THE INFLUENCE OF ELECTROTHERMAL TREATMENT ON HYDROGEN EMBRITTLEMENT OF AISI 4340 STEEL

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ABSTRACT

Results are presented showing that the passage of electric current during the tempering of AISI 4340 steel (electrothermal treatment) produces a reduction in its susceptibility to hydrogen embrittlement, without altering the mechanical properties.

KEYWORDS

Hydrogen embrittlement, electrothermal treatment.

INTRODUCTION

The increasing use of high strength steels has, in recent years, resulted in growing concern about the phenomenon of hydrogen embrittlement. The damaging effect of hydrogen on the mechanical behavior of metals is a long known fact, but in spite of considerable effort the phenomenon has still many aspects which are not fully understood (Thompson and Bernstein, 1980).

For some time it has been observed that the passage of current in a metal brings with it changes in mechanical properties and microstructure. By the use of direct (d.c.) or alternating (a.c.) low density current, or high density pulses, changes have been observed in the mechanical properties of aluminum and iron alloys (Klypin, 1979), in structural effects during the ageing of iron-carbon and aluminum-copper alloys (Erdmann-Jernitzer, 1959; Shine, 1972; Koppenall, 1963), in the kinetics of phase formation in copper-tin films (Silveira, 1982), and in the recrystallization of electrolytic copper (Conrad, 1983; Silveira, 1984). There is, however, no agreement on the reasons for the observed interaction between electric current and structural or mechanical properties of metals.

The present work reports an improvement in the resistance to hydrogen embrittlement of AISI 4340 steel after undergoing electrothermal treatment. We use electrothermal treatments to imply heat treatments which are assisted by the simultaneous passage of an electric current. In the present work, low density d.c. was used and the results obtained by this technique at temperatures in the range of 673-923 K were compared with those obtained in the same material, after undergoing conventional tempering at the same temperatures. This application of electrothermal treatment should be further studied as a possible new and promising method to obtain steels which combine high mechanical strength with improved resistance to hydrogen embrittlement.

EXPERIMENTAL

The composition of AISI 4340 used in this research is shown in Table 1. Samples were initially normalized and annealed in order to achieve homogeneous compositions and stress relief. They were then rough-machined, to produce specimens as shown in Figure 1. An allowance of 0.5 mm above final dimensions was made, except for screw threads which were protected by steel nuts to avoid warping during subsequent hardening. The full heat treatment sequence is shown in Table 2. Conventional and electrothermal tempering was done on sample pairs, for one hour, in the range 673-923 K. Temperatures were measured by thermocouples fixed on the samples. For electrothermal treatments d.c. of 60 A was used, which corresponds to a nominal density of 1.85 $MA.m^{-2}$. This electric current results in a heating by the Joule effect of about 20 K and the tempering furnace temperature was adjusted in such a way as to ensure that the samples were actually at the desired temperature.

After tempering all specimens were measured for hardness (Rockwell C scale). Of each pair, one was used for tensile tests and the other for hydrogen embrittlement tests. Tensile tests were run on a Instron machine at room temperature and $\dot{\varepsilon} = 3.28 \times 10^{-4}\ s^{-1}$.

The evaluation of hydrogen embrittlement was made by uniaxial tension at constant load, using a "Cortest proof ring" (Harris, 1974). The gauge length of test sample was subjected to a load equivalent to 60% of the yield stress, with cathodic polarization of 10 $A.m^{-2}$ in a solution of sulphuric acid (4%) with 12 mg/ℓAs_2O_3, at room temperature. All samples were examined by metallography and fractography.

RESULTS

Results obtained from mechanical and hydrogen embrittlement tests are presented in Table 3 and Figures 2 and 3. Material electrothermally treated shows increased resistance to hydrogen; in the most effective case (923 K), specimens do not fail for times at least one order of magnitude larger.

The microstructure of tempered steel is predominantly martensitic as shown in Figures 4a and 4b. As tempering temperature is raised, the structure shifts from distinctly acicular martensite to one having increasing quantities of precipitated carbide. We have observed no difference in the microstructures between the samples heated under the two different conditions.

Scanning electron fractography of samples broken in tension also shows no difference arising from the two treatments. Fractographic studies of samples broken by hydrogen embrittlement again indicated similar fracture, showing an intergranular brittle fracture (hydrogen cracking) and a ductile center (Figure 5). We noted, however, a small increase in the extent of the hydrogen cracked region in the material which had been electrothermally tempered (Figure 5). The average crack size, as indicated in Figure 5a, is shown in Table 4 for the different heat treatment temperatures. The crack size from specimens at 923 K was not evaluated because the fracture pattern of Figure 5 was not repeated in this case, as indicated in Figure 6. This change in fracture aspect has been previously reported (Araújo, 1982).

