IMPROVING BOTH K_{Ic} AND CVN FRACTURE ENERGY OF AISI 4340 STEEL THROUGH HIGH TEMPERATURE THERMOMECHANICAL TREATMENT

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ABSTRACT

It has been reported for as-quenched AISI 4340 steel that high temperature austenitizing treatments at 1470K instead of conventional heat treatment at 1170K result in a twofold increase in fracture toughness, K_{Ic}, but a decrease in charpy impact energy. In this paper an attempt has been made to improve both K_{Ic} and CVN energy simultaneously by the application of high temperature thermomechanical treatment. The improvement in the toughness properties of AISI 4340 steel has been rationalized in terms of microstructural changes caused by HTMT.

KEYWORDS

High temperature thermomechanical treatment; austenitizing temperature; fracture toughness; CVN fracture energy; prior austenite grain size; One Step Temper Embrittlement (OSTE); impurity segregation.

INTRODUCTION

The strong influence of the fine scale microstructural features on mechanical properties has become evident during recent years. This is especially true for fracture toughness of quenched and tempered ultra high strength low alloy structural steels. Recent researchers (Lai, Wood, Clark and co-workers, 1974; Parker and Zackay, 1975) have shown that by increasing the austenitizing temperature to 1470K as compared to conventional austenitizing at 1140K the plane strain fracture toughness (K_{Ic}) of AISI 4340 type steels in quenched and tempered conditions can be increased by almost twice without decreasing the yield strength. This enhancement has been attributed to the presence of thin films of retained austenite between martensite laths, segregation effects, dissolution of carbides, etc. However, concurrent with this improvement in K_{Ic} there is a perplexing reduction in the charpy impact energy (Ritchie, Francis and Server, 1976). Similar behavior has been reported in

300-M steel (McDarmaid, 1978).

It is well known that thermomechanical treatments bring out many beneficial microstructrual changes and hence inproved mechanical properties (Kula and Azrin, 1978). Therefore, the aim of the present investigation is to examine the influence of thermomechanical treatments at high austenitizing temperatures on the toughness properties of AISI 4340 steel.

EXPERIMENTAL

The material used in this investigation was aircraft quality (vacuum-arc-melted) AISI 4340 hot rolled bars of 51 mm thickness obtained from Latrobe Steel Company, in fully annealed condition and having the following composition (wt. percent):

TABLE 1.

C	Si	Mn	S	P	Cr	Ni	Mo
0.41	0.24	0.82	0.004	0.007	0.8	1.72	0.25

As-received steel rods were given the following treatment:

(1) Austenitizing at 1173K for 1 hour, in an inert atmosphere, followed by oil quenching.

(2) Austenitizing at 1473K for 1 hour, in an inert atmosphere, step cooling at 1173K, holding at 1173K for 15 minutes, followed by oil quenching. These two treatments will hereafter be referred to as the Standard Heat Treatment (SHT).

(3) Austenitizing at 1473K for 1 hour, in an inert atmosphere, 50% deformation by forging, holding at 1473K for 10 minutes, step cooling to 1173K, holding for 15 minutes, followed by oil quenching. This treatment will hereafter be referred to as the High Temperature Thermomechanical Treatment (HTMT).

(4) Tempering at various temperatures in the range of 473K-873K for two hours after quenching as in (1), (2), and (3).

Specimens for mechanical testing were prepared from both HTMT and SHT treated bars. Tensile testing was carried out on ASTM standard tensile specimens of 6.35 mm diam, gage sections 31.75 mm in length, on an Instron machine. Toughness properties were evaluated using ASTM standard charpy specimens on a Dynatup instrumented impact tester. Plane strain fracture toughness values were evaluated using 12.7 mm thick ASTM standard compact tension (CT) specimens on a MTS machine. All the mechanical tests were carried out at room temperature and in air. Fractured samples were examined using the Scanning Electron Microscope (SEM). Optical microscopy was conducted on specimens prepared from the cut sections of broken charpy and CT specimens. Detailed measurements of prior austenite grain size, martensite lath thickness and inclusion spacing were carried out using qualitative metallography techniques.

