FRACTURE TOUGHNESS OF 7075-T7351 ALUMINUM PLATES

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Fracture toughness of 7075-T7351 aluminum alloy plates ranging from 27 mm to 63 mm in thickness has been determined on a total of 31 plates at 243 K, 293 K, and 363 K. It was found that test temperature and specimen size had an effect on the toughness measured. For the material investigated the "mean value" of fracture toughness was 43.4 $MPa \cdot m^{1/2}$ with a "standard deviation" of 2.4 $MPa \cdot m^{1/2}$ for a 99 % confidence level.

INTRODUCTION

Fracture toughness "K_{IC}" is used as a quality criterium of structural materials and as design parameter against fracture in fracture critical structures. In aircraft industry, fracture toughness requirements are specified for a number of materials. Over the past decade the parameter "fracture toughness" has entered the respective material specifications. Concurrently, material developments at the production level to improve the fracture toughness or assure the attainment of a specified value were quite successful. Today, the fracture toughness value finds steadily increasing application in the design of fracture critical parts. Out of this particular use result some basic questions as to the relation between material specification-value and the design-value.

The material specification value of fracture toughness is a deterministic value, i.e., proof of fulfillment of the requirement, under more or less specified conditions, serves to qualify the whole batch of material for the quality level spelled out by the respective specification. Fracture toughness as a design parameter should be based on a statistical assessment of this material parameter. Since production methods, and therewith fracture toughness, had been continually improved, the basis for a statistical treatment of fracture toughness is very slim, if the results of such a statistical treatment should characterize present-day materials.

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This paper is the first report on a continuing effort to characterize statistically the fracture toughness of 7075-T7351 aluminum plates ranging from 25 mm to 63 mm in thickness. The service temperature range for this material was assumed between 243 K and 363 K. Therefore, fracture toughness was determined at the two bounding temperatures in addition to the determination at room temperature. The statistical analysis includes all the fracture toughness values measured. The effects of temperature, plate thickness, and specimen dimensions are analysed. A partition into two quality groups with respect to fracture toughness is discussed.

EXPERIMENTAL PROCEDURES

Fracture toughness of 7075-T7351 aluminum plates was determined according to ASTM E 399-78 for the TL, LT, and in some cases for the SL orientation at room temperature. The mechanical properties satisfied the German aircraft industry specification (1) VFN 13327, and VFN 13314 (Table 1), i.e., the material qualifies for 7475-T7351, too. Since the fracture toughness in LT orientation was consistently higher than that in TL orientation, fracture toughness at 243 K and 363 K was determined in TL orientation only. Thus, it is assumed that the TL orientation gives the minimum fracture toughness for in-plane loading.

Compact tension (CT-)specimens according to ASTM E 399 were cut from the plates such that the mid-plane of the plates coincides with the mid-plane of the CT-specimen. CT-specimens with thickness B = 25 mm were cut from plates with thickness of 45 mm or less, while CT-specimens with B = 38 mm were cut from plates with 45 mm or greater thickness. CT-specimens tested at 363 K were modified as to measure the load line displacement (since we were not sure that a valid K_{IC}-value could be obtained at this temperature). A total of 31 different plates was tested with respect to fracture toughness.

RESULTS AND DISCUSSION

Figure 1 shows the result of the K_{IC} determination. The fracture toughness "K_{IC}" (abscissa) is plotted against the cumulative probability in percent (ordinate). In Table 2, the statistical data for the individual test series at 243 K, 293 K, and 363 K are listed together with the infered data for the total population. The same procedure was followed in the last row of Table 2, but in this case the sample size consisted of all fracture toughness data. In addition, Table 2 contains in the last two columns the fracture toughness values which are to be expected with 95 % and 99.9 % probability and 99 % confidence. It should be mentioned that the probability was arbitrarily selected as example in this case. In practical design application one would select the probability value based on the fracture criticality of the subject structure. The confidence level is intimately related to the parameter measured, i.e., the K_{IC}-value is always associated with a confidence level of 99 %. (The interrelation between probability and confidence is treated in a separate publication.)