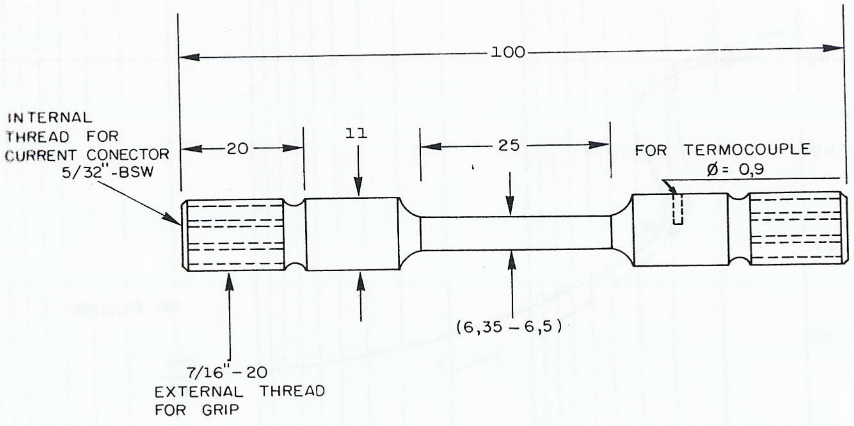


Fig. 1. Test specimen (dimensions, mm)

TABLE 1 Chemical Composition of AISI 4340 Steel

COMPOSITION (IN WEIGHT PERCENT)							
C	Mn	Si	Cr	Ni	Mo	P	S
0.40	0.66	0.32	0.84	1.67	0.27	0.024	0.018

TABLE 2 Sequence for Obtaining Specimens

TREATMENT	TEMPERATURE K	TIME min	OBSERVATIONS
As received			
Austenitizing	1143	40	
Cooling			in air
Annealing	813	60	
Rough machining			
Austenitizing	1073	60	
Hardening			in oil
Tempering	673-923 range	60	with and without passage of d.c.
Fine machining			

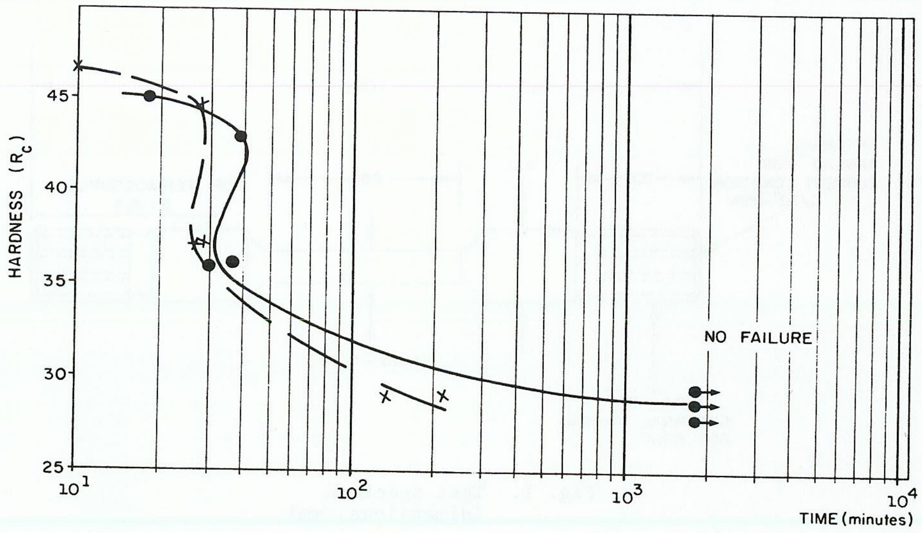


Fig. 2. Time to failure in hydrogen embrittlement tests of AISI 4340 steel quenched and tempered to various strenghts with (.) or without (x) direct current.

