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Hardenability of Austenite in a Dual-Phase Steel

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A low-carbon, low-alloy steel was intercritically heat treated and thermomechanically processed to study the martensitic hardenability of austenite present. Rolling of the two-phase ($\alpha + \gamma$) microstructure elongated austenite particles and reduced their martensitic hardenability because the α/γ interface where new ferrite forms during cooling was increased by the particle elongation. The martensite particles obtained in rolled material were also elongated or fibered in the rolling direction. Therefore, the thermomechanical processing of a two-phase ($\alpha + \gamma$) mixture has the detrimental effect of increasing the quenching power needed to yield a specific amount of martensite.

Keywords dual-phase steel, hardenability, intercritical heat treatment, low-carbon steels

1. Introduction

Dual-phase steels have characteristic mechanical properties, which include low proof strength and high tensile strength relative to conventional low-carbon formable steel. They also exhibit high work hardening rates in the early stage of plastic deformation and good ductility during forming relative to strength in the formed condition. As a result, dual-phase steels play an important role in reducing the weight of automobile components, such as car body panels, and in increasing fuel efficiency. These steels are conventionally produced by the annealing of low-carbon steel within the intercritical, austenite-plus-ferrite phase field, followed by cooling at a rate that ensures that an optimum amount of austenite transforms to martensite. The annealing temperature in the ($\alpha + \gamma$) phase field controls the volume of fraction of austenite and establishes the austenite carbon content, thus affecting the hardenability of the austenite volume.

This article addresses the effect of thermomechanical processing on the martensitic hardenability of austenite.

2. Experimental Details

2.1 Material

The composition of the steel (wt%) employed in the present study is 0.16 C, 0.24 Si, 1.03 Mn, 0.010 P, 0.009 S, 0.14 Cr, 0.04 Mo, 0.15 Ni, and 0.20 Cu.

The material was supplied in the form of hot-rolled 13 mm thick and 105 mm wide plate. Metallographic investigation of the as-received microstructure showed that it consisted of unbanded ferrite and pearlite and traces of martensite or retained austenite. To study the effect of intercritical annealing temperature on the volume fraction of austenite, specimens approximately 10 mm square and 2 mm thick were heat treated in the range 725 °C to 830 °C in argon for 20 min and then quenched in iced brine. The austenite volume fraction was measured by the point counting technique.

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2.2 Specimen Preparation

For the rolling experiments, a set of specimens with initial thickness of 10 mm and an area of 60 by 30 mm were machined so that after a 50% reduction, all specimens exited from the rolls at a common thickness of 5 mm. In addition, another set of specimens with 5 mm initial thickness and an area of 50 by 50 mm were heat treated but were not rolled. The purpose of the common thickness of 5 mm for rolled and nonrolled specimens was to ensure the same cooling rates in both.

2.3 Intercritical Heat Treatment and Effect of Warm Rolling

For studying the effect of warm rolling at the intercritical annealing temperature on the martensitic hardenability of austenite, the experiments were divided into two groups.

For group 1, the specimens with initial thickness of 5 mm and an area of 50 by 50 mm were heat treated for 20 min at 780 °C. This temperature was selected to obtain a planned austenite volume fraction of 55% based on the results of the experiments described in Fig. 1. At the end of the heat treatment, the specimen was removed from the furnace and plunged into one of the following cooling media: ice brine (10% NaCl at –6 °C), cold water, hot water, boiling water, oil, hot air blast, still air, and a bed of vermiculite.

In group 2, the thermomechanical treatment was carried out to study the effect of controlled rolling on the martensitic hardenability of the austenite. Specimens with initial thickness of 10 mm were intercritically annealed at 780 °C in a muffle furnace situated close to and facing the entry to the rolls. After the required soaking time, the door of the furnace was opened, and the specimen was pulled by its handling rod from the furnace directly into the rolls. Immediately after exit from the rolls, the specimen was cooled in one of the above-mentioned media.

The volume fractions of the constituents present after cooling were determined by quantitative optical metallography.

3. Results and Discussion

3.1 *Dependence of Austenite Content on Intercritical Annealing Temperature*

Figure 1 shows the variation of austenite content with intercritical annealing temperature. It can be seen that the volume fraction of austenite increased with increase in the intercritical annealing temperature.

3.2 *Microstructure Map after Zero Reduction*

The dual-phase steel that developed after intercritical annealing at 780 °C for 20 min and brine quenching contained a very small quantity of new ferrite formed before the remaining austenite transformed to martensite. In Fig. 2 the cumulative volume fraction of microstructural constituents present after intercritical annealing at 780 °C are plotted versus cooling rate. The individual determinations of the austenite present at the intercritical temperature varied slightly around the mean value of 57.5%. For this reason a normalizing procedure was used to produce the microstructure map in Fig. 2. In this normalizing procedure, the measured amount of ferrite/carbide aggregate, epitaxial ferrite, and martensite/austenite constituents were multiplied by the ratio $0.575/f\gamma$, where $f\gamma$ was the experimentally determined volume fraction of austenite present in that specimen, and 0.575 was the average volume fraction of austenite for all the specimens.

