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Effect of continuous-cooling transformation structure on mechanical properties of 0.4C–Cr–Mo–Ni steel

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Commercially available 0.4C–Cr–Mo–Ni steel was studied to determine the effects on its mechanical properties of various microstructures produced by continuous-cooling transformation after austenitization. A good combination of strength and notch toughness was obtained independently of test temperatures (293 and 193 K) when the steel was austenitized at 1173 K and then continuously cooled at an average rate of $\sim$ 3.1 K s^{-1} (expressed as the average cooling rate from 823 to 573 K) before final rapid cooling. The microstructure of the steel consisted of a mixed structure of martensite and 10–15 vol% lower bainite, which appeared in acicular form in association with the martensite. Slower cooling had a detrimental effect on the mechanical properties of the steel; the microstructure of this steel consisted of a mixed structure of martensite and upper bainite, which appeared as masses in the matrix. As the average cooling rate increased, the lath size and internal stringer-carbide size in the upper bainite were larger, and retained a somewhat increased austenite content.

1. Introduction

A considerable research effort has been directed towards clarifying the relationship between the various microstructures resulting from phase transformation, and the mechanical properties in low-alloy steels, heat-treated at high strength. For example, the importance of martensitic or bainitic structure (i.e. the packet, block and lath, and carbide morphology) in controlling the mechanical properties has been reported [1–8]. However, there have been few systematic studies of the effects of various microstructures produced by continuous cooling at the required rate after austenitization on the mechanical properties of these steels. Such microstructures have frequently been encountered in commercial practice, and improvements in mechanical properties may be associated with such microstructures [9]. Therefore better understanding of these microstructures should provide new suggestions for modification of commercial heat-treatment techniques, and/or lead to new ideas for developing better mechanical properties of high strength low-alloy steels.

In the present work, the commercially available 0.4C–Cr–Mo–Ni steel has been studied to determine the effects of various microstructures produced by continuous cooling after austenitization on the mechanical properties of high-strength low-alloy steels.

2. Experimental procedure

The commercially available 0.4C–Cr–Mo–Ni steel (AISI 4340 or BS En24 grade) was used in this investigation. The chemical composition of the steel was a 0.40C–0.23Si–0.76Mn–0.78Cr–0.25Mo–1.84Ni. The steel was supplied as a hot-rolled bar, 130 mm in diameter. Test specimens with their longitudinal axis parallel to the rolling direction were machined from the bar. Each specimen was fully annealed.

The heat-treatment schedules in this investigation are given in Table I. All the specimens were austenitized in a vacuum tube furnace. The required argon gas was fed into the furnace to cool rapidly or continuously from 823 to 573 K. To obtain a controlled cooling rate, a recorder was used to automatically plot the change in temperature against time. The temperature was measured using a chromel/alumel thermocouple wire, spark-welded to the centre of the face of the test specimen. For all the specimens, rapid cooling to 823 K, whereby the precipitation of ferrite or pearlite could be neglected through the heat treatment, was carried out. Tempering was carried out in an oil bath.

Smooth and notch tensile properties were determined at ambient temperature (293 K) or low temperature (193 K) using an Instron machine, at a constant strain rate of 6.50×10^{-4} s^{-1}. Smooth tensile specimens with a gauge length of 12.5 mm and a cross section of 1.5×4.0 mm, and notch tensile specimens with a 2 mm "V" notch on both sides and a net cross section of 1.5×4.0 mm, were used. Testing at 193 K was performed in a stainless chamber cooled with liquid nitrogen gas, which controlled the temperature within $\pm$ 1 K. Subsize Charpy V-notch specimens (5 mm thickness) were used to determine the transition temperature, and the values quoted were for the 50–50 ductile-to-brittle transition temperature (DBTT). In the Charpy test, the specimens were well heated with

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TABLE I Heat-treatment schedules

Designation of steel	Heat treatment				
	Austenitization	Rapid cooling	Continuous cooling	Rapid cooling	Tempering
15B	1173 K for 3.6 ks	To 823 K	3.1 $K s^{-1}$ 823–573 K	To 293 K	473 K for 7.2 ks
25B	1173 K for 3.6 ks	To 823 K	1.6 $K s^{-1}$ 823–573 K	To 293 K	473 K for 7.2 ks
50B	1173 K for 3.6 ks	To 823 K	0.9 $K s^{-1}$ 823–573 K	To 293 K	473 K for 7.2 ks
75B	1173 K for 3.6 ks	To 823 K	0.6 $K s^{-1}$ 823–573 K	To 293 K	473 K for 7.2 ks
Conventionally heat-treated	1173 K for 3.6 ks	*	*	*	473 K for 7.2 ks

*Oil quench.