The fracture toughness values obtained with CT-specimens of B = 25 mm thickness are plotted in Fig. 2, those obtained with

CT-specimens of B = 38 mm thickness are plotted in Fig. 3. Figures 2 and 3 indicate what is clearly evident in comparing the fracture toughness data of each individual plate at the three different test temperatures, namely, that the room temperature tests give generally higher K_{IC}-values. These results are explained in Fig. 4 which shows the different load-displacement records (schematically) at the three different test temperatures. At 243 K the material displays little plasticity up to stable crack propagation, while at room temperature plasticity effects delay stable crack propagation to higher loads "F". Plasticity effects at 363 K are so pronounced that the 5 % secant-line is traversed at relative low loads. It should be noted that the criterion $P_{max}/P_Q \leq 1.10$ was exceeded in a few specimens by a couple of percent.

Another aspect should be noted in Figures 2 and 3, namely, that the CT-specimens with B = 38 mm thickness give fracture toughness data at the lower end of the distribution which were 10 % of the mean value higher than the respective values from CT-specimens with B = 25 mm thickness. At the upper end of the distribution both specimen types reach approximately the same fracture toughness level. An explanation could be that at relative low fracture toughness values crack initiation starts with little plasticity effects. Therefore, the 5 % secant-line corresponds to 2 % of the ligament width crack growth; this criterion gives higher fracture toughness for the larger specimen. This effect is very pronounced if the material exhibits R-curve behavior with stable crack growth. The specimen size effect was clearly documented by the work of Munz (2) on 7475-T7351. The reason why this spreading behavior at high toughness end of the distribution does not occur is presently investigated.

Looking at the statistical data of Table 2, one finds that the mean value for the fracture toughness values obtained at 293 K is somewhat higher than the other or the total of all data. But, the difference is not considered significant with respect to K_{IC} in practical application. The same can be said for the mean value of the population infered from each sample size and the respective standard deviation. The statistical data for the total population consist of two numbers which come about that these data were calculated for a confidence level of 99 %. The calculations were based on the work of Struck (4). From a practical standpoint are only the lower numbers of the mean values of interest. It was decided to base the subsequent arguments on the data derived from the sample of all fracture toughness data.

First, the specification value for fracture toughness of 7475-T7351 (VFN 13314) is looked at. The last row of Table 2 gives the fracture toughness values for this type of material which are obtained with a 99.9 % probability and 99 % confidence. Comparing these data with the specification requirement of 36 $MPa \cdot m^{1/2}$, one can conclude that one out of thousand plates must be expected not to qualify. Therefore, the data presented here allow a cost-risk estimate in respect to a particular specification requirement.

Many structural parts are not critical for the failure of the entire structure even if structural failure occurs in that part. For economical reason it might be desirable for fracture safe design to use a fracture toughness value with a low probability, since the stress level and non-destructive evaluations are based on statistical data, too. In essence, the probability level is dictated by the particular design problem and is essentially independent of the specification value of fracture toughness.

It might be desirable to use for a particular application a material with relative high fracture toughness. One can envision a structural part which is fracture critical for failure of the entire structure. In addition, the accessibility for in-service inspection might be difficult. In such a case, one might be willing to take the higher cost of producing (selecting) a plate of higher fracture toughness. Starting from specification VFN 13314 with a specified fracture toughness of 36 $\mathrm{MPa \cdot m^{1/2}}$, a second quality group with respect to fracture toughness could be established which can tolerate a crack with 50 % longer crack length (approximately). The required fracture toughness would be 44 $\mathrm{MPa \cdot m^{1/2}}$. Comparing the mean value of the total population, Table 2, with the requirement 44 $\mathrm{MPa \cdot m^{1/2}}$, one finds that only one out of two plates can meet that requirement. The authors cannot judge how much this fall-out risk can be reduced by proper selection of chemical composition or modification of processing procedures in the bounds mandatory for 7075-T7351 or 7475-T7351. Yet, the data presented here can give some indication, whether such a selection for higher fracture toughness is possible. The question as to the uniformity in one plate and the influence of plate thickness has to be answered. Figure 5 shows the fracture toughness data for the 31 plates, measured at room temperature, ordered according to the lowest value measured. From left to right the lowest measured fracture toughness increases. It can be seen that, if a plate has one low fracture toughness value, all fracture toughness values are relatively low. This trend consists also for the data at 243 K and 363 K. Each data set in Fig. 5 has written the plate thickness on the abscissa. It is concluded that the thickness of the plate does not substantially influence the fracture toughness level. Because Fig. 5 gives only an indication related to the uniformity and the influence of plate thickness, an extensive investigation in this direction is presently under way. While it is recognized that fracture toughness varies across the thickness (3), it is not known how much of it depends on the physically imposed thickness (2) of the CT-specimen.