RESULTS

Optical Metallography on unetched specimens indicated that mean particle spacing increased with an increase in austenitizing temperature. The particles covered were both inclusions and carbides.

The microstructure of the as-quenched specimens consisted of martensite.

Martensite plate thickness measurements indicated that there was no appreciable change in the thickness with the austenitizing temperature and thermomechanical treatment.

Prior austenite grain size measurements for SHT and HTMT specimens are included in Table 2. It is clear that for SHT samples, higher austenitization increased the grain size. There is considerable reduction in prior austenite grain size in the 1470-1170K HTMT as compared with the 1470-1170K SHT.

TABLE 2. Room Temperature Tensile Properties of AISI 4340 Steel in Quenched Condition.

Treatment	0.2%YS (MPa)	UTS (MPa)	El %	RA %	ε_f^*	Prior Austenite Grain Size (μm)
1170K SHT	1600	2200	8.3	28.5	0.20	25-30
1470-1140K (SHT)	1610	2208	4.0	10	0.09	~ 280
1470-1170K (HTMT)	1650	2220	10.0	30	0.25	65-85

Room temperature tensile data is also given in Table 2. While yield and tensile strengths were unaffected by high temperature austenitization in the SHT steel, the ductility was reduced to some extent. On the other hand, HTMT steel exhibited improved values of yield, tensile strength and ductility.

CVN fracture energy recorded from the instrumented impact test results has been shown to be a function of tempering temperature in Fig. 1, which illustrates the following features:

(1) The 1470-1170K quench resulted in inferior CVN fracture energy in comparison with the 1140K quench in the SHT samples, confirming the earlier observations.

(2) The 1470-1170K HTMT gave superior CVN fracture in comparison with the 1470-1170K and the 1170K SHT specimens.

(3) The One Step Temper Embrittlement (OSTE) was found to occur in both the SHT and HTMT steel. OSTE is more pronounced in the 1470-1170K, SHT steel.

Fig. 2 shows a plot of plane strain fracture toughness as a function of tempering temperature. This figure indicates that

(1) 1470-1140K quench produced higher values of K_{Ic} than the 1140K quench.

(2) The HTMT resulted in improved K_{Ic} values in comparison with the SHT.

DISCUSSION

Despite the significant improvements in K_{Ic} with increase in austenitizing temperatures (from 1140K to 1470K) for a variety of structural steels (Lai, Wood, Clark and co-workers, 1974; Parker and Zackay, 1975; Ritchie, Francis and Server, 1976; McDarmaid, 1978), similar increases in CVN energy values are not observed. The present investigation also confirms such behavior for AISI 4340 structural steel. Ritchie, Francis and Server (1976) explained this discrepancy on the basis of the effect of notch root radius on the toughness.