TABLE II Mircrostructural analysis and bainite start temperature (B_s) of steels investigated

Designation of steel	Microstructural analysis			
	Martensite	Bainite (vol%)	Retained austenite (vol%)	B_s^*
15B	Balance	Lower, 10–15	Vestigial	593 K
25B	Balance	Upper, 25–30	3.8	658 K
50B	Balance	Upper, 50–60	4.3	683 K
75B	Balance	Upper, 75–80	4.8	708 K
Conventionally heat-treated	Predominant	–	Vestigial	–

*Determined by standard dilatometric measurement.

silicon oil or were cooled using a refrigerant composed of a mixed solution of liquid nitrogen and petroleum ether.

The microstructure was categorized using optical microscopy, thin-foil transmission electron microscopy (TEM), and X-ray diffraction (XRD). The Bainitic structure was delineated by etching in a 5 wt % picric alcohol solution. The volume percentage of bainite was determined using point counting [10, 11], in which the specimen is viewed directly on the stage of an optical microscope. Thin foils for TEM were prepared by grinding to 0.1 mm thickness, then chemically thinning in a mixed solution of hydrofluoric acid and hydrogen peroxide, followed by electropolishing in a mixed solution of phosphoric and chromic acids. The retained austenite content was measured by XRD using Miller's technique [12] of rotating and tilting the sample surface about an incident beam of MoK_α (using a Zr filter). The sample surface was electropolished in a mixed solution of phosphoric and chromic acids. A scanning speed of $0.003^\circ\ s^{-1}$ was used, and the combination of peaks chosen for analysis was $(200)\alpha$, $(211)\alpha$, $(200)\gamma$, $(220)\gamma$ and $(311)\gamma$.

Fractography was made on the fresh surface of notch tensile specimens using scanning electron microscopy (SEM).

3. Results

3.1. Microstructure

The microstructural analysis and bainite start temperatures (B_s) of the steels produced by the continuous-cooling and conventional heat treatments are given in Table II. Representative optical and TEM micrographs of the steels investigated are shown in Figs 1 and 2, respectively. When the steel was cooled continuously at the average rate of 3.1 K s^{-1} (15B steel) from 823 to 573 K, the microstructure of the steel consisted of a mixed structure of martensite and 10–15 vol % lower bainite, in which internal carbide precipitates were oriented in one direction (Fig. 2b). The lower bainite appeared in acicular form in association with martensite (Fig. 1a). The martensite in the mixed structure possessed a predominantly lath morphology. The size of the martensitic packets, which were composed of parallel laths decreased as compared with that obtained by conventional heat treatment (Fig. 2a and b). A slower cooling rate (25B, 50B and 75B steels) produced a mixed structure of martensite and upper bainite with an internal carbide stringer lying along the length of the laths (Fig. 2c and d). The upper bainite appeared as masses in the matrix (Fig. 1b, c and d). As the average cooling rate increased, the lath size and internal stringer carbide size in the upper bainite were larger ([Fig. 2c and d]) and the retained austenite content somewhat increased.

3.2. Mechanical properties

Table III shows mechanical properties of the steels obtained by continuous cooling and conventional heat treatment. The results showed that a good combination of strength and notch toughness was obtained by the 15B heat treatment, independent of test temperature. Compared to the conventionally heat-treated steel, the 15B steel had improved notch tensile stress at an equivalent strength level, at temperatures of 293 and 193 K, owing to lowering the ductile-to-brittle transition temperature (DBTT). Compared to the conventional heat treatment, the steels with a slower cooling rate (25B, 50B and 75B steels) showed a significant decrease in notch tensile strength and a markedly raised DBTT, owing to decreased strength. The detrimental effect on the strength and notch toughness was evident as the average cooling rate increased.

