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Effect of Side Grooves and Fatigue Crack Length on Plane-Strain Fracture Toughness

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ABSTRACT

An investigation has been made to determine the effect of side grooving on plane-strain fracture toughness K_{Ic} values obtained with smooth single-edge-notched tension specimens. In most cases the smooth and side-grooved values differed by only ±1 to ±3% for high strength steels and alloys of titanium and aluminum. The side-grooved specimens tended to slightly underestimate K_{Ic}.

Side grooves accentuate the displacement due to crack instability on the load-displacement record and permit K_{Ic} values to be computed for specimens in which detection of crack initiation could not otherwise be made. The specimen is likely to fracture at or near maximum load when side grooves are employed.

For the specimen geometry used in this investigation it has been determined that fatigue cracks of 0.05 in. and less in length cause the K_{Ic} values for side-grooved specimens to be overestimated. There seems to be no relationship between the length of the crack, below 0.05 in., and the amount by which K_{Ic} is increased.

PROBLEM STATUS

This is an interim report; work is continuing.

AUTHORIZATION

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EFFECT OF SIDE GROOVES AND FATIGUE CRACK LENGTH ON PLANE-STRAIN FRACTURE TOUGHNESS

INTRODUCTION

Linear elastic fracture mechanics may be applied to predict the conditions which will cause failure for certain geometrically simple structures. The critical stress intensity factor for a plane-strain state of stress K_{Ic} is a function of the stress at the tip of the crack and the crack length. In principle, if the K_{Ic} value of the material is known and the length of the longest flaw has been established, the stress which will cause initial crack instability may be calculated.

A condition necessary for the achievement of plane-strain is sufficient elastic constraint at the crack tip. The crack (or flaw) in a structure acts as a stress concentrator, and the stress at the tip of the crack invariably exceeds the yield stress, causing a small enclave of plastically deformed metal to develop. This plastic zone is surrounded and constrained by an elastic stress field consisting of metal which is subjected to stresses less than the yield stress.

When the plastic zone at the crack tip is large compared to the section thickness, significant strain occurs through the thickness direction, and plane stress conditions exist. In this case a stress in the gross region of the crack exceeding the yield stress is necessary for crack movement. On the other hand if only a very small plastic zone is developed, then the stress state at the leading edge of the crack is one of plane strain, i.e., the strain component through the thickness approaches zero. Under a plane-strain state of stresses the conditions for crack instability in a generally elastic stress field may be calculated.

The load at which initial crack movement occurs may be difficult to discern for materials which have a toughness such that the ratio of the plane-stress plastic zone size $(2r_Y)$* to the thickness approached 1/2.5 (1). It has been found that the use of sharp side grooves machined symetrically across the width of the specimen parallel to the edge notch improves the detectability of initial crack extension for K_{Ic} determination (2). The arrangement of the side grooves on a single-edge-notched (SEN) tension specimen is shown in Fig. 1.

An important feature of the fracture mechanics approach to fracture toughness is that a fatigue crack is introduced into the specimen. For the fatigue crack to represent the flaw or crack which will exist in a structure two conditions must be met: the crack must be formed using a low stress intensity range ΔK so that the crack tip will attain a degree of sharpness such that still greater sharpness does not additionally decrease the critical K for onset of rapid fracture; and the fatigue crack should be long enough so that an additional increase in its length would not cause the K_{Ic} measurement to decrease.

This report is concerned with two aspects of plane strain fracture toughness: (a) To establish whether K_{Ic} values obtained from side-grooved SEN specimens are significantly different from those obtained with smooth (not side grooved) SEN specimens, (b) and to determine the extent to which K_{Ic} values are affected by fatigue cracks generally considered too short for valid measurements. In this investigation a comparison is made of

*$2r_Y = 1/\pi\,(K_I/Y_S)$.