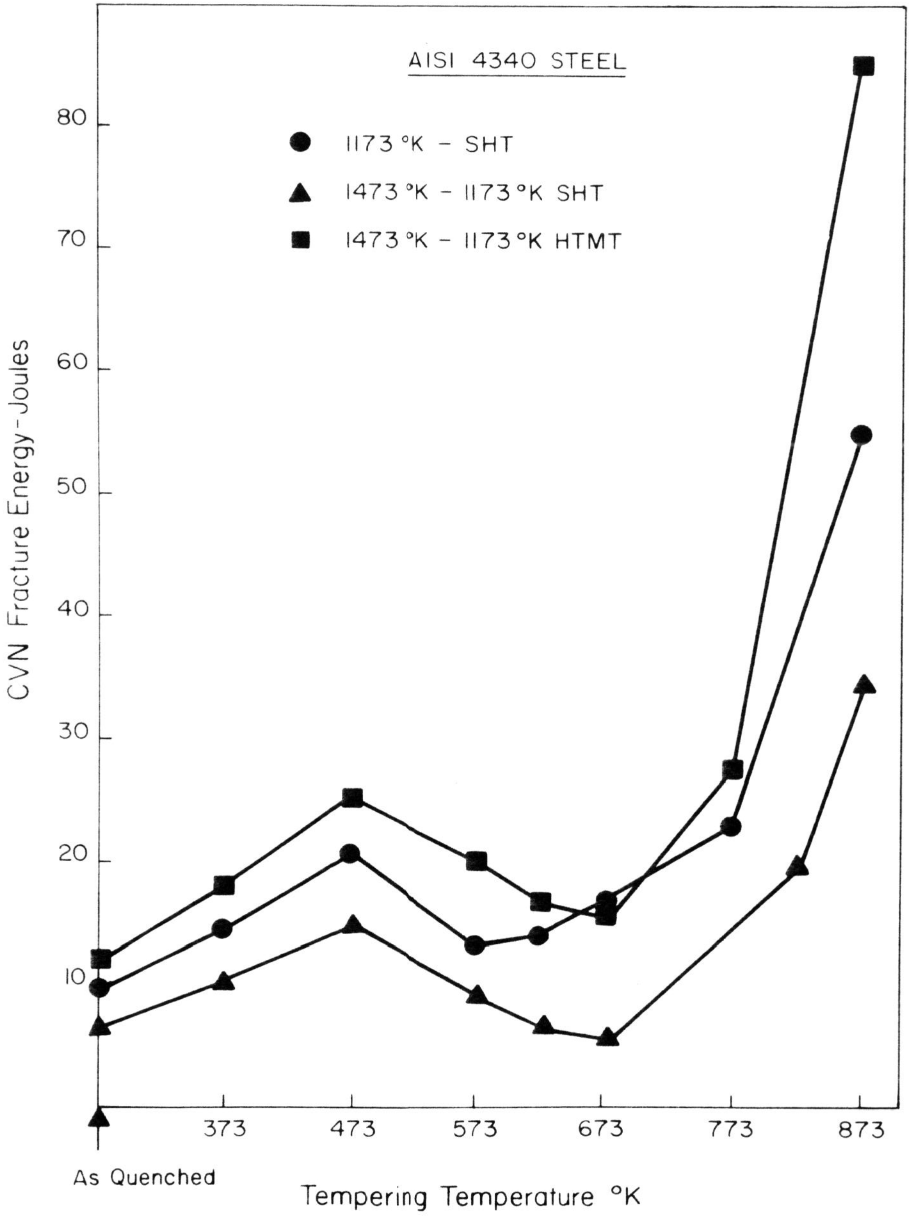

Fig. 1. Effect of tempering and austenitizing temperature on the room temperature CVN energy of AISI 4340 steel.

