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Mixed structures in continuously cooled low-carbon automotive steels

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ABSTRACT

Mixed microstructures have been studied in low-carbon microalloyed steels suitable for automotive applications, after continuous cooling from the hot-rolled condition. Microstructural features such as polygonal ferrite, bainitic and acicular ferrite and microphase constituent are identified using transmission electron microscopy. The influence of these mixed structures on the tensile strength, impact toughness and fracture behaviour is examined. It is found that improvements in impact toughness as compared with microalloyed medium-carbon ferrite/pearlite steels can be achieved from these predominantly acicular structures developed by controlling alloy composition and continuous cooling of these lower carbon steels.

INTRODUCTION

For certain automotive applications microalloyed bainitic steels are found to be a higher-toughness alternative, at similar strength levels, to microalloyed ferrite/pearlite steels. The recent extension of microalloying from the high-strength low-alloy (HSLA) structural steels (e.g. 1) to medium-carbon forging steels and high-carbon hot-rolled steels with ferrite/pearlite or wholly pearlitic microstructures (e.g. 2, 3) has already led to cost-effective improvements in their engineering application (4 - 11) as compared with customary alternative materials. One of the major factors responsible for strengthening of these ferrite/pearlite steels is precipitation strengthening by fine dispersions of vanadium carbide or carbonitride in both ferrite and pearlite (2, 3, 12). However, for certain purposes ferrite/pearlite steels can be limited by toughness and so it has been necessary to search for higher toughness alternatives for more critical applications (13 - 15). Recently (16), low-carbon multi-phase steels with improved toughness have been developed which rely on the processing and alloying additions for their strength instead of the carbon content as for the ferrite/pearlite steels.

The intermediate structures which develop during continuous cooling transformation (CCT) of modern HSLA steels are more complex as compared to those which form by isothermal transformation (IT). Some of the difficulties in metallographic identification of the phases formed have been highlighted previously (17, 18). The present work examines the microstructural changes caused by microalloying and continuous cooling from the hot-rolled condition, identifies the mixed phases formed over a range of transformation temperatures, and evaluates the effect of mixed microstructures on the mechanical properties and fracture behaviour.

EXPERIMENTAL

The chemical compositions of the steels used in this investigation are presented in Table 1. The steels were continuously cooled after hot-rolling into 28 mm diameter bars. Tensile and impact testing was carried out according to BS18 and BS131, respectively. Microstructural evaluation was carried out using standard metallographic techniques described elsewhere (3). Fracture surfaces of impact specimens were examined in a Hitachi S 530 electron microscope operated at 25 kV and TEM foil specimens were examined in a Philips CM 20 electron microscope operating at 200 kV.
RESULTS AND DISCUSSION

**a - Mixed Microstructures**

Fig. 1(a) and (b) show examples of the mixed structures observed in steels 1 and 2 in the continuously cooled condition. An acicular structure is predominant in steel 1 whereas polygonal ferrite grains are also evident in steel 2. Evidently the concentration of slightly higher Mn, and Cr and Ni additions, have suppressed the higher temperature reaction products more effectively in steel 1 than the Mo addition of steel 2. TEM examination allows a more detailed characterization of the various phases in both steels. Fig. 2 shows evidence of grain boundary ferrite in steel 1 formed at higher temperatures during continuous cooling after hot rolling, and that this ferrite contains a fine dispersion of V(CN) formed by an interphase precipitation mechanism (12) (Fig. 2(b)). Evidence for fibrous precipitation of V(CN) was also observed in the polygonal ferrite in steel 2. A high dislocation concentration within both the proeutectoid ferrite grains and the surrounding acicular ferrite grains is also evident. Fig. 3(a) and (b) show distinct examples of upper and lower bainite found in steel 1; the carbide particles are nucleated either at the lath boundary or within the ferrite laths, respectively. In addition, less distinctive regions containing both intralath and interlath carbide were also found (Fig. 3(c)) as a consequence of the wide range of transformation temperature. Evidence for bainitic structure was also found in steel 2. However, in steel 1 the major part of the microstructure comprised of a highly dislocated bainitic lath structure. Acicular ferrite laths containing a high dislocation density but no evidence of carbide precipitation were also found, as shown in Fig. 4. Twinned martensite laths were also observed in steel 1 (Fig. 5) which is consistent with similar observations described as microphases in previous work (19).

