HIGH TEMPERATURE PROPERTIES AND FRACTURE OF 4340 ALLOY STEEL

B. Kim and A. H. Shabaik*

INTRODUCTION

Medium-carbon alloy steel 4340 is industrially important. It has high hardenability and is capable of giving good properties in large sections. It is relatively free from temperature brittleness and retains useful machineability at relatively high hardness (43Rc). It is used for automotive crack shafts and rear axle shafts, aircraft crank-shafts, connecting rods, propeller hubs, gears, drive shafts, landing gear parts, and heavy duty parts of rock drills.

Most of the work done [1,2,3,4] on this alloy has been to determine the various properties, e.g. tensile strength, ductility, fracture stress, and fracture surface configuration in the temperature range from 77°K to 473°K. The main objective of this investigation is to examine the high temperature properties and fracture of 4340 alloy steel. Simple tension tests were used to determine the high temperature strength, (yield strength, ultimate tensile strength, and fracture stress), ductility (true strain at necking and fracture point), and fracture mode (fracture surface configuration) of 4340 alloy steel in the hot working temperature range (533° to 1255°K).

EXPERIMENTAL PROCEDURE

This investigation focused on a commercial quality AISI 4340 alloy steel. The composition (in wt pct.) and the hardness of the alloy in the as received condition are as follows:

Fe	C	Mn	Ni	Cr	Mo	Si	P	S	C	BHN	Rc
Bal.	.40	.76	1.76	.78	.26	.20	0.11	.011	.15	235	17.15

Tension specimens 9 x 10^{-3}m. in diameter, and 36 x 10^{-3}m. in gauge length were machined. The specimens were austenitized at 1016°K for 2 hours, oil quenched, and then tempered at 810°K for 2 hours. The hardness of the alloy after treatment was found to be 35 Rc. Tension tests were then carried out at different temperatures (from 533 to 1255°K) and a constant crosshead speed of 2.5 x 10^{-4}m/sec. on an electrohydraulic mechanical testing system (MTS). The specimen was heated after assembling to the desired test temperature and held at temperature for 10-15 minutes before testing. A quad-elliptical radiant heating furnace was used. The temperature of the specimen was measured and controlled throughout the test within ±3° of the desired temperature. The tension test was carried out until fracture. The load-elongation curve was obtained in each case.

*Materials Dept., University of California, Los Angeles, California.

RESULTS AND DISCUSSION

Mechanical Properties

The high temperature strength and ductility of 4340 alloy steel were determined from the load-elongation curve and the following relationships.

$$\sigma_y = \frac{L_y}{A_o}, \quad \sigma_n = \frac{L_n}{A_n}, \quad \text{and } \sigma_f = \frac{L_f}{A_f};$$

$$\varepsilon_n = \ln \frac{A_o}{A_n}, \quad \varepsilon_f = \ln \frac{A_o}{A_f}, \quad A_n = \frac{A_o \ell_o}{\ell_n}$$

where L_y, L_n, and L_f are the loads at yield, necking, and fracture points respectively; A_n, is the cross sectional area at necking, ℓ is the gauge length at necking; σ_y, σ_n, and σ_f are true stresses at yield, necking, and fracture respectively; ε_n and ε_f are true strains at necking and fracture respectively.

Figure 1 shows the variation of σ_y, σ_f, ε_n, and ε_f with test temperature. From the strain temperature plot ductility peaks at approximately 755°K, and 920°K are observed. Small modulation in the σ values can also be seen to take place at these ductility peaks. Similar findings have been reported by Sherby et al [5,6] for low carbon polycrystalline iron and commercial carbon steel.

Fractography

The fracture surfaces at different temperatures were examined using a scanning electron microscope. Two main zones of fracture were observed; namely, fibrous and shear zones. The radial zone, characterized by spoke-or-star shaped cracks and generally found to take place at temperatures below 373°K[1,2], was not observed at any of the test temperatures. Fibrous and shear zone size measurements were determined by area measurements of each zone. Figure 2 shows the total fracture area and the shear area as measured by planimeter from a 50X enlarged cross section of the sample. The relative size of each of the two zones vary with temperature. In the lower temperature region the fracture is predominantly shear, in the intermediate temperature region the fracture is both fibrous and shear, and in the high temperature region it is mostly rupture as it is seen from area measurements and the superimposed scanning micrographs. From these results it can be concluded that failure is initiated by normal rupture followed by shear. As temperature increase the shear mode decrease and failure is predominantly by normal rupture. The tilt angle of the shear lip from the tensile axis was measured at different temperature, in the temperature range from 533°K to 810°K, using the scanning electron microscope and an interferometer. The angle was found to vary between 42° and 53°.