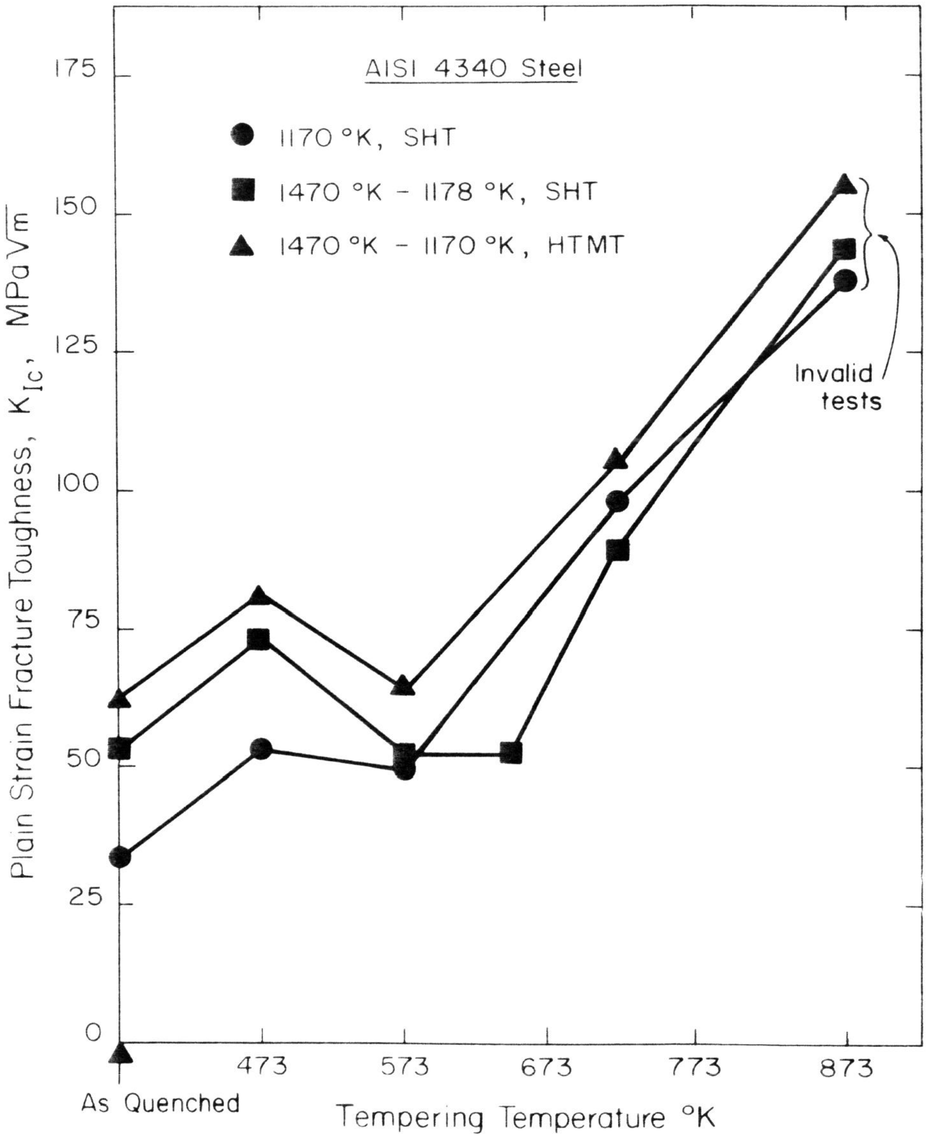

Fig. 2. Fracture toughness of AISI 4340 steel as a function of tempering temperature at three different austenitizing treatments.

Higher austenitizing treatment (1470-1140K) was shown to cause grain boundary embrittlement due to S or P segregation. For a stress controlled fracture, this reduces the critical fracture stress, σF, thereby decreasing the charpy fracture energy for strain controlled ductile fracture energy. For strain controlled ductile fracture, decrease in fracture energy has been attributed to the reduction in critical fracture strain occurring due to higher austenitizing temperatures (Ritchie and Horn, 1978).

On the other hand, an increase in K_{Ic} values with an increase in austenitization temperature has been attributed (Ritchie, Francis and Server, 1976; Ritchie and Horn, 1978) to larger "effective" root radius or "characteristic distance" resulting from either increased grain size or dissolution of void initiating particles at high austenitizing temperatures. Carlson, Rao and Thomas (1979) also have concluded that K_{Ic} does not increase with an increase in austenitizing temperature if the microstructure does not coarsen, i.e., the characteristic distance, ρ_o, does not significantly increase.

Many research workers (Parker and Zackay, 1975; Thomas, 1973; Lai, 1975) have explained from qualitative transmission electron microscopy studies in terms of larger proportions of austenite films retained around martensite plates and packet laths after austenitizing at high temperatures. Such films of retained austenite are typically 100 to 200°A thick in oil quenched 4340 steels. However, Ritchie and Horn (1978) have concluded that the presence of films of retained austenite is unimportant in contributing to the increase in toughness arising from changes in austenitizing temperatures.

