TEMPERATURE AND FREQUENCY EFFECTS ON FATIGUE CRACK PROPAGATION

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Fatigue crack propagation in hot work (H13) and special purpose (L6) tool steels has been studied at temperatures of 20, 300 and 500°C. The crack growth rate increased with increase in temperature and this effect can be expressed by introducing an apparent activation energy term (Q) into the Paris equation. The value of Q was found to be lower than that for volume diffusion, indicating a complex rate controlling process occurring at the crack tip. A decrease in frequency from 5 Hz to 0.145 Hz at 500°C resulted in a faster crack propagation rate at high ΔK values. Considering other work on H13 tool steel a further modification to the Paris equation may be made by including a frequency term.

INTRODUCTION

In critical regions of tools and dies used in hot working operations cracks nucleate during the initial phases of operation. Consequently, the period of cyclic crack propagation is very important in determining life. This calls for knowledge of crack growth parameters at the temperature corresponding to the operating conditions of the die block.

MATERIALS AND EXPERIMENTAL PROCEDURE

The materials used in this study were a hot-work tool steel AISI type H13 and a special-purpose tool steel AISI type L6. The chemical analyses are given in Table I and the heat treatments with resulting hardness values are given in Table II. The higher tempering temperatures of the different H13 tool steels resulted in lower hardness values yet the average spacing between the alloy carbides was lower as seen in Table II. The L6 tool steel contained some

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cementite and a few alloy carbides. Its as-tempered hardness was lower than any of those recorded for the H13 tool steels. The as-tempered yield stress and fracture toughness values for all the materials are given in Table III.

TABLE I
Chemical Composition of Tool Steels Investigated (% wt)

Steel Type	C	Si	Mn	S	P	Cr	Ni	V	Mo
H13A	0.40	0.92	0.52	0.014	0.01	4.7	0.16	0.82	1.4
H13B	0.40	0.92	0.52	0.014	0.01	4.7	0.16	0.82	1.4
H13K	0.39	0.96	0.26	0.004	0.01	5.1	—	0.87	1.26
L6	0.55	0.32	0.66	0.027	0.026	0.67	1.66	0.09	0.19

TABLE II
Heat Treatment, Hardness and Carbide Information

Steel Type	Quench Temp. °C	Tempering Temp.°C	Temper Hardness (VPN)	Max. Carbide Dia. nm	Av. Carbide Dia. nm	Carbide Spacing nm
H13A	1040	610(2h),580(1h)	465-485	450	60	65
H13B	1040	580(2h),550(1h)	520-540	450	60	100
H13K	1040	610(2h),580(1h)	455-475	450	60	67
L6	860	540(2h)	400-425	225	50	188

TABLE III
Yield Stress and Fracture Toughness at Different Temperatures

Steel	Yield Stress σ_{ys} (MPa)			Fracture Toughness $K_{IC}(MPa\sqrt{m})$		
Type	20°C	300°C	500°C	20°C	300°C	500°C
H13A	1407	1238	1133	66.4	126.5	109.2
H13B	1609	1408	1351	58.7	101.2	—
H13K	1357	1270	1150	52.2	130.1	126.5
L6	1247	1028	686	52	—	—

Single edge notch fatigue specimens, 4.84 thick, 50.8 mm wide were used in this investigation. The notch and crack plane was perpendicular to the rolling direction. A series of isothermal fatigue crack propagation tests was carried out under load control with $R = 0.1$. A frequency of 5 Hz with a sinusoidal wave was employed for the majority of the work and the crack growth in air at temperatures of $20°C$, $300°C$, and $500°C$ was studied. The progress of the crack was monitored with a travelling microscope and the crack growth rates (da/dN) were determined using the secant method (ASTM E647). After testing the fracture surfaces were examined in a scanning electron microscope (SEM).

RESULTS AND DISCUSSION

1) Temperature Effects

Fig. 1 shows the crack propagation rate (da/dN) for H13A tool steel plotted against stress intensity factor range (ΔK) at the various temperatures investigated. This plot is typical for the other chromium-based hot work tool steels. Crack propagation results for L6 tool steel are included in Fig. 1 in order to give an indication of the range of data recorded. The Paris equation may be applied to these results at each temperature for a given material:

$$da/dN = C\Delta K^n \tag{1}$$

where C, and n are constants whose respective values for all the materials at the different temperatures are given in Table IV. The smaller temperature variation in n for L6 tool steel is presumably due to a lower internal strain in the matrix.

TABLE IV
Values For Constants in Equations (1) and (3)

Steel Type		Equation (1) 20°C	300°C	500°C	Equation (3) Q_o cal/mole	2.3×g
H13 A	n	2.87	2.43	2.04	2997	1695
	C	1.5×10^{-8}	1.17×10^{-7}	5.17×10^{-7}		
H13 B	n	3.21	2.43	1.96	4150	2536
	C	4.6×10^{-9}	1.18×10^{-7}	5.52×10^{-7}		
H13 K	n	3.09	2.36	1.92	3268	1800
	C	7.21×10^{-9}	1.43×10^{-7}	6.99×10^{-7}		
L6	n	2.33	2.32	2.22	1005	107
	C	6.85×10^{-8}	1.39×10^{-7}	2.55×10^{-7}		

From Fig. 1 and Table IV, it is apparent that the crack propagation rate increased with increasing temperature for all steels. Accordingly the fatigue life decreased. It is interesting to note that the effect of temperature appeared to be more significant than that of microstructure. In order to analyze the effect of temperature on fatigue crack propagation, $\ell n\ da/dN$ was plotted against $1/T°K$. The apparent activation energy, Q, was obtained from the slope of this Arrhenius-type plot i.e.

