Crack Initiation at Notches in Low Cycle Fatigue

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I. INTRODUCTION

The authors proposed[1] that crack initiation in notched specimens can be interpreted as the failure of a small **ligament** near the notch root subjected to the same strain cycling history.

The present work is an extension of the previously reported work. Careful measurements and analyses of the strain distributions near notch roots made it possible to devise a simple method for directly measuring the strain range at the notch root. Experimental studies on low cycle fatigue of four materials and three notch geometries (notch depth 30%, $K_t = 2,3,4$) are presented and analyzed in light of this more detailed understanding of the stress and strain distribution in the plastic range near the notch root.

II. EXPERIMENTAL

A. Local Strain Distribution Near the Notch Root

The plastic strain distribution has been studied for a variety of notch geometries in annealed AM-350 steel sheet (ultimate strength 1310 N/mm^2, 0.2% yield strength 1172 N/mm^2, thickness 1.57 mm). Theoretical elastic stress concentration factors ranged from 2 to 12.5. The strain distribution was obtained from measurements on a 200 lines per inch grid printed on the flat surface of the specimen by photoresist methods.

B. Fatigue Crack Initiation Studies

The specimen geometries are shown in Fig. 3. The notch depth was 30% and root radii were chosen corresponding to theoretical elastic stress concentration factors, K_t, of 2,3 and 4. The strain cycling was symmetrical about zero mean strain and controlled by means of the 0.3 in. gage length extensometer attached to the specimen across the notch.

III. RESULTS AND CONCLUSIONS

(1) An experimental study of the plastic strain distribution near notches was undertaken to aid in the analysis of low cycle fatigue crack initiation. It was found that the strain at the notch root can be readily obtained from measurement of the root radius change and is given by $\varepsilon_{t,NR} = \ln\sqrt{\frac{\rho}{\rho_o}}$ (where ρ and ρ_o are the root radii after and before loading respectively) as shown in Fig. 2. Away from the notch root, the longitudinal strain decreases as $(1/\text{distance})^m$, with $m = 0.5$ to 0.67, i.e. not too different from the strain distribution predicted from the theory of elasticity as shown in Fig. 1[2]. This similarity between elastic and plastic strain distribution for AM 350 steel sheet is further confirmed by the experimental result that the true strain concentration factor is approximately equal to the elastic stress concentration factor, and is certainly related to the strain hardening behavior of the test material.

(2) Notch effects on crack initiation in low cycle fatigue were studied on Al 2014-T6, Al 7075-T6, AISI 4340 steel heat-treated to a yield strength of 1127 N/mm^2, and HY-80 steel.

(i) The results show that crack initiation follows a Manson-Coffin type relationship between the number of cycles to crack initiation, N_o, and the total strain range at the notch root, $\Delta\varepsilon_{t,NR}$, i.e. $N_o^{\alpha'}\Delta\varepsilon_{t,NR} = C_1(K_t)$ where the constant $C_1(K_t)$ is a function of the notch geometry. The exponent α' has a value of approximately 0.25 to 0.33 for all materials investigated.

(ii) When the number of cycles to crack initiation, N_o is presented as a function of the average plastic strain range in a small ligament near the notch root, $\Delta\bar{\varepsilon}_{p,NR}$, the data become independent of notch geometry, i.e. $N_o^{\alpha}\Delta\bar{\varepsilon}_{p,NR} = C_2$ where C_2 is material constant. The exponent α has a value of 0.62 to 0.96. This averaging procedure was done considering the plastic constraint factors μ as listed in Figs. 4a to d.

(iii) From the hysteresis loops on Al 2014-T6 and Al 7075-T6 (see Fig. 5), it was also possible to relate the plastic energy absorption per cycle, W_p, to the number of cycles to crack initiation, N_o. The data show that $W_p \cdot N_o \simeq C_3(K_t)$ where the constant, $C_3(K_t)$, is a function of notch geometry; it is proportional to K_t^2. Furthermore, $W_p/(\sigma_Y \cdot \rho^2 t)$ is proportional to $(\Delta\varepsilon_{p,NR})^2$, the square of the range of the maximum strain as measured at the notch root, and hence

$$\left[\frac{W_p}{\sigma_Y \rho^2 t} \cdot \frac{1}{K_t^2} \cdot N_o\right]^{1/2} = N_o^{1/2} \cdot \frac{\Delta\varepsilon_{p,NR}}{K_t} = \text{const.}$$

The logical relationship, that the maximum strain range at the notch root $\Delta\varepsilon_{p,NR}$, is proportional to the product of the elastic stress concentration factor K_t, and the average strain range inside the critical strained test volume, may prove to be of practical use in the analysis of low cycle fatigue in construction elements with stress concentrations.