In the present investigation, it is found that 1470-1170K HTMT has improved both CVN fracture energy and K_{Ic} values simultaneously, as compared to 1470-1170K SHT values. It is known that the HTMT of steels improves mechanical properties such as toughness, ductility and strength (Kula and Azrin, 1978; Azrin and co-workers, 1980). This improvement in the mechanical properties has been attributed to microstructural changes, e.g., a decrease in austenite grain size, fine carbide precipitation, increased dislocation density.

The improvement in CVN fracture energy in the 1470-1170K HTMT can be mainly attributed to a reduction in segregation and a decrease in the prior austenite grain size. Reduction in segregation improves the value of critical fracture stress, σF, for stress controlled fracture. SEM fractographs recorded for quenched steel are shown in Fig. 3. Fig. 3a indicates that a 1470-1140K SHT specimen has failed due to complete intergranular fracture, while a 1470-1140K HTMT specimen has failed, as seen in Fig. 3b, in a mixed mode, i.e., ductile and cleavage fracture. The SEM fractograph shown in Fig. 4 for 1470-1170K HTMT, 473K temper, indicates a ductile fracture. For a strain-controlled ductile fracture, the improvement in CVN values is due to increased critical fracture strain, which in turn can be attributed to a reduction in both segregation and prior austenite grain size. Tensile data documented in Table 1 bear ample evidence of improved critical fracture strain.

From Fig. 1 it is clear that OSTE has occurred in both the SHT and HTMT structures. OSTE seems to be more pronounced at high temperatures in SHT structures. In the temper embrittlement regime for the SHT specimens (both 1170K and 1470-1170K), the failure occurs by an intergranular mechanism and is associated with grain boundary embrittlement due to impurity segregation (Banerji, McMahon and Feng, 1978; Briant and Banerji, 1978). The SEM fractograph shown in Fig. 5 in which a 1470-1170K HTMT, 600K tempered specimen is recorded indicates that failure has occurred by way of a fibrous rupture. This again suggests that the reduction in grain boundary segregation has resulted from thermomechanical treatment.

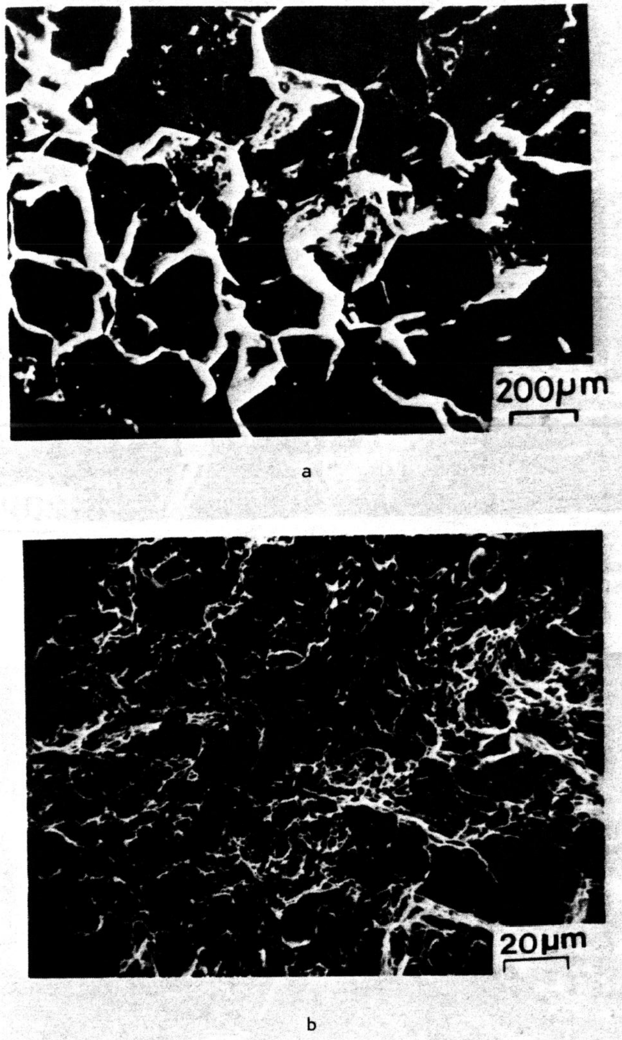

Fig. 3. Mechanism of fracture in as-quenched steel: (a) 1470-1170°K SHT, (b) 1470-1170°K HTMT.

