CORRELATION BETWEEN FRACTURE TOUGHNESS AND FINAL FATIGUE FRACTURE OF CAST STEELS AT ROOM TEMPERATURE AND -45°C

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Variable amplitude fatigue tests and monotonic R-curve tests were performed on five cast steels at room temperature and -45°C (-34°C for 0030 steel) using compact type (CT) specimens. The specimen thickness was 8.2 mm, H/W was 0.60 or 0.49 and W was 64.8 mm. Specimens were machined from carefully poured castings. The five cast steels were: SAE 0030, SAE 0050A, C-Mn, Mn-Mo and AISI 8630. The chemical compositions are given in Table 1. The 0030 and 0050A steel castings were normalized and tempered giving a ferritic-pearlitic microstructure while C-Mn, Mn-Mo and 8630 cast steels were normalized, quenched and tempered giving a tempered martensitic microstructure. Monotonic .2% yield strengths, S_y, are given in Table 2 and these varied from approximately 300 to 1000 MPa at room temperature. Cyclic yield strengths, S_y', are also given in Table 2 along with Charpy V notch, CVN, impact energies and NDT temperatures. For C-Mn and Mn-Mo steels, room temperature tests were in the upper shelf CVN

Table 1 Cast Steel Chemistry - % by Weight

	C	Mn	Si	S	P	Cr	Ni	Mo	Al
0030	.24	.71	.44	.026	.015	.10	.10	.08	.06
0050A	.49	.93	.61	.023	.024	.11	.08	.04	.08
C-Mn	.23	1.25	.39	.028	.036	.10	.09	.04	.02
Mn-Mo	.34	1.32	.40	.035	.024	.11	.11	.22	.06
8630	.30	.84	.53	.022	.021	.51	.61	.17	.08

at both room and low temperature with little scatter at the instability as shown in Fig. 1. Total stable surface crack extension varied from essentially zero to only 2.5 mm due to the load control test procedure. To have a valid plane stress fracture toughness test, the uncracked ligament, W-a, should be $\geq 8\, r_y$ where

$$r_y = \frac{1}{2\pi}\left(\frac{K}{S_y}\right)^2 \qquad (1)$$

Values of r_y near unstable crack extension were all too large, except for 8630 at -45°C, to satisfy valid K and K_c calculations.

In order to have a comparison of the fracture toughness for the five cast steels at room and low test temperatures, a quantitative "elastic" fracture toughness, K_e, was obtained by using the maximum applied load and the initial crack length. K_e is directly related to the residual static

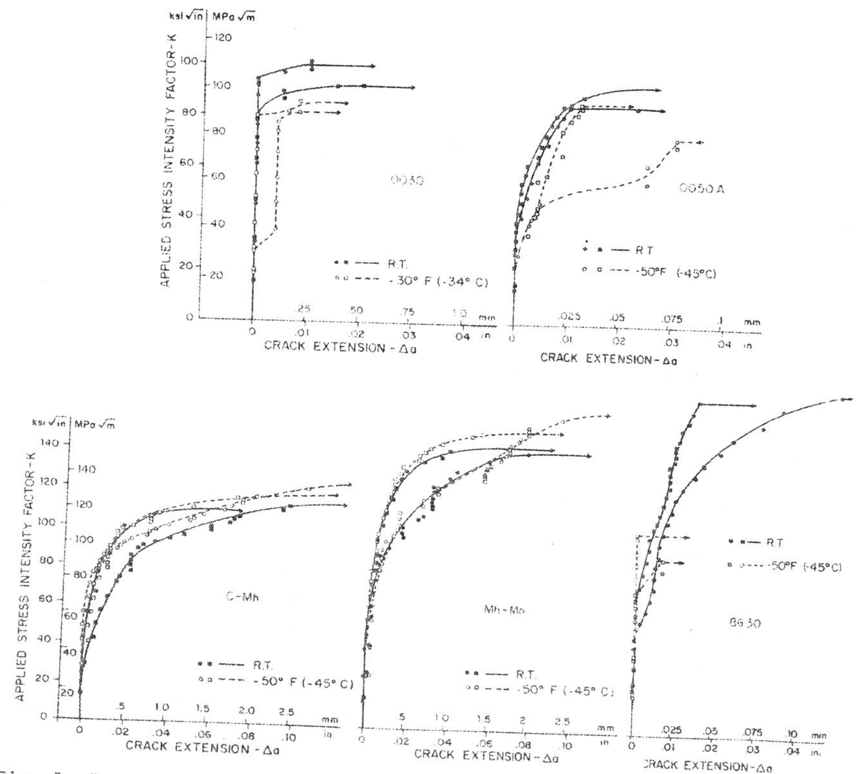

Fig. 1 R-curves

region, while the -45°C tests were in the CVN transition region. For 0030, 0050A, and 8630 steels, room temperature tests were in the CVN transition region and -45°C (-34°C for 0030) was in or near the lower shelf CVN region.