REFERENCES

1. V. Weiss, et al., "Crack Propagation and Initiation in Low Cycle Strain Controlled Fatigue," Czech. J. Phys. B 19 (1969).

2. V. Weiss, "Notch Analysis of Fracture," in book Treatise on Fracture, ed. H. Liebowitz Academic Press, Vol III, (1971).

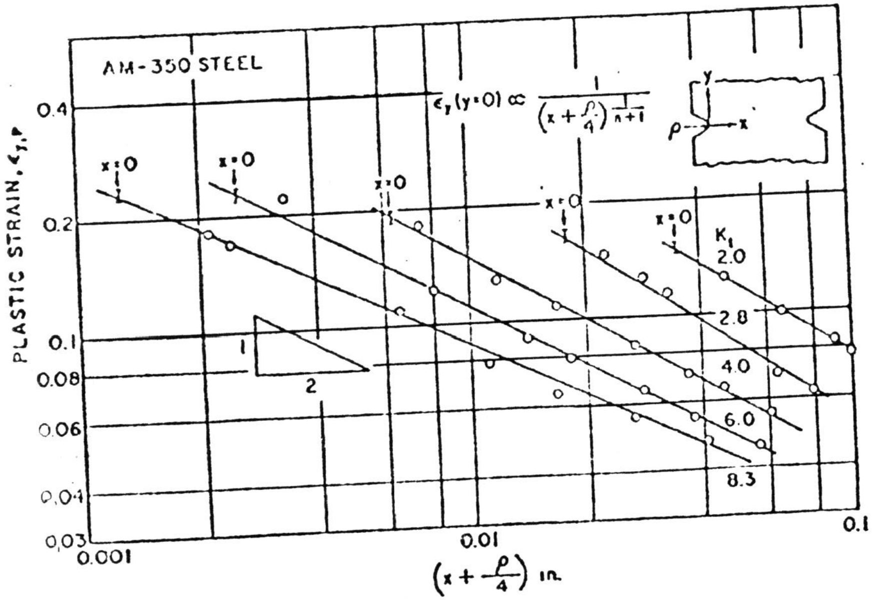


Fig. 1 DISTRIBUTION OF THE MAXIMUM PRINCIPAL STRAIN, $\varepsilon_y(y=0)$, NEAR THE NOTCH ROOT. PLOT OF $\ln(x+\rho/4)$ VS $\ln \varepsilon_y$ ALLOWS EXTRAPOLATION TO x=0, i.e. THE DETERMINATION OF $\varepsilon_{P,NR}$ AT THE NOTCH ROOT.

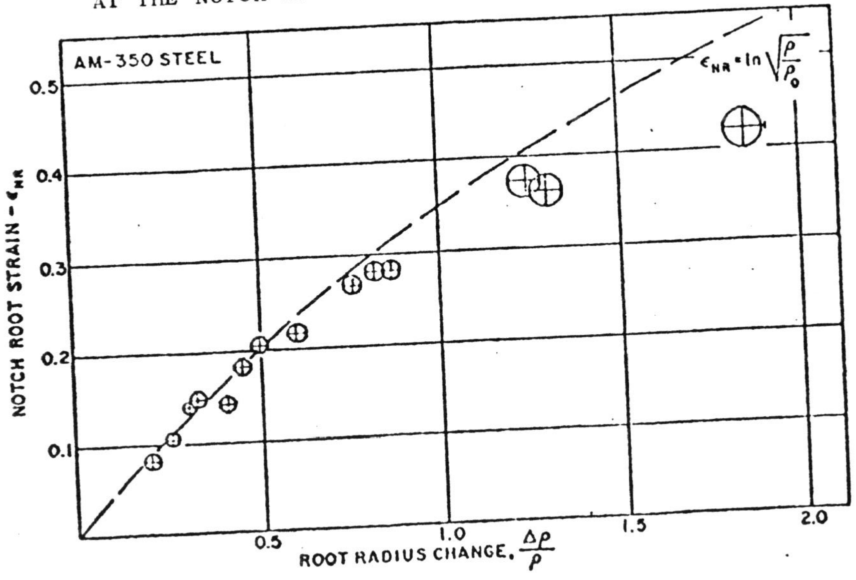
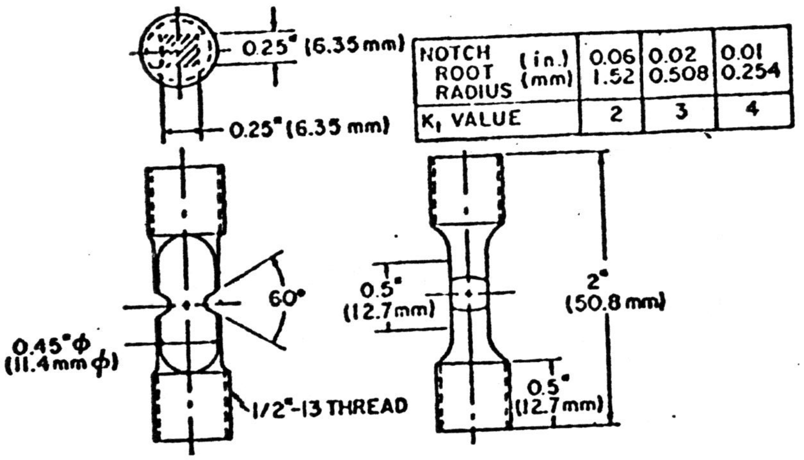