From Fig. 2 it is evident that there is no appreciable improvement in the K_{Ic} values of the 1470-1140K HTMT steel as compared to the 1470-1170K SHT steel. This may be due to the reduction in prior austenite grain size (as seen from Table 1) which in turn reduces the characteristic distance and hence the K_{Ic} values.

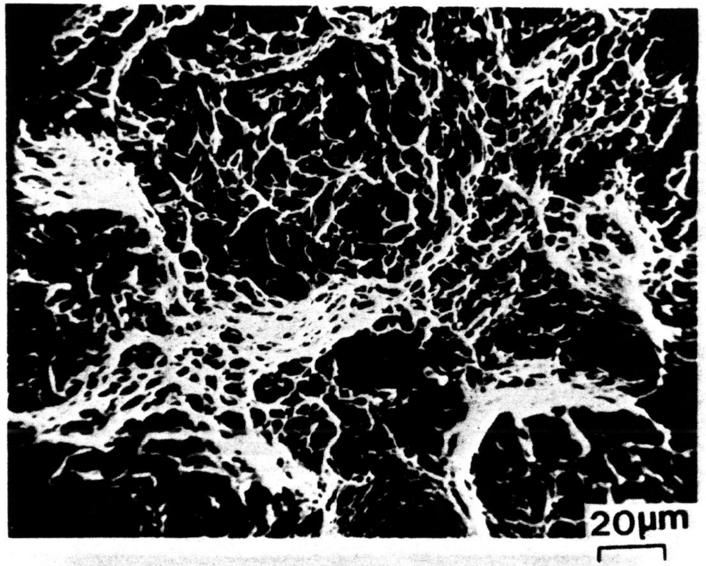

Fig. 4. Ductile Fracture in 473°K tempered 1470-1170°K HTMTreated AISI 4340 Steel.

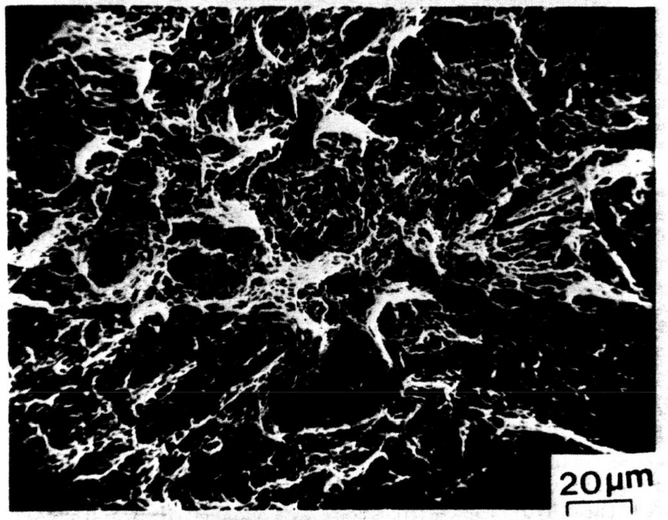

Fig. 5. Mechanism of fracture in 600°K tempered, 1470-1170°K HTMTreated AISI 4340 steel.

CONCLUSIONS

(1) It has been verified again that a high temperature austenitizing treatment of 1470-1170K SHT improves the fracture toughness of as-quenched AISI 4340, but gives rise to CVN energies inferior to those of 1170K SHT.

(2) By introducing deformation after high temperature austenitization at 1470K and then step cooling to 1170K, followed by oil quenching (high temperature thermomechanical treatment), both CVN energy and fracture toughness values can be improved.

(3) This improvement in the toughness values of AISI 4340 can be attributed to microstructural changes such as reduction in segregation and prior austenite grain size achieved during HTMT.

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