$$\ell n\ da/dN = \ell n\ B - Q/RT \tag{2}$$

where B is a temperature independent constant for a given material and R is the gas constant. The apparent activation energy was found to be a function of stress intensity which could be expressed by

$$Q = Q_o - gln\ \Delta K \tag{3}$$

where Q_o is the apparent activation energy for crack propagation independent of ΔK and a is a material constant. The respective values of Q_o and g are given in Table IV. It is important to note that the values of Q_o are much lower than those reported in the literature for either creep or oxidation indicating that the activation energy barrier for enhanced crack growth is quite small and the temperature effect on cyclic crack propagation is complex. However, the cyclic crack propagation rate may be given by:

$$da/dN = C_1\ exp(-Q/RT)\Delta K^{n'} \tag{4}$$

2) Frequency Effects

Additional tests were performed on H13A tool steel at 0.145 Hz at 500°C. A faster crack propagation rate was observed at high ΔK values as shown in Fig. 1. Examination of the fracture surface revealed a change from transgranular (Fig. 2a) to intergranular (Fig. 2b) fracture mode.

Lu[1] conducted a wide range of cyclic crack propagation tests (R=0.1) on H13 K tool steel at different temperatures and frequencies. Analyzing his results for the two frequencies of 0.145 Hz and 5 Hz with a balanced triangular waveform at 20, 125, 425 and 500°C, the crack propagation rate may be expressed as follows

$$da/dn = A\ exp(-Q/RT) f^{\alpha}\ \Delta K^{n} \tag{5}$$

where A is a material constant ($= 1.086 \times 10^{-5}$), n is an exponent ($= 1.29$) both frequency and temperature independent, Q is an apparent activation energy ($\simeq$ 1600 cal/mole) independent of ΔK and $\alpha (= -0.07)$ is an exponent for the frequency (f). By taking account of frequency, the ΔK dependency on Q has been eliminated together with the temperature influence on the Paris exponent.

For a given temperature then,equation (5) may be simplified:

$$da/dn = C_2\ f^{\alpha}\ \Delta K^{n} \tag{6}$$

where $C_2[= A\ exp(-Q/RT)]$ is a material constant for a particular temperature. This equation is in agreement with previous work by Plumtree and Schuchter[2] on type 304 stainless steel at 570°C.

CONCLUSIONS

1. It has been shown that the faster fatigue crack propagation rates in tool steels at higher temperatures may be expressed by a modified Paris equation which includes an apparent activation energy term. The measured apparent activation energy is much lower than established values for oxidation or creep in ferritic steels, indicating an enhanced yet complex damage mechanism at the crack tip.

2. Decreasing cyclic frequency at high temperatures results in an increased crack growth rate, especially at high values of the stress intensity factor range. A change in fracture mode has been observed under these conditions. A further modification to the Paris equation may be made by introducing a frequency term as well as apparent activation energy to take into account both temperature and frequency effects on cyclic crack growth rate.

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REFERENCES

[1] F-J. Lu, Thesis, Department of Mechanical Engineering, University of Waterloo, 1988.

[2] Plumtree, A. and Schuchtar in Proc. Ninth Congress on Material Testing, Budapest, Ed. E. Czoboly, Soc. of Mech. Eng, Budapest 1986, Vol. I, pp. 19-23.

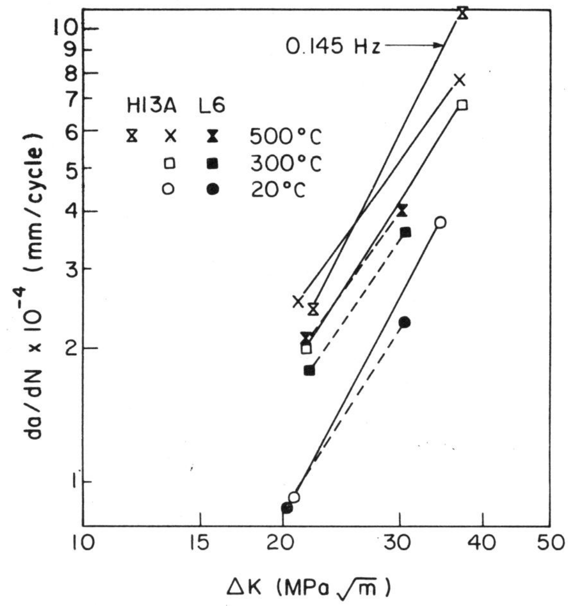


Figure 1 Crack propagation rates at 5Hz in H13A and L6 tool steels

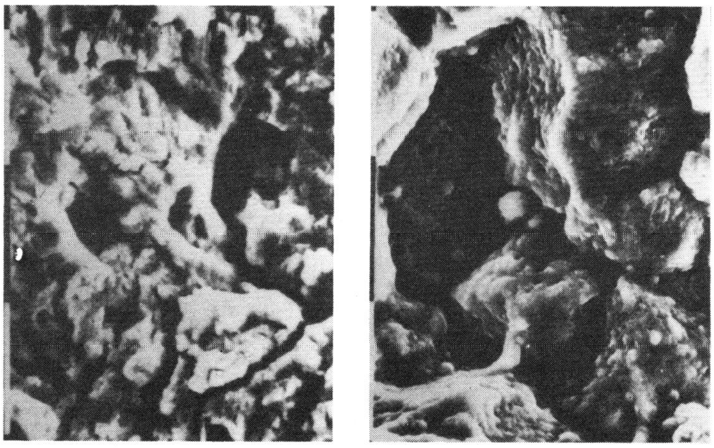
a)  b)

Figure 2 Fracture surfaces in H13A tool steel at 500° C.
(a) Transgranular at 5Hz (b) Intergranular at 0.145 Hz and $\Delta K = 34$ MPa $\sqrt{m}$, Bars to left represent 10μm.