Fig. 2 RELATIONSHIP BETWEEN ROOT RADIUS CHANGE AND MAXIMUM STRAIN AT NOTCH ROOT.



NOTCH ROOT RADIUS	(in.) (mm)	0.06 1.52	0.02 0.508	0.01 0.254
K_t VALUE		2	3	4

Fig. 3 SPECIMEN DESIGN AND K_t VALUES.

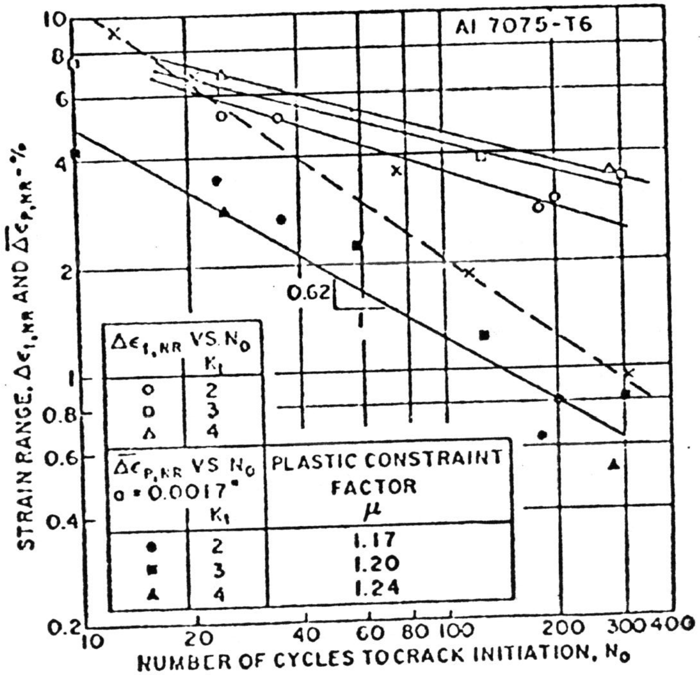


Fig. 4(a) LOW CYCLE FATIGUE CRACK INITIATION AT NOTCHES FOR Al 7075-T6.

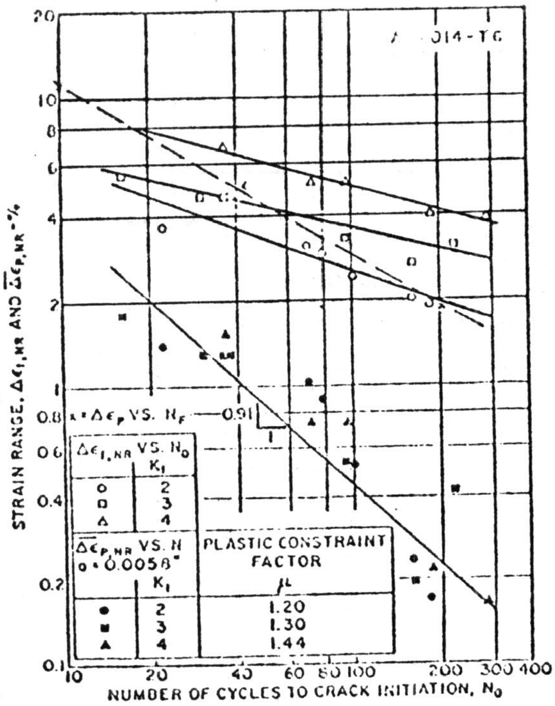


Fig. 4(b)

LOW CYCLE FATIGUE CRACK INITIATION AT NOTCHES FOR AL 2014-T6.

