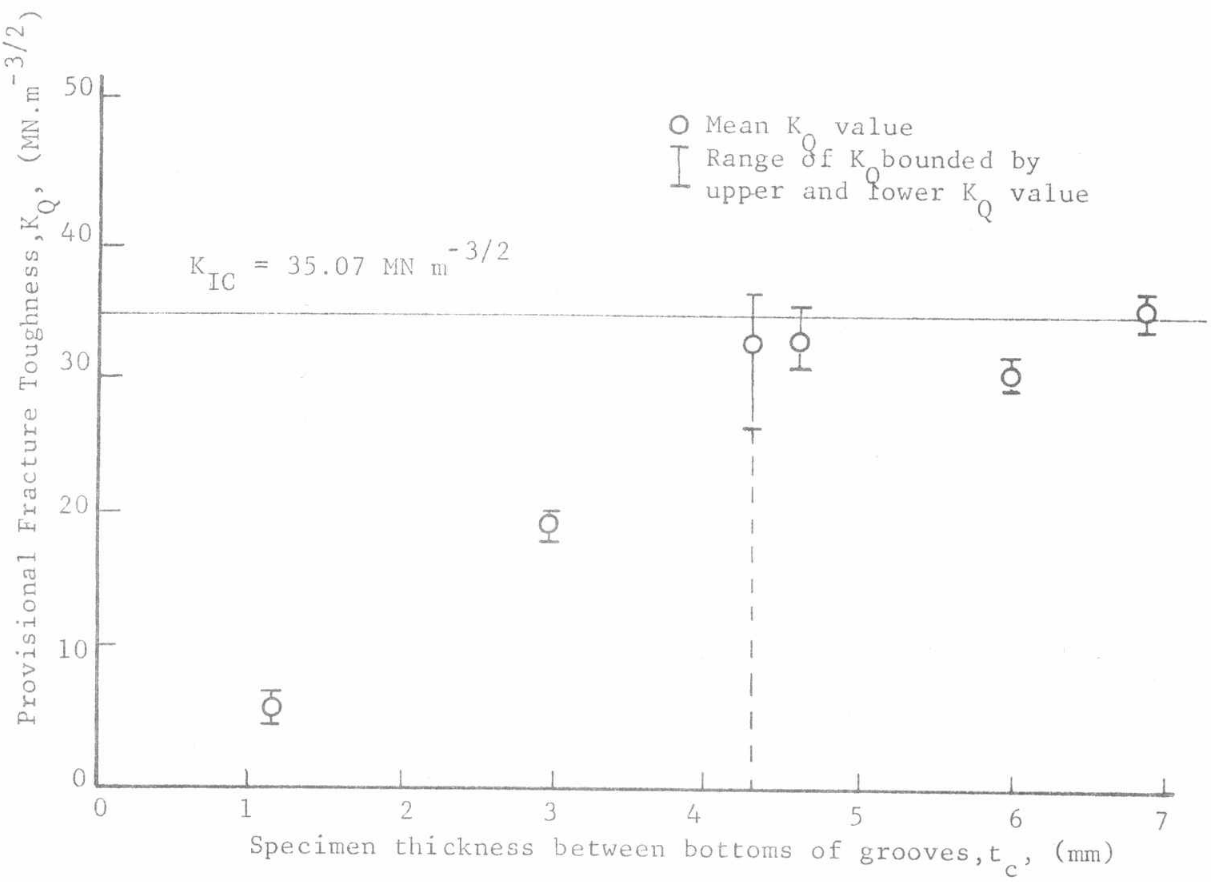

Fig.6 Relationship between provisional fracture toughness, K_Q, and thickness of specimen between bottoms of grooves, t_c, for double torsion fatigue precracked 2124-T851 aluminum alloy specimens.