3.3. Fractography

It is well known that fractography directly describes the fracture process and provides valuable evidence for the causes of failure. Thus fracture profiles of notch-tensile specimens were investigated. The results were compared with those obtained by the conventional heat treatment. Fig. 3 shows representative fractographs from notch-tensile specimens tested at 293 K. SEM observation revealed that for 15B steel with superior notch tensile strength, the small dimple fracture mode was observed under the V notch (Fig. 3b), while the conventionally heat-treated steel consisted of a mixture of dimple fracture and quasi-

TABLE III Mechanical properties of steels investigated

Designation of steel	Test temperature (K)	0.2% Yield stress (MPa)	Ultimate tensile stress (MPa)	Total elongation (%)	Notch tensile stress (MPa)	Ductile-to-brittle transition temperature (K)
15B	293	1585	1905	6.1	2380	285
	193	1645	1952	4.0	2280	–
25B	293	1410	1740	6.5	1910	389
50B	293	1240	1480	7.2	1620	418
75B	293	890	1220	8.2	1250	425
Conventionally	293	1580	1903	5.8	2050	308
heat-treated	193	1641	1953	3.9	1720	–

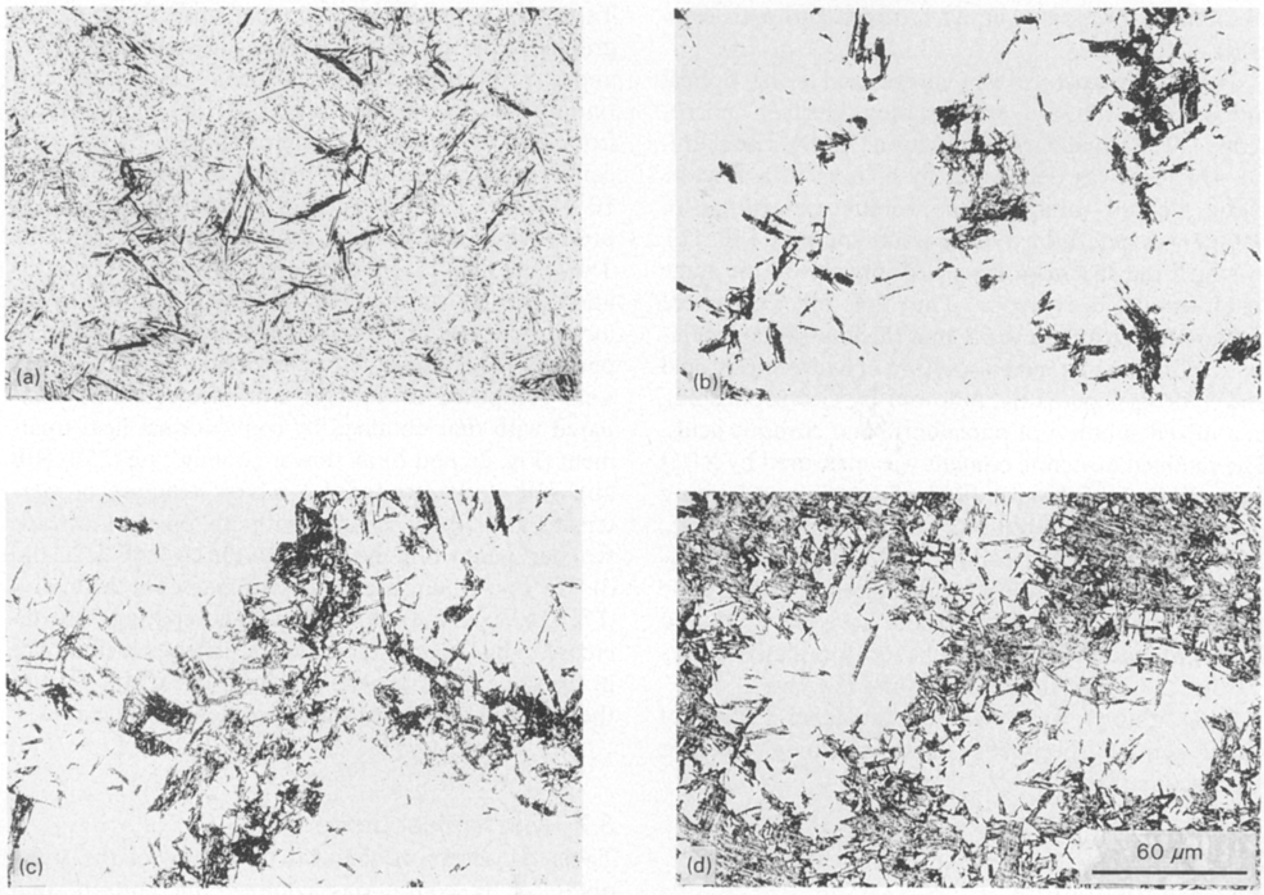

Figure 1 Optical micrographs of continuously cooled steels (as-quenched). Black and white show bainite and martensite, respectively. (a) 3.1; (b) 1.6; (c) 0.9; (d) 0.6 K s^{-1}.