Scanning Electron micrographs of the center of the fracture surface at 755°K, 890°K, 922°K, 977°K, and 1140°K are shown in Figure 3. The presence of "equiaxed dimples" can be seen. The size of these dimples increases with temperature. The shallow dimples are typical of failures involving a void coalescence mechanism. Comparing the fractographs the fracture at the higher temperatures show evidence of greater ductility. At temperature below 755°K, the tensile fracture surfaces shows a little

evidence of visible dimple structure. At 922°K, one of the ductility peaks, the dimple size is large compared to that at 866°K and 977°K. At 1140°K the dimples are shallow and large in size.

Fracture Criterion

In view of the differing techniques used to assess ductility and the vast amount of data that is available for different test geometries, it would clearly be desirable to establish some criterion of fracture that would make possible a rationalization of the data. Several fracture criterion based on stress, strain, and or energy have been proposed in the literature [7,8,9,10]. The fracture stress and fracture strain as a function of temperature are shown in Figure 1.

Plastic work at fracture was calculated using the following equation:

$$P = \text{plastic work/unit vol.} = C \frac{\varepsilon_f^{n+1}}{n+1}$$

where C and n are materials constants in the workhardening equation $\bar{\sigma} = C\,\bar{\varepsilon}^n$; $\bar{\sigma}$ and $\bar{\varepsilon}$ are effective stress and effective strain respectively. Using the above equation, the plastic work/unit vol. versus test temperature is as follows:

Temp. °K	644	755	811	866	922	950
P $10^6 N/m^2$	2006	1758	1455	1393	1579	1469

The results show that plastic work/unit volume at fracture is approximately constant and is independent of temperature.

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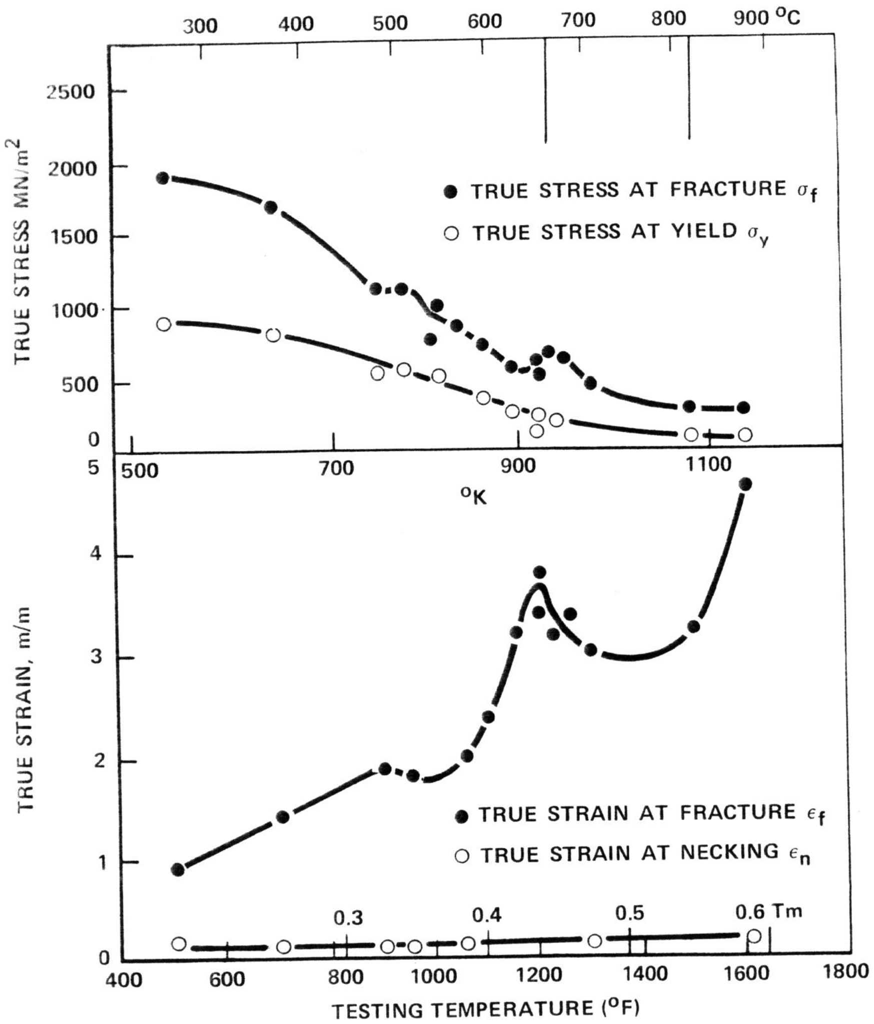