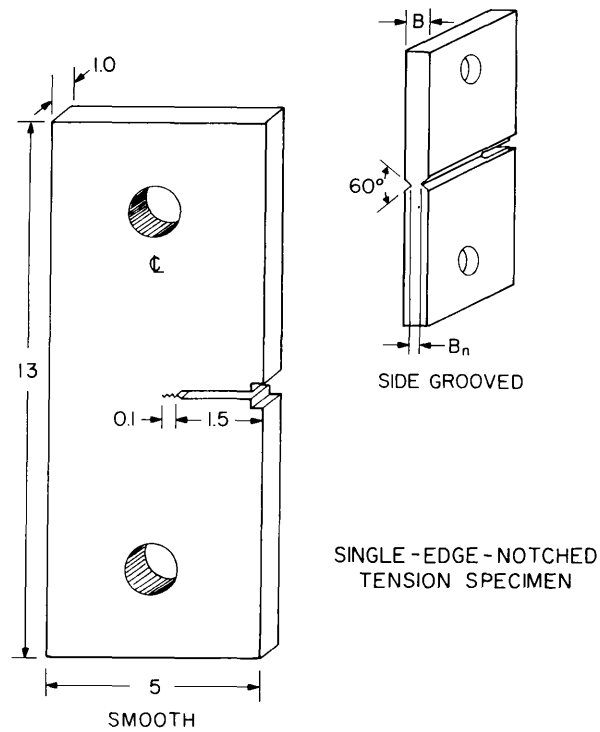

Fig. 1 - Dimensions of the single-edge-notched (SEN) tension specimen used to determine K_{Ic} values. B represents the specimen thickness, and B_n is the distance between the apexes of the side grooves. All dimensions are in inches.

K_{Ic} values for SEN specimens with fatigue cracks longer and shorter than the accepted minimum of 0.05 in.

MATERIALS AND PROCEDURE

High-strength steels and titanium and aluminum alloys were investigated. The mechanical properties of the alloys are given in Table 1 together with the heat treatment data.

All of the K_{Ic} results presented in this report were obtained with the SEN tension specimen modeled after that employed by Sullivan (3). The dimensions of the specimen are given in Fig. 1. The side-grooved specimens of thickness B were machined to a predetermined depth on each side of the fracture plane, leaving a distance B_n between the notch apexes. The grooves contained an included angle of 60° and had a notch root radius of 0.002 in.

An experimental compliance calibration was used to calculate K_{Ic} (3). A mathematical stress analysis has been developed by Gross (4) which provides essentially the same K_{Ic} value as the compliance calibration for the crack length-to-width ratios used in these tests. The calculation to determine K_{Ic} from side-grooved specimens is presented in the appendix.

Table 1
Mechanical Properties Data

Alloy Composition and Code Number	Fracture Direction	YS (ksi)	UTS (ksi)	Elong. (%)	R.A. (%)	Charpy V at 32°F (ft-lb)	DT Test at 32°F (ft-lb)	Heat Treatment
Titanium:								
T-27 (Ti-6Al-4V)	RW	132.5	150.5	10.6	25.2	25.0	1251	1700°F/1 hr/WQ, then 900°F/2 hr/AC
T-27 (Ti-6Al-4V)	WR	140.1	155.9	10.6	23.1	19.8	930	1700°F/1 hr/WQ, then 900°F/2 hr/AC
T-36 (Ti-6.5Al-5Zr-1V)	WR	124.5	131.1	12.1	21.5	17.0	960	As-received
T-55B (Ti-6Al-4Zr-2Mo)	WR	132.0	147.1	9.0	13.1	23	748	1800°F/1 hr/WQ, then 1000°F/2 hr/AC
T-67 (Ti-6Al-4V-2Sn)	RW	114.1	123.5	12.6	27.6	—	888	As-received
T-67A (Ti-6Al-4V-2Sn)	RW	129.8	141.2	8.0	12.9	24	540	1775°F/1 hr/WQ, then 1000°F/2 hr/AC
T-68A (Ti-6Al-4Zr-2Sn-1/2Mo-1/2V)	RW	117.5	130.6	11.2	18.2	18	1086	1800°F/1 hr/WQ, then 1100°F/2 hr/AC
T-68B (Ti-6Al-4Zr-2Sn-1/2Mo-1/2V)	RW	119.2	130.2	9.7	22.4	30	1036	1750°F/1 hr/WQ, then 1100°F/2 hr/AC
T-68D (Ti-6Al-4Zr-2Sn-1/2Mo-1/2V)	RW	121.3	129.1	9.3	15.3	27	1056	1825°F/1 hr/WQ, then 900°F/4 hr/AC
Aluminum:								
2024-T4	WR	43.9	65.8	17.0	19.5	6.6	281	As-received
2219-T851	WR	58.4	74.3	9.4	19.6	5.0	281	As-received
7075-T6	RW	64.7	75.4	—	—	—	167	As-received
7075-T7351	RW	63.9	75.4	11.4	33.3	6	339	As-received
7075-T7351	WR	65.6	75.5	9.7	27.0	4	198	As-received
7106-T63	WR	52.5	60.8	13.9	40.0	8	573	As-received
Steel:								
J66 (12Ni)	WR	176.3	179.9	52.1	13.5	38	—	NRL heat-treated*
J67 (12Ni)	WR	178.0	181.9	54.9	14.0	40	—	NRL heat-treated*
J70 (9-4-0.25)	WR	176.3	186.6	55.2	16.0	40	2112	As-received
J70X (9-4-0.25)	WR	186.1	198.0	55.2	16.0	36	1280	NRL heat-treated*
J71 (12Ni)	WR	176.8	183.2	59.6	14.5	42	—	As-received
J72 (12Ni)	WR	177.3	183.3	59.2	14.5	47	3251	As-received
J72X (12Ni)	WR	177.1	180.2	63.4	16.0	65	3538	NRL heat-treated*
J88 (9-4-0.25)	WR	180.2	191.3	54.1	16.0	42	1692	As-received
H57 (4140)	WR	176.6	194.8	32.6	9.5	14	593	NRL heat-treated*
D63A (18Ni)	RW	229.5	240.3	9.0	45.9	24	400-500	As-received
D63B (18Ni)	RW	234.5†	245.7†	7.0	29.2	—	400-500	As-received