Table 2 Average Monotonic and Cyclic Properties

Material	NDT	S_y	S'_y	CVN	K_e	r_y	K_{fc}	r'_y	$\frac{K_{fc}}{K_e}$
	°C	MPa	MPa	J	MPa$\sqrt{m}$	mm	MPa$\sqrt{m}$	mm	
					Room Temperature				
0030	-23	303	317	36	102	22	101	16	.99
0050A	+27	413	379	17	97	10	112	14	1.16
C-Mn	-55	400	331	48	104	13	125	23	1.20
Mn-Mo	-65	544	386	58	136	12	147	23	1.09
8630	-23	985	661	32	185	7	185	12	1.01
					-45°C or -34°C*				
0030		317	317	8*	96*	18*	106*	18*	1.11*
0050A		434	352	5	87	8	66	5	.75
C-Mn		462	359	13	110	11	125	19	1.14
Mn-Mo		558	414	30	146	13	152	21	1.01
8630		999	751	10	106	2	102	3	.97

TESTS AND RESULTS

Both R-curve tests and fatigue tests were performed using a closed-loop electrohydraulic test system. Low temperature tests were enclosed in a CO_2 automated test chamber. R-curve tests using pre-fatigue cracked specimens with a_o = 25.4 mm were performed in load control using incremental steps as described in ASTM Standard Practice E561. R-curves for the five cast steels are shown in Fig. 1 where Δa is the physical crack length extension. K was obtained from CT specimen expressions without plastic zone corrections. Duplicate tests were run for each steel

strength of the precracked specimens. Values of K_e and the accompanying large plastic zone sizes r_y obtained from Eq. 1 using K_e values are given in Table 2. Scatter in K_e for duplicate tests was less than 15 percent. It is seen that K_e provides essentially the same behavior pattern as found from comparing K values in Fig. 1 at instabilities due to the small crack extension prior to the instabilities. Based upon K_e, the low temperature was slightly detrimental (< 10%) for 0030 and 0050A steels, slightly beneficial (< 10%) for C-Mn and Mn-Mo, and substantially detrimental (43%) for 8630 steel.

Variable amplitude fatigue tests were performed on the CT specimens loaded through a monoball grip system with cracks growing from a keyhole notch. Final fatigue crack lengths at fracture varied from 3 to 28 mm as measured from the keyhole notch edge and these resulted in total crack lengths of 22 to 47 mm as measured from the load line. Two load histories were used in the fatigue tests and these are shown in Fig. 2. The first history labeled T/H in Fig. 2(a) is a transmission history formed as part of an SAE round robin test program and includes 1710 reversals per block. The second history, labeled mod T/H in Fig. 2(b) is a modification of the T/H history. The modification was done by omitting all the compression loadings. Each history was applied to a specimen and repeated until fracture. Each history begins and ends with a peak tensile load and three different peak values were used for the T/H history while two values were used for the mod T/H history. The stress intensity factor or fatigue fracture toughness, K_{fc}, at final fracture was calculated using the final fracture crack length and the peak load value for each specimen. All tests were duplicated at both temperatures. The average values of K_{fc} for the five cast steels at room and low temperature are given in Table 2.