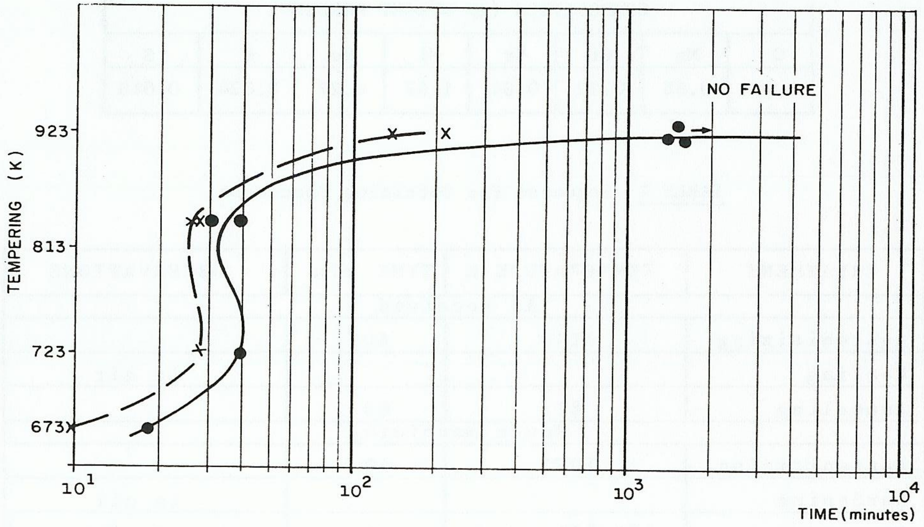
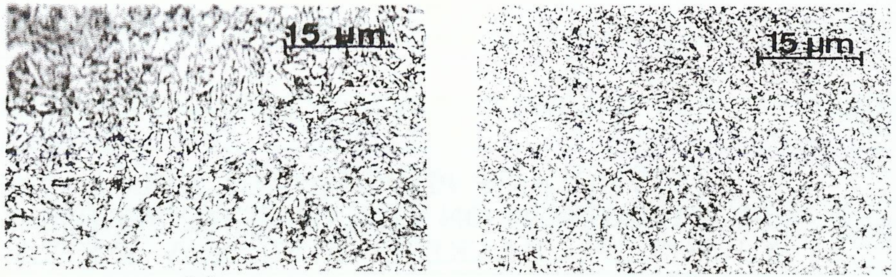


Fig. 3. Time to failure in hydrogen embrittlement tests of AISI 4340 steel quenched and tempered at temperatures shown with (.) or without (x) direct current.

TABLE 4 Properties of AISI 4340 Steel Hardened and Tempered at Different Temperatures

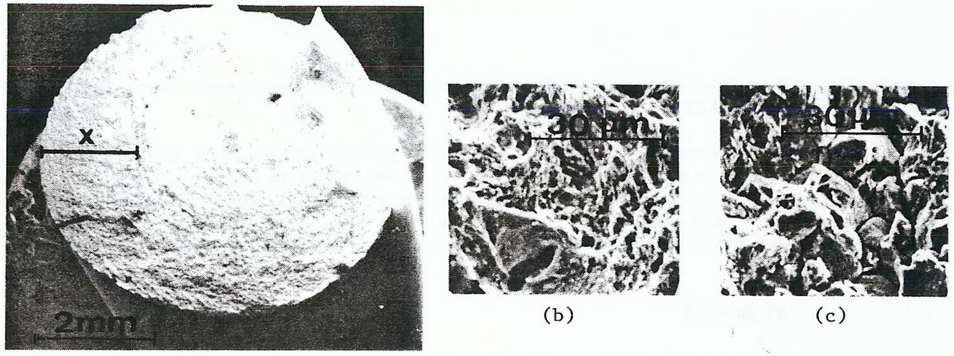
	SPECIMEN	TEMPERATURE (K)	YIELD STRENGTH (NM/m^2)		UTS NM/m^2	ELONGATION %(20 mm)	AREA REDUCTION %	HARDNESS HRC ±1	TIME TO FAILURE IN THE TESTS
			LOWER	UPPER					
Conventional Tempering	S2	923	810	860	920	26	62	30	—
	S1		—	—	—	—	—	29	135
	S11		830	900	920	26	62	29	—
	S12		—	—	—	—	—	29	219
	S4	813	1090	1100	1150	20	52	37	—
	S3		—	—	—	—	—	37	27
	S14		1110	—*	1110	19	48	37	—
	S15		—	—		—	—	37	31
	S5	723	1310	—*	1350	15	48	44	—
	S6		—	—	—	—	—	43	28
	S7	673	1390	—*	1510	15	45	46	—
	S8		—	—	—	—	—	46	10
Electrothermal Tempering	C2	923	780	830	890	26	60	30	No failure after 1440 (24 hours)
	C1		—	—	—	—	—	29	
	C10		810	830	910	26	63	28	
	C9		—	—	—	—	—	28	
	C12		810	870	910	27	63	29	
	C11		—	—	—	—	—	29	
	C4	813	1090	—*	1150	21	53	36	—
	C3		—	—	—	—	—	36	32
	C14		1110	—*	1160	19	55	36	—
	C15		—	—	—	—	—	37	37
	C5	723	1290	—*	1360	15	46	44	—
	C6		—	—	—	—	—	43	39
	C7	673	1430	—*	1540	13	37	45	—
	C8		—	—	—	—	—	45	18