*Heat treatment details are presented in Quarterly NRL Reports ("Metallurgical Characteristics of High Strength Structural Materials").
†WR fracture direction.

Load-displacement curves for each K_{Ic} specimen were drawn by an X-Y recorder. When initial deviation from lineality occurred at or very near maximum load, this load was used to calculate K_{Ic}; otherwise the load at the lowest distinct instability was chosen for the calculation. The detection of the initial crack extension was made with a beam displacement gage instrumented with a strain gage circuit.

Among the criteria used to determine the validity of the K_{Ic} values was the requirement that the specimen thickness equal about 2.5 times the plane-stress plastic zone size $(2r_Y)$. According to Ref. 1 the thickness B should be more than $2(2r_Y)$ for a correct K_{Ic} value to be determined from a 7075-T6 aluminum alloy. A similar minimum thickness requirement $[2.5(2r_Y)]$ was determined to be adequate in Ref. 2 for both smooth and side-grooved SEN specimens. Although this thickness requirement is less than that recommended by Committee E-24 of ASTM, the author believes that when used with discretion it is sufficient for the particular alloys and heat treatments described in this investigation.

TEST RESULTS AND DISCUSSION

Comparison of Smooth and Side-Grooved K_{Ic} Values

A comparison of the load-displacement curves for smooth and side-grooved specimens of 7075-T7351 aluminum is noted in Fig. 2. The smooth specimens (curves 1 to 4) usually demonstrated a gradual departure from lineality as a result of slow crack growth. The arrows indicate the load used to calculate K_{Ic}, but the absence of a distinct pop-in indication detracted from the accuracy of the K_{Ic} value. The load-displacement curves for the side-grooved specimens of the same material are represented by curves 5 to 10; the load at fracture was used to compute the plane-strain fracture toughness. This is a typical illustration of the efficacy of side grooves in improving the detection of crack instability.