Fig. 6 illustrates the high dislocation density in the acicular bainitic ferrite laths in steel 2. The dislocation density was determined according to the procedures described in (20) and found to be of the order of 1.40 x 10^10 cm^-2 which is in agreement with previous work (21, 22). It is also estimated (23) that this amount of dislocation density can contribute approximately 145 Nmm^-2 to the strength of acicular ferrite.

The microstructural observations suggest that the vanadium microalloying addition in the steels has produced either particulate or fibrous precipitation of V(CN) only in the small fractions of grain boundary or polygonal ferrite as no evidence for V(CN) precipitation was found in the acicular and bainitic ferrite. Therefore, the main factors contributing towards the strengthening of these steels are precipitation of V(CN) in the polygonal ferrite, lath size and dislocation substructure of the bainitic ferrite and solid solution hardening from the Mn, Cr, Ni and Mo additions, and also from residual V that has not precipitated. These strengthening factors have been discussed in detail in previous reviews (24, 25).

**b - Mechanical Properties**

Fig. 7(a) and (b) illustrate the tensile strength and impact toughness values of the steels tested at room temperature. The mixed structure has shown an increase in toughness up to 35 percent as compared with medium- carbon ferrite/pearlite microalloyed steels in the as-rolled condition reported previously (26). This follows from the refined structure of both the effective ferrite grain size and carbide particle sizes expected in the acicular steels. The further small difference between the two experimental steels considered here could be attributed to the relative amounts of lower toughness structure in their respective microstructures, for example, upper bainite and high- carbon martensite, both observed in steel 1.

**c - Fractographic Study**

Fig. 8 shows fracture surfaces of the impact specimens and indicates quasi-cleavage fracture in both steels. The sections perpendicular to the nickel-plated fracture surface revealed that crack propagation occurred across grains or packets, or along grain and lath boundaries, as shown in Figs. 9(b) and (d). However, the fracture path appeared generally to be more irregular than in medium- carbon ferrite/pearlite steels which exhibit a more distinctive cleavage failure under equivalent testing conditions (27).
Figure 1 - Microstructure of steels in continuously cooled condition.

Figure 2 - (a) and (b) Precipitation (arrow) and dislocations observed in grain boundary ferrite BF, steel 1.

Figure 3
Figure 3 - (a) - (c) Examples of bainitic structures BF. steel 1.

Figure 4 - Dislocation substructure in acicular ferrite laths BF. steel 1.

Figure 5 - Twinned martensite observed in steel 1, (a) BF and (b) DF.

Figure 6 - High concentration of dislocations in bainitic ferrite laths (a) BF and (b) WBDF $g=\langle 011 \rangle k$, steel 2.
Figure 7 - (a) and (b) Mechanical properties of steels.

Figure 8 - SEM micrographs showing quasi-cleavage fracture surfaces and crack paths, (a), (b) steel 1 and (c), (d) steel 2.
SUMMARY AND CONCLUSIONS

Mixed structures have been identified in low-carbon microalloyed continuously cooled automotive steels. TEM examination revealed grain boundary ferrite, acicular ferrite, upper and lower bainite, highly dislocated substructures and microphase constituents (e.g. high-carbon twinned martensite) in both steels. Precipitation of V(CN) was observed only in the high temperature transformation products which limited the effect of precipitation strengthening. However, the predominantly acicular structure of the steels has contributed to a better combination of strength and impact toughness values compared with ferrite/pearlite microalloyed steels. The toughness can be attributed to more resistance to crack propagation from the refined mixed acicular structure.

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REFERENCES