From the room temperature data of Fig. 2, specimen thickness B = 25 mm, two specimens were selected from plates with nearly equal thickness (30 and 32 mm) but a fracture toughness of 41 and 49 $\mathrm{MPa \cdot m^{1/2}}$. Surely, microstructural effects must be responsible for the difference in fracture toughness. An exploratory investigation covering grain size and texture, inclusion distribution and content, second phase morphology, and precipitate particle size and distribution did not reveal a visible difference. A chemical analysis did not reveal any significant difference.

It should be noted that the conclusions drawn from the results of data presented tacitly assume that other mechanical properties are not influenced in a negative way by efforts to improve fracture toughness in the frame set by the material specification 7075-T7351 or 7475-T7351.

CONCLUSIONS

The 7075-T7351 (7475-T7351) material investigated gave the highest fracture toughness at room temperature in relation to that at 243 K and 363 K. This is due to the different deformation behavior at the respective temperatures.

For the material with fracture toughness below 40 $MPa \cdot m^{1/2}$ there is a pronounced influence of specimen size on fracture toughness, even if the test qualifies as valid according to ASTM E399. This is due to the "ASTM E399" 5 % secant criterium used for evaluation.

For materials with fracture toughness above 40 $MPa \cdot m^{1/2}$ the specimen size effect is seemingly absent. The reason for it is presently not known.

The fulfillment of the German aircraft industry specification requirement of 36 $MPa \cdot m^{1/2}$ for 7475-T7351 has approximately a 99.9 % probability and 99 % confidence level of being fulfilled by the material investigated.

The mean value of fracture toughness for the type of material investigated is approximately 44 $MPa \cdot m^{1/2}$. It seems therefore possible to add for special application a second quality group with a fracture toughness in TL orientation corresponding a tolerable crack size of 50 % larger than the present specification, i.e.,

Group A: $K_{IC} \geq 36\ MPa \cdot m^{1/2}$ (VFN 13314)
Group B: $K_{IC} \geq 44\ MPa \cdot m^{1/2}$

in TL orientation. Though the present results indicate a fairly uniform distribution of fracture toughness over each individual plate, further work must be done to validate the splitting in two quality groups.

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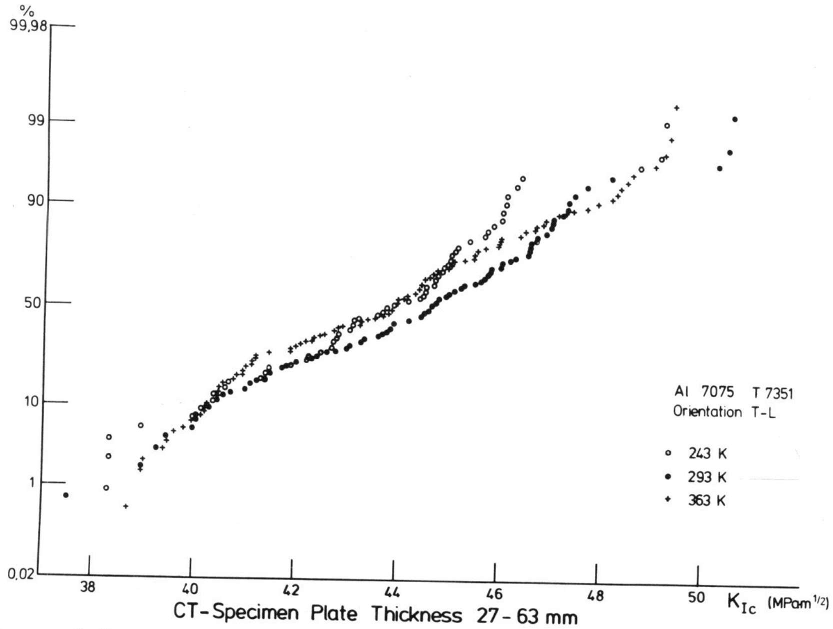