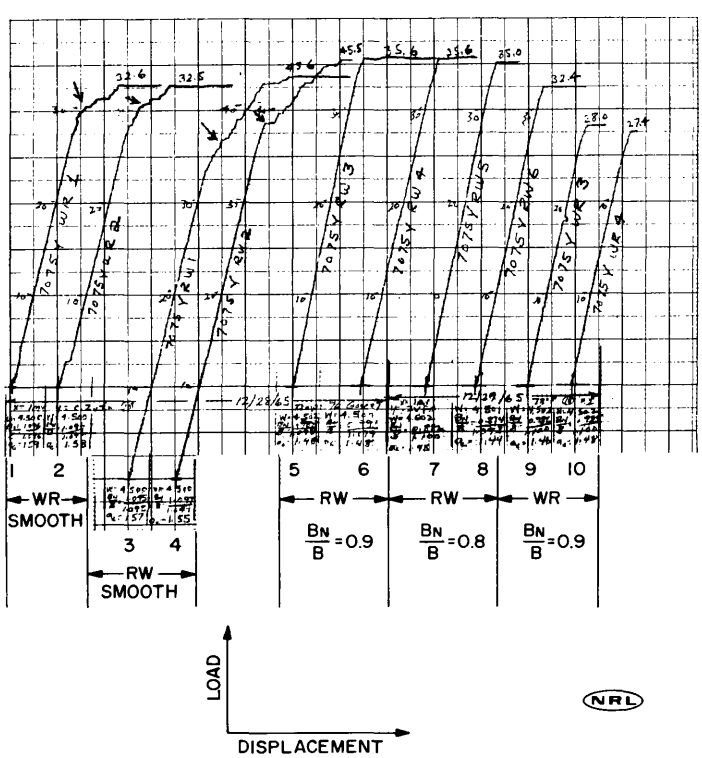

Fig. 2 - Load-displacement records of smooth and side-grooved 7075-T7351 aluminum SEN specimens

The smooth and side-grooved K_{Ic} values calculated for titanium and aluminum alloys and steels are compared in Table 2. The fatigue cracks on all specimens exceeded 0.05 in., and the side grooves were usually machined to a depth of 5 to 6% of the thickness on each side of the specimen. Figures 3 and 4 demonstrate graphically the data reported in Table 2.

The data indicate that there is little difference between K_{Ic} values obtained from smooth and side-grooved specimens. Among the titanium alloys which were tested in the "as-received" condition (and not subjected to the additional heat-treatment variable) the greatest difference between smooth and side-grooved K_{Ic} values is ±4% (T-36). For the heat-treated titanium alloys the greatest variation is ±6% (T-67A). The steels show maximum variations of ±3% for both "as-received" and heat-treated specimens. One aluminum alloy (7075-T7351) indicates a ±7% difference between smooth and side-grooved K_{Ic} values.

In most cases, however, the side-grooved K_{Ic} values are only ±1% to ±3% different than the smooth values. Since the purpose of side grooving is to enable the determination of K_{Ic} data which might not have been obtainable using only smooth specimens, the small variation is not considered to be a handicap.

Another point which is evidenced in Table 2 is that the smooth K_{Ic} value is almost always higher than the side-grooved value. This underestimation of side-grooved K_{Ic} values is abetted by the nature of the correction factor used to calculate K_{Ic} for side-grooved specimens. The background reasoning and experiments used to establish the correction factor is presented in Ref. 2.

The fracture surface appearance of smooth and side-grooved SEN specimens is shown in Figs. 5 and 6. A heat-treated titanium alloy (T-27RW) is illustrated in Fig. 5. It is evident that the side grooves in Fig. 5b (5% deep on each flank) practically eliminate the shear lips found on the smooth specimen. It is believed that this decrease in the influence of the free surface improves the detectability of initial crack movement by increasing the likelihood of the existance of a plane-strain state of stress at the crack front.

The fracture surfaces of a 9Ni-4Co-0.25C quenched and tempered (Q&T) steel (J-70 WR) are shown in Fig. 6. The side grooves again act to suppress the shear lips, although a slight concavity of the surface may be discerned in specimen YY. The side grooves in this case further altered the shape of the fatigue crack front from one which leads in the center of the smooth specimen to one which has its foremost points at the specimen edges.

Effect of Fatigue Crack Length on K_{Ic}

During the course of the investigation concerned with the effects of side-grooving it was noted that specimens which contained very short fatigue cracks produced higher K_{Ic} values than were found when longer cracks were employed. A comparison was subsequently made of K_{Ic} values from specimens with cracks 0.05 in. and less specimens with fatigue cracks longer than 0.05 in. The results of this compilation are reported in Table 3 and in Fig. 7.

The values in Table 3 represent every instance in which a short fatigue crack (0.05 in. and less) was found in a SEN specimen. With but one exception the short crack raised the K_{Ic} number above the average value obtained for a particular alloy and heat treatment. (Only side-grooved specimens are listed in Table 3 as there were no instances of short fatigue cracks in smooth specimens.) There seems to be no relationship between the length of the crack for fatigue cracks less than 0.05 in. and the degree of overestimation of K_{Ic}. For the steels the error introduced due to fatigue cracks less than 0.05 in. appears to increase with higher toughness.