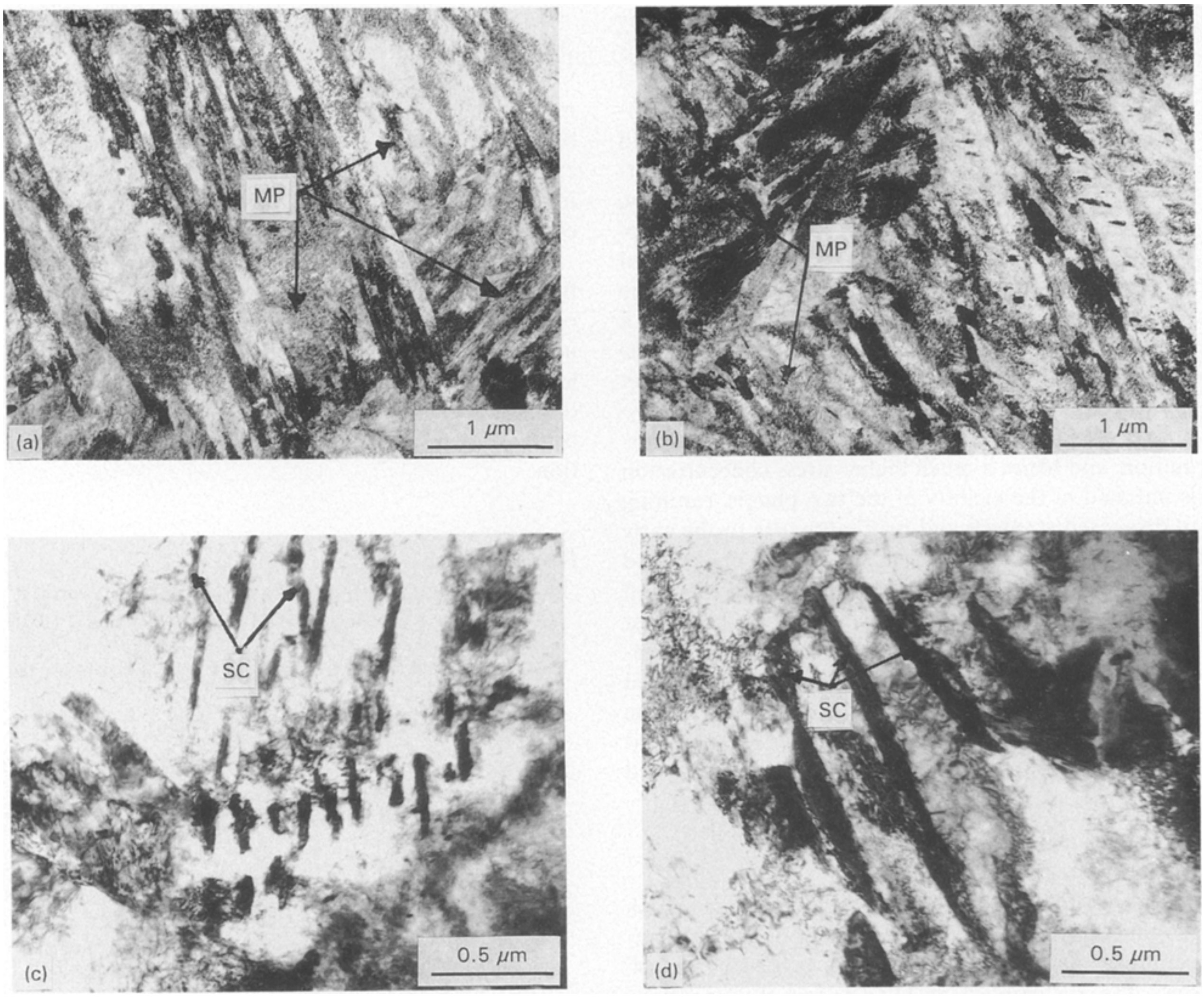

Figure 2 TEM micrographs of conventionally heat-treated and continuously cooled steels (as-quenched). (a) conventionally heat-treated; (b) 3.1; (c) 0.9; (d) 0.6 K s^{-1}. MP, martensitic packet; SC, stringer carbide.