Figure 1 Fracture toughness versus cumulative probability (%)

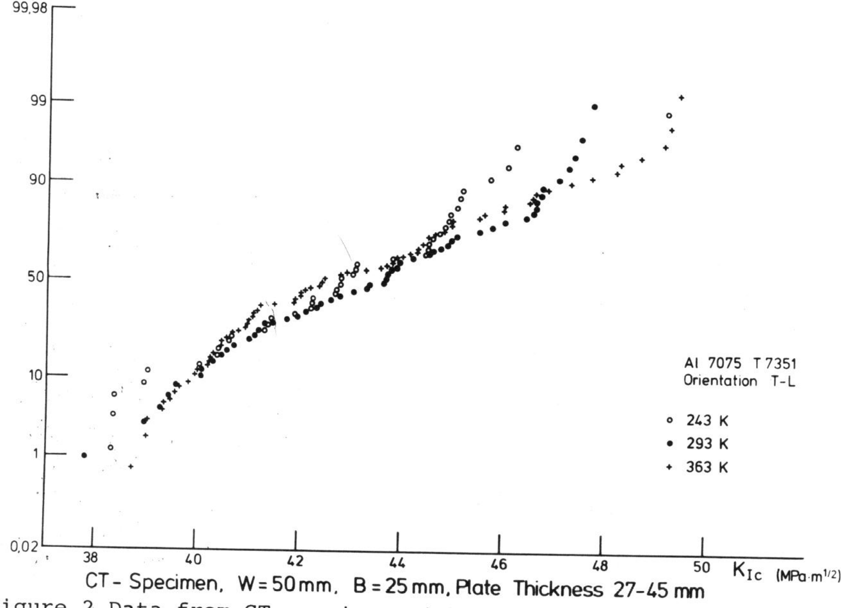
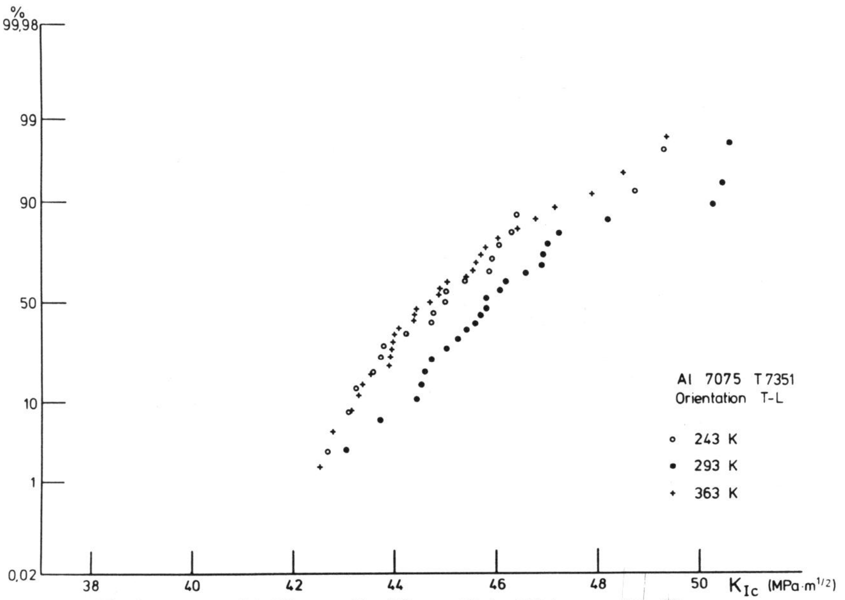