*No discontinuous yield point observed.



(a) (b)

Fig. 4. Microstructures of AISI 4340 steel after tempering at (a) 673 K and (b) 923 K. No microstructural effect due to passage of current has been observed. Nital 2%.



(a) (b) (c)

Fig. 5. SEM fractographs of tensile specimen tempered at 813 K, broken in hydrogen embrittlement test. General view (a) showing peripheral region of hydrogen crack, mostly intergranular (b), and central region of final rupture, which occurred by microvoid coalescence (c). Samples tempered at 673 and 723 K show similar pattern.

TABLE 4 Depths of hydrogen embrittlement cracks

SPECIMEN	$\bar{X}$ (mm)	T (K)
C3 S3	1.41 1.22	813
C6 S6	1.28 1.13	723
C8 S8	0.68 0.36	673

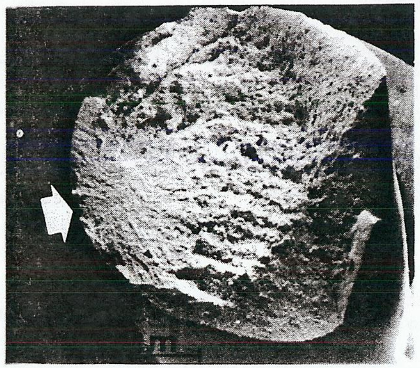


Fig. 6. SEM fractograph of tensile specimen tempered at 923 K, broken in hydrogen embrittlement test. Hydrogen crack appears as flat area at left.

DISCUSSION

If one compares the two heat treatments in terms of the results of tension and hardness tests as well as metallography, there is no significant difference between them. Such small variations in hardness and lower and upper yield strength as are observed (Table 4) can be understood as a normal dispersion of results of such tests. On the other hand, hydrogen embrittlement tests showed considerable difference in the behavior of samples tempered with and without the passage of electric current. The time to rupture under test at constant load was always larger for samples treated electrothermically at all tested tempering temperatures. In particular, the most striking effect was observed at 923 K. Material tempered electrothermally at this temperature was resistant to hydrogen embrittlement, no fracture occurring under the severe test conditions.

The interpretation of the present observations is difficult since both phenomena involved, namely hydrogen embrittlement and electrothermal treatment, are subject to considerable uncertainty regarding their mechanism. If one considers only two effects which might be of importance in hydrogen embrittlement, namely the formation of precipitates or their interaction with dislocations, it is seen that electrothermal treatment could conceivably interfere with either one. For instance, the effect of the passage of electric current on dislocation structure has been reported previously (Klypin, 1979; Silveira, 1982) in the study of the variation of mechanical properties in materials where electric current was passed during mechanical stress. Also, observations have been made (Erdmann-Jernitzer, 1959; Shine, 1972; Koppenall and Simcoe, 1963) from which it can be concluded that the passage of electric current has an effect on carbon segregation and precipitation, as well as on precipitation of phases from solid solution in other systems.

The observed increase in the critical size of cracks before final fracture is, in effect, related to an increase in fracture toughness of the steel (increased K_{IC}). We plan to pursue these studies further by exploring the effect of various such treatments on fracture and impact toughness.

CONCLUSIONS

The passage of low density d.c. during tempering of AISI 4340 steel does not alter its mechanical properties as compared to those measured after conventional tempering. It does, however, substantially alter the response of this material towards hydrogen embrittlement.

For all tempering temperatures examined in the range 673-923 K, the time to failure under static stress hydrogen embrittlement conditions improved substantially, with the best results (no failure after exposure times an order of magnitude longer) being observed for tempering at 923 K.

The optimum conditions for electrothermal tempering should be explored further since they present a potentially promising method of diminishing catastrophic hydrogen embrittlement fracture in such steels.

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