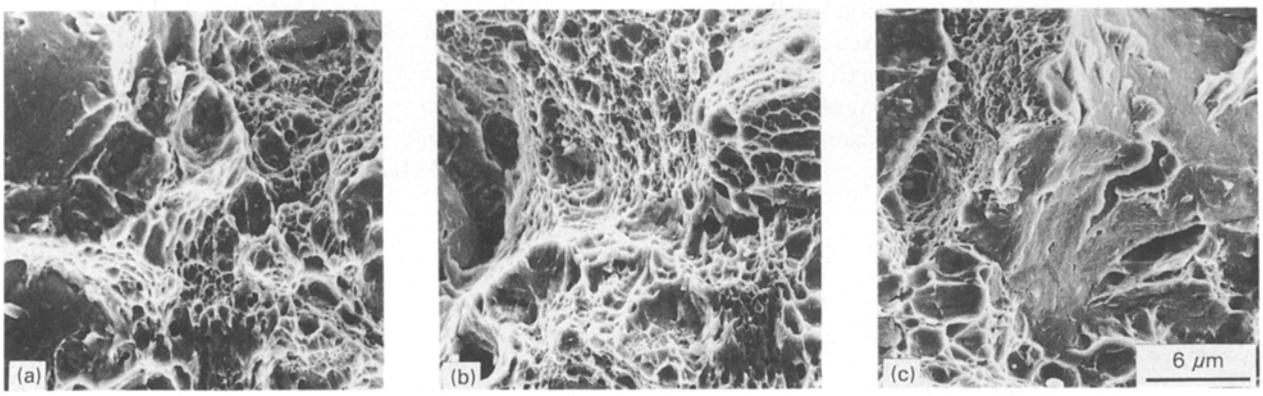

Figure 3 SEM fractographs from notch tensile specimens of conventionally heat-treated and continuously cooled steels. (a) conventionally heat-treated; (b) 3.1; (c) 0.9 K s^{-1}.

cleavage fracture modes. (Fig. 3a). SEM observation also revealed that for the steels with a slower cooling rate and inferior notch tensile strength, large brittle fracture facets were found under the V notch (Fig. 3c).

4. Discussion

The most notable result obtained in this investigation is that a good combination of the strength and notch toughness was obtained, independent of test temperature, when the steel was austenitized at 1173 K and then continuously cooled at the average cooling rate of 3.1 K s^{-1} from 823 to 573 K. The improved strength is probably due to the fact that lower bainite, which appeared in acicular form in association with martensite, produces a refinement of the matrix. The strength of the bainite is enhanced by the martensite as a result of the higher plastic restraining of bainite by martensite [13, 14]. Improved notch toughness is attributed to the fact that the lower bainite has a stress-relieving effect on the higher stress concentration, and produces a crack-arresting effect just ahead of the existing crack, which leads to increased resistance against brittle fracture. The slower cooling rate produced martensite and upper bainite, which appeared as masses in the matrix and had a detrimental effect on the strength and notch toughness. From the results of this investigation together with those of a previous paper [14], the detrimental effect on the mechanical properties may be explained by the fact that non-uniform strain occurs between the two phases of martensite and bainite during plastic deformation, and hence a much higher stress concentration is initiated in the vicinity of the two phases, resulting in decreased strength and brittle fracture in the early stages of plastic deformation. An increase in retained austenite content may have a beneficial effect on toughness, contributing to relaxation of the higher stress concentration. However, as far as this investigation is concerned, the energy absorbed by the retained austenite will be inadequate to compensate for the brittle fracture which occurs due to non-uniform strain between the two phases of martensite and bainite.

5. Conclusions

1. A good combination of strength and notch toughness was obtained, independent of the test temperatures of 293 and 193 K, when 0.4C–Cr–Mo–Ni steel was austenitized at 1173 K and then continuously cooled at an average cooling rate of 3.1 K s^{-1} (expressed as the average cooling rate from 823 to 573 K).

2. The microstructure of the steel consisted of martensite and 10–15 vol% lower bainite, which appeared in acicular form in association with martensite.

3. The beneficial effect of the mixed structure on the mechanical properties could be due to the fact that the lower bainite produces a refinement of the martensite matrix, and increased resistance against brittle fracture.

4. Slower cooling rates had a detrimental effect on strength and notch toughness.

5. The microstructure of the steels consisted of martensite and upper bainite, which appeared as masses in the matrix. As the average cooling rate increased, the lath size and internal stringer-carbide size in the bainite were larger, and the retained austenite content increased.

6. The detrimental effect on the mechanical properties could be due to the fact that non-uniform strain occurs between the two phases of martensite and upper bainite during plastic deformation, and hence a higher stress concentration is initiated in the vicinity of the two phases, resulting in decreased strength and brittle fracture in the early stages of plastic deformation.

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