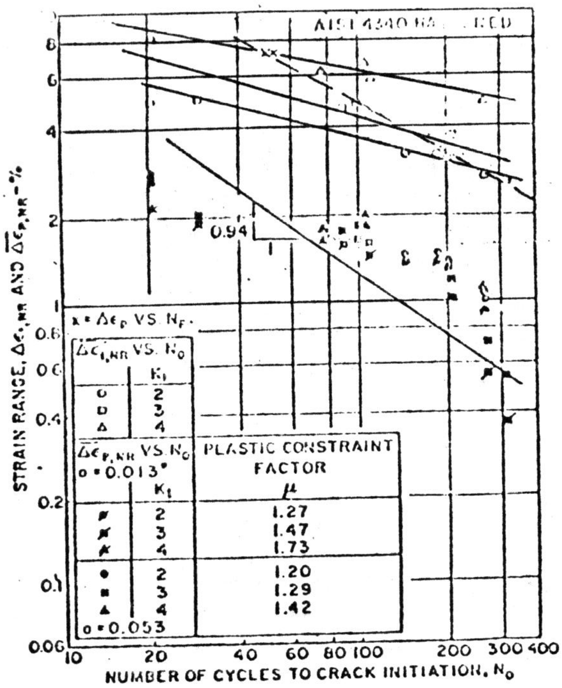


Fig. 4(c)

LOW CYCLE FATIGUE CRACK INITIATION AT NOTCHES FOR AISI 4340 HARDENED.

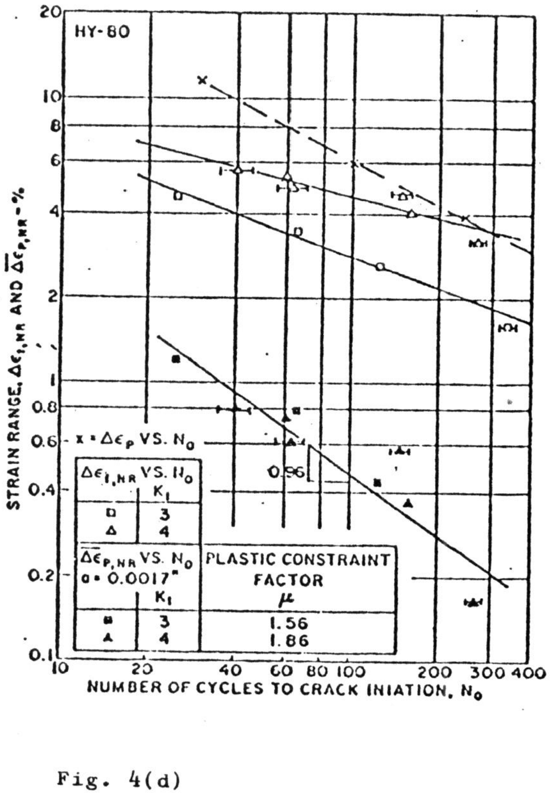


Fig. 4(d)

LOW CYCLE CRACK INITIATION AT NOTCHES FOR HY-80.
X: DATA FOR HY-100

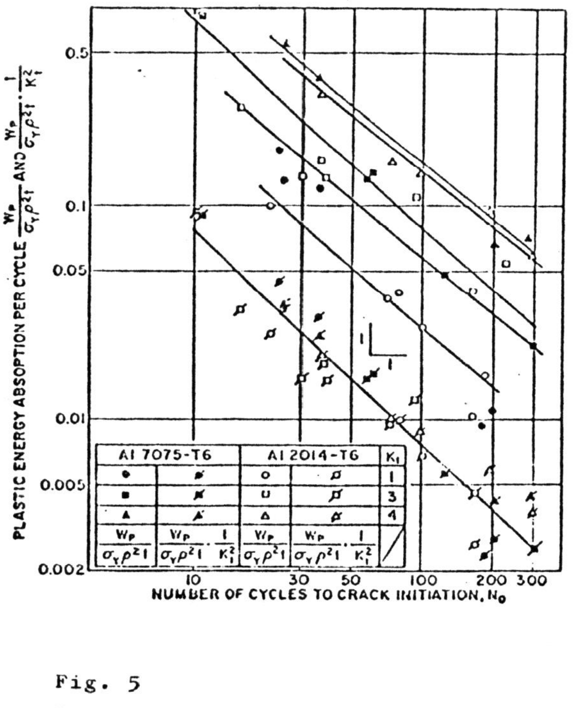


Fig. 5

PLASTIC ENERGY ABSORPTION PER CYCLE vs. NUMBER OF CYCLES TO CRACK INITIATION, N_o, FOR AL 7075-T6 AND AL 2014-T6.