Table 2
Comparison of Smooth and Side-Grooved K_{Ic} Data

Specimen Designation	Fracture Direction	Total Depth of Side Grooves (%)	K_{Ic} (ksi-$\sqrt{in.}$) Smooth	K_{Ic} (ksi-$\sqrt{in.}$) Side-grooved
Titanium				
T-27L	RW	0	106	
T-27RW3	RW	0	111	
T-27RW1	RW	11		107
T-27RW4	RW	11		114
T-27RW2	RW	20		102
T-27RW1-6	RW	42		101
Av.			109	106
T-36WR1	WR	0	91	
T-36WR7	WR	10		97
T-36WR8	WR	11		100
Av.			91	99
T-55BWR17	WR	0	99	
T-55BWR16	WR	0	102	
T-55BWR15	WR	0	97	
T-55BWR7	WR	11		92
T-55BWR10	WR	11		95
Av.			99	94
T-67RW1	RW	0	96	
T-67RW2	RW	0	105	
T-67RW4	RW	8		95
Av.			101	95
T-67ARW7	RW	0	88	
T-67ARW8	RW	0	78	
T-67ARW5	RW	0	71	
T-67ARW6	RW	10		90
Av.			79	90
T-68ARW2	RW	0	124	
T-68ARW6	RW	0	117	
T-68ARW4	RW	11		118
T-68ARW5	RW	12		117
Av.			121	118
T-68BRW1	RW	0	104	
T-68BRW3	RW	0	116	
T-68BRW7	RW	10		113
T-68BRW8	RW	10		106
Av.			110	110
T-68DRW5	RW	0	131	
T-68DRW9	RW	11		124
T-68DRW10	RW	11		124
Av.			131	124
Aluminum				
2219-T851WR3	WR	0	37	
2219-T851WR4	WR	0	37	
2219-T851WR6	WR	0	38	
2219-T851WR2	WR	10		34
2219-T851WR5	WR	10		34
2219-T851WR1	WR	9		34
2219-T851WR7	WR	20		32
2219-T851WR9	WR	20		33
Av.			37	33
7075-T6RW1	RW	0	32	
7075-T6RW2	RW	0	33	
7075-T6RW5	RW	0	34	
7075-T6RW3	RW	10		32
7075-T6RW4	RW	10		32
7075-T6RW6	RW	10		32
Av.			33	32
Aluminum (Cont.)				
7075-T7351RW1	RW	0	32	
7075-T7351RW2	RW	0	33	
7075-T7351RW3	RW			30
7075-T7351RW4	RW			30
Av.			33	30
7075-T7351WR1	WR	0	27	
7075-T7351WR2	WR	0	27	
7075-T7351WR3	WR	10		23
7075-T7351WR4	WR	10		23
Av.			27	23
Steel				
H-57WR1	WR	0	89	
H-57WR3	WR	0	88	
H-57WR2	WR	20		87
Av.			89	87
J-66WR3	WR	0	143	
J-66WR4	WR	11		131
J-66WR5	WR	10		138
Av.			143	135
J-67WR3	WR	0	136	
J-67WR4	WR	10		131
J-67WR5	WR	10		137
Av.			136	134
J-70WR1	WR	0	163	
J-70WR2	WR	0	166	
J-70WR3	WR	15		163
Av.			165	163
J-70XWR5	WR	0	156	
J-70XWR6	WR	11		150
J-70XWR7	WR	12		154
J-70XWR8	WR	11		151
Av.			156	152
J-71WR1	WR	0	198	
J-71WR2	WR	11		206
J-71WR3	WR	11		204
Av.			198	205
J-72WR1	WR	0	201	
J-72WR2	WR	12		213
J-72WR3	WR	12		210
Av.			201	212
J-88WR1	WR	0	165	
J-88WR3	WR	0	166	
J-88WR2	WR	11		159
Av.			166	159