Figure 2 Data from CT-specimen with 25 mm thickness



CT - Specimen, W = 76 mm, B = 38 mm, Plate Thickness 45 - 63 mm

Figure 3 Data from CT-specimen with 38 mm thickness

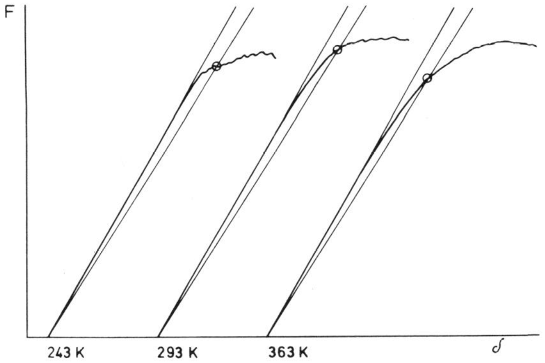


Figure 4 Load vs. displacement curves at different temperatures

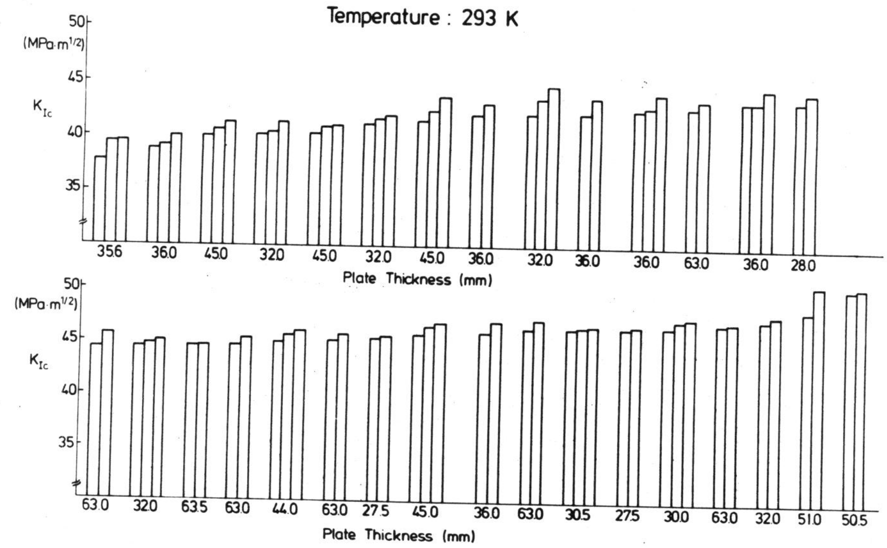


Figure 5 Effect of plate thickness on fracture toughness

Minimum Mechanical Properties

VFN 13327 (VFN 13314)				VFN 13314	
Orientation + Thicknes (mm)	R_m (N/mm²)	$R_{p0.2}$ (N/mm²)	A_5 (%)	Orientation + Thickness (mm)	K_{Ic} (MPa · $m^{1/2}$)
L 25-40	470	390	6	L-T 25-60	41.74
L 40-63	460	370	6	L-T 60-100	36.05
LT 25-40	470	390	6	T-L 25-60	36.05
LT 40-63	460	370	6	T-L 60-100	32.89
ST 25-40	440	360	4	S-L 25-60	-
ST 40-63	430	340	4	S-L 60-100	27.51

TABLE 1 - Specified mechanical properties

Aluminum Alloy 7075-T7351 (7475-T7351)

Temperature	Sample		Total population		95/99	99.9/99
	Mean value	Standard diviation	Mean value	Standard deviation		
243 K	43.6	2.50	42.75-44.5	2.00-3.22	38.10	34.95
293 K	44.3	2.79	43.4 -45.1	2.30-3.49	38.26	35.20
363 K	43.7	2.70	43.0 -44.4	2.32-3.34	38.14	35.49
Temperature range	43.85	2.69	43.4 -44.3	2.41-3.05	38.46	36.31

TABLE 2 - Statistical data related to fracture toughness