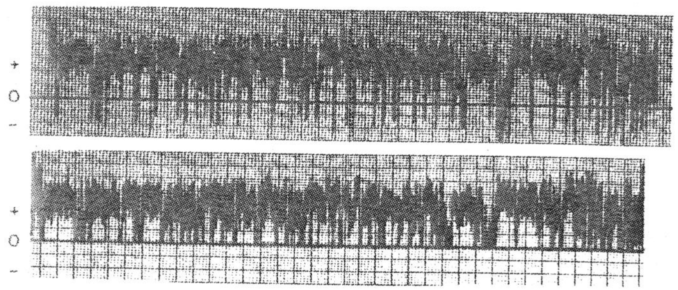

Fig. 2 Variable amplitude fatigue histories

These values were calculated without plastic zone corrections which are also given in Table 2 as r_y'. The average value of K_{fc} was obtained from ten different test specimens for each material and test temperature. Scatter for a given material and temperature varied from factors of only 1.1 to 1.25. The r_y' values were obtained from Eq. 1 using the cyclic yield strengths, S_y', and ranged from 3 to 23 mm which indicates that K_{fc} for all but two cases invalidates the use of linear elastic fracture mechanics. These values however are still related to residual strength. Thus a correlation between K_e and K_{fc} can still be made, but the actual numbers standing alone are not valid fracture toughness values. Based upon K_{fc} the low temperature was not detrimental for the 0030, C-Mn and Mn-Mo cast steels but was significantly detrimental for the 0050A and 8630 cast steels.

DISCUSSION OF RESULTS

The comparison between the average monotonic fracture toughness, K_e, and the average fatigue fracture toughness, K_{fc}, is given in the last column of Table 2 as a ratio of the two values. All K_{fc} values were either similar to or within 20% higher than K_e values except for 0050A at -45°C where K_{fc} was 25% lower than K_e. Thus there was a reasonable conservative estimate of fracture toughness under the fatigue conditions compared to the monotonic conditions except for 0050A at -45°C. This comparison is somewhat complicated however, due to the large plasticity that existed at fracture in most cases.

SEM fractographs for the monotonic tests are shown in Fig. 3. Final fracture regions for the fatigue specimens were essentially the same as Fig. 3 for each material and test temperature. These are summarized as follows:

0030 - ductile dimples at room temperature and mostly cleavage at -34°C
0050A - cleavage at both temperatures
C-Mn - ductile dimples at both temperatures with some cleavage at -45°C
Mn-Mo - ductile dimples at both temperatures
8630 - ductile dimples at room temperature and cleavage at -45°C

The above results are also reasonably consistent with CVN energy results and NDT values given in Table 2.

CONCLUSION

Based upon residual strength using "elastic" values of K_e and K_{fc}, a reasonable conservative qualitative correlation existed for the five cast steels at room temperature and for four of the five cast steels at low temperature despite the appreciable plasticity at fracture.

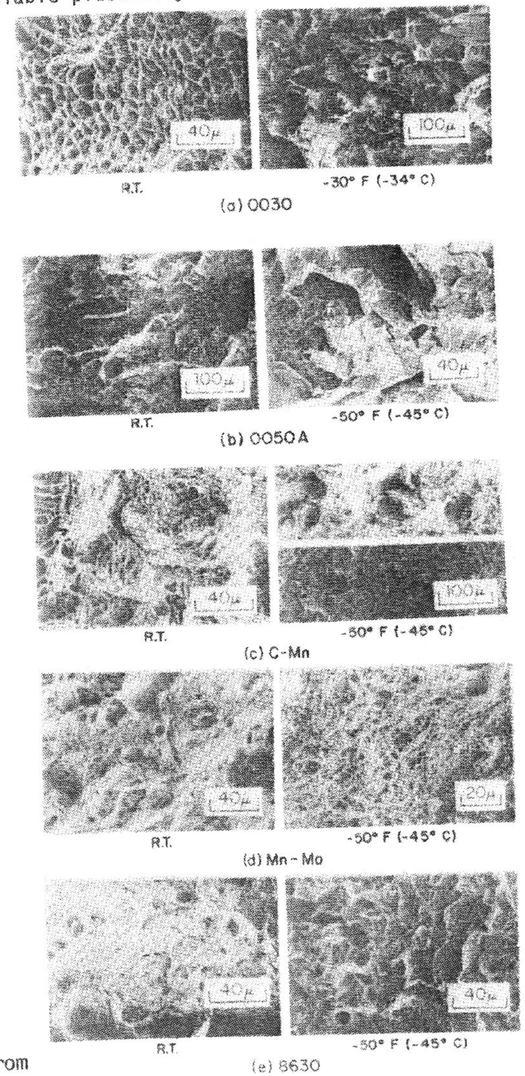

Fig. 3 SEM Fractographs from R-curve tests