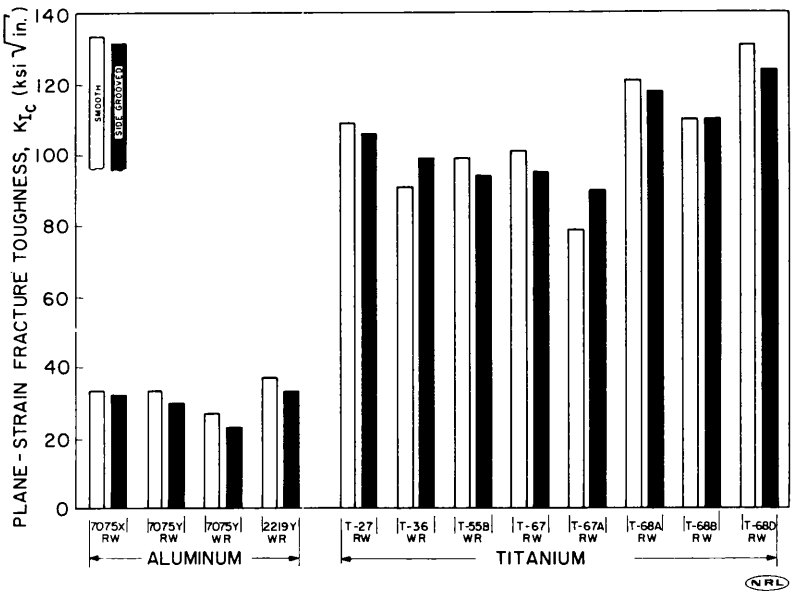

Fig. 3 - Comparison of K_{Ic} values obtained from smooth and side-grooved SEN specimens for aluminum and titanium alloys

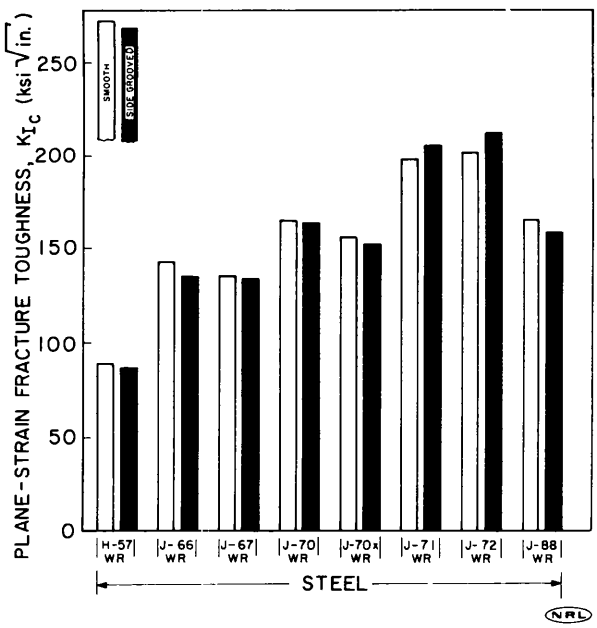

Fig. 4 - Comparison of K_{Ic} values for smooth and side-grooved specimens of various ferrous alloys

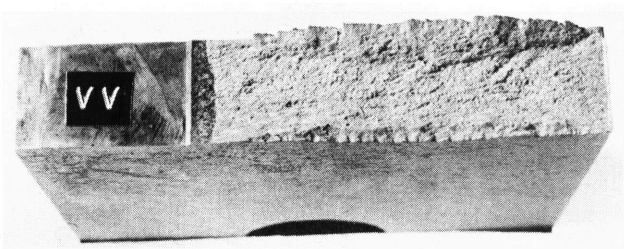

Fig. 5a - Fracture surface of a smooth titanium alloy (T-27 RW)

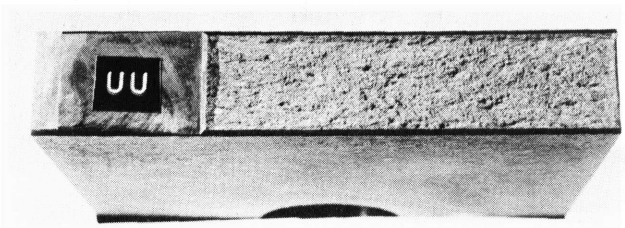

Fig. 5b - Fracture surface of a side-grooved titanium alloy (T-27 RW)

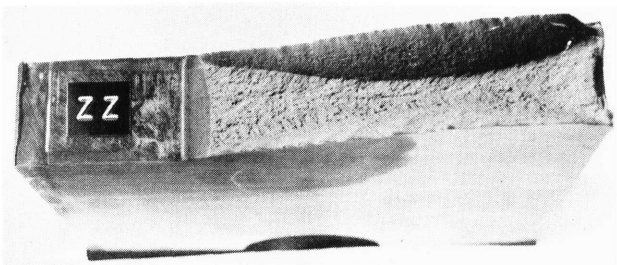

Fig. 6a - Fracture surface of a smooth ferrous alloy (J-70 WR)