Figure 1

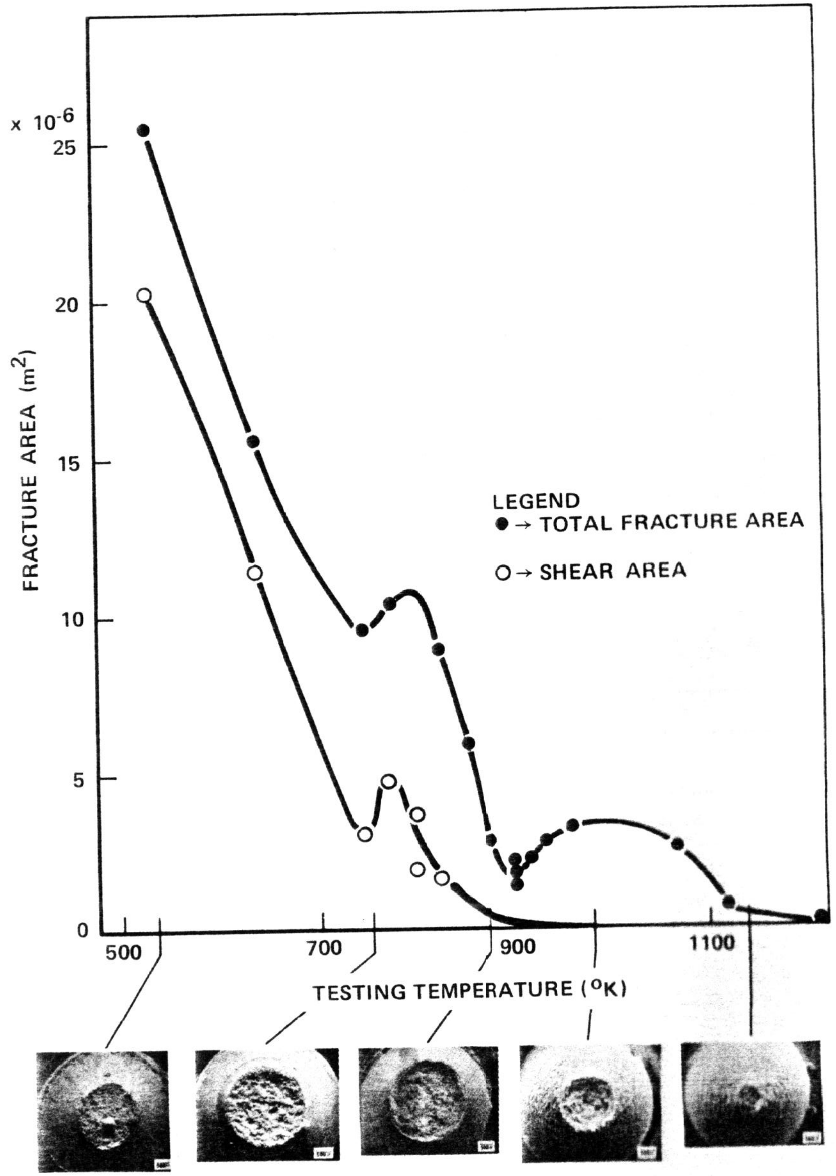

Figure 2 Fracture Area at Various Testing Temperature

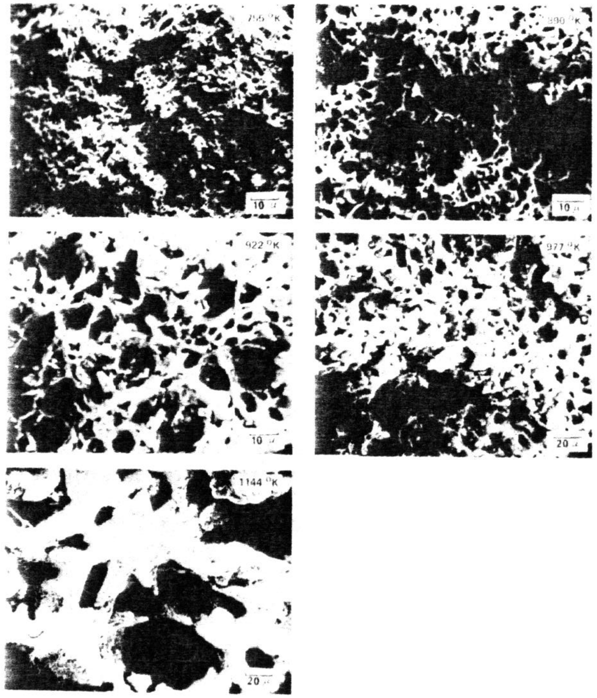

Figure 3 Scanning Electron Micrographs of the Fracture Surfaces at Different Temperatures