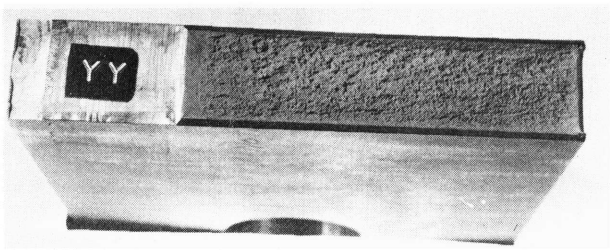

Fig. 6b - Fracture surface of a side-grooved ferrous alloy (J-70 WR)

Table 3
Effect of Very Short Fatigue Cracks on K_{Ic} Indication

Specimen	Total Depth of Side Groove (%)	Fatigue Crack Length (in.)	Indicated K_{Ic} (ksi-$\sqrt{in.}$)	Actual Av K_{Ic} (side-grooved) (ksi-$\sqrt{in.}$)
Titanium:				
T-27WR1	37	0.01	108	105*
T-27WR2	41	0.04	114	105*
T-27RW1-5	49	0.02	108	106
T-27RW2	50	0.01	112	106
T-27RW2-7	32	0.02	123	106
T-67RW3	6	0.04	106	100
Aluminum:				
2219-T851WR8	20	0.01	32	33
2024-T4WR8	20	0.01	35	31
2024-T4WR7	20	0.01	33	31
7106-T63WR5	11	0.01	47	41
Steels:				
D-63B1D	30	0.05	85	76
D-63B1E	30	0.03	81	76
D-63A1A	30	0.01	81	69
D-63A1D	30	0.01	78	69
J-70WR4	14	0.02	191	163
J-72XWR5	11	0.03	248	211*
J-72XWR6	11	0.04	258	211*

*These values represent K_{Ic} of smooth specimens. Side-grooved K_{Ic} values might be slightly lower.

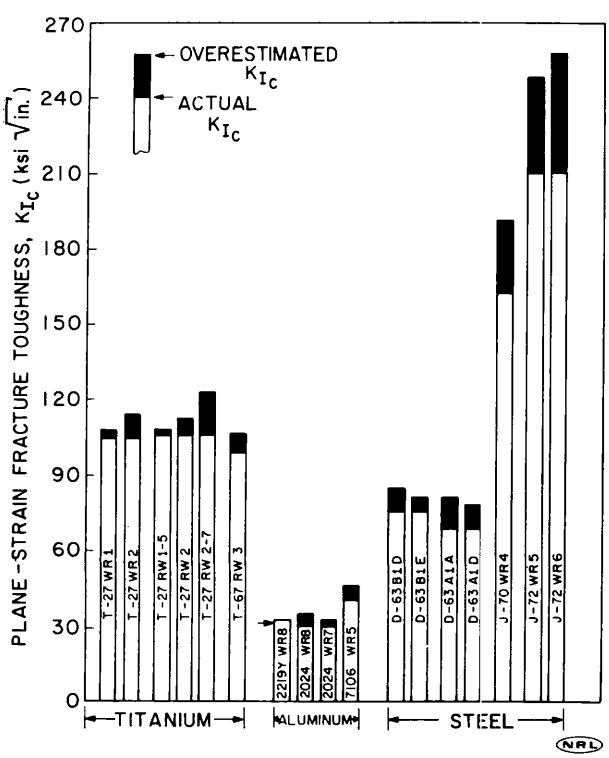

Fig. 7 - Bar graph representing overestimation of K_{Ic} when fatigue crack is too short (0.05-in. or less). One exception is 2219Y WR8; the arrow indicates that the apparent K_{Ic} is slightly less than the actual value.

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13. ABSTRACT

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Side grooves accentuate the displacement due to crack instability on the load-displacement record and permit K_{Ic} values to be computed for specimens in which detection of crack initiation could not otherwise be made. The specimen is likely to fracture at or near maximum load when side grooves are employed.

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Plane-strain fracture toughness						
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Crack instability						
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Steel						
Titanium						

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Security Classification