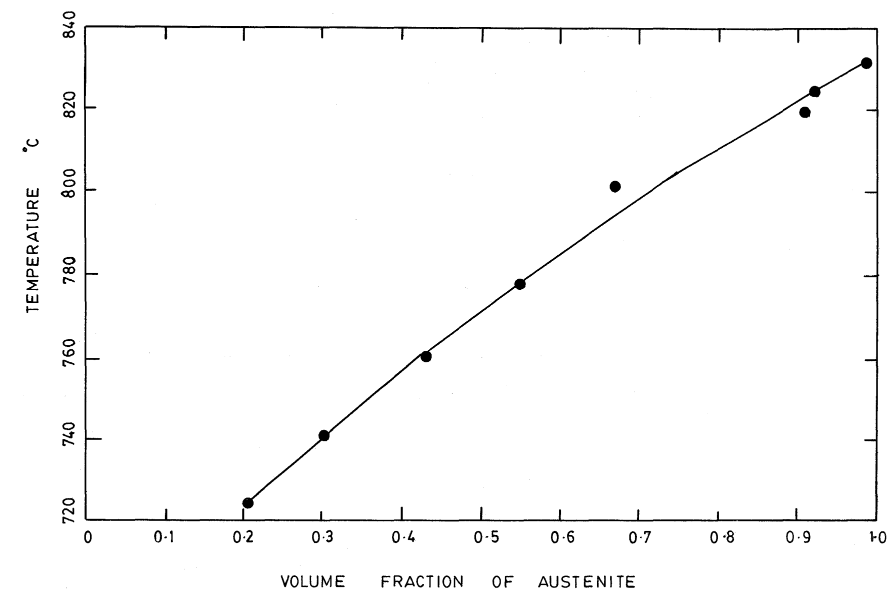

Fig. 1 Dependence of austenite content on intercritical annealing temperature

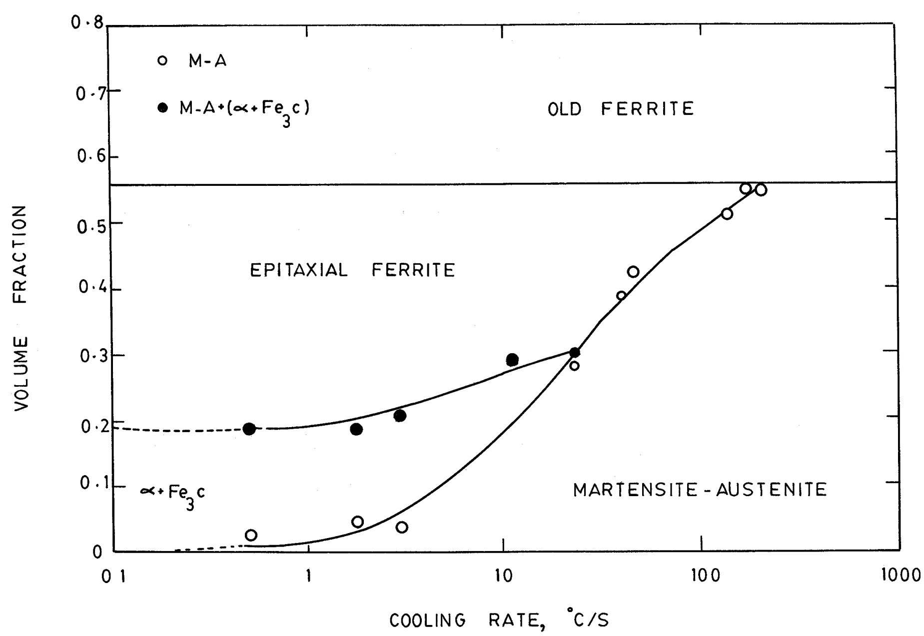

Fig. 2 Quantitative microstructure map showing the effect of cooling rates on the microstructure of steel ICHT at 780 °C with 0% reduction

As shown in Fig. 2, even at the fastest cooling rate used, a small amount of epitaxial ferrite formed before the onset of martensite transformation. The amount of epitaxial ferrite increased with decreasing cooling rate until approximately 23 °C/s was reached. At cooling rates less than this, ferrite/carbide was formed, the amount of which increased at the expense of martensite at still slower cooling rates. Within the range of cooling rates studied below 23 °C/s, the amount of epitaxial ferrite increased only slightly. The microstructure map of material rolled to 48% reduction at 780 °C is shown in Fig. 3. Approximately 10% of the austenite transformed to ferrite during rolling due to a temperature drop of approximately 65 °C during rolling. As before, the data were normalized to the mean amount of austenite determined for all the specimens, in this case 57.5%.

Several authors (Ref 1-4) have reported that deformation of single-phase austenite promoted its transformation to ferrite. Generally, this effect is attributed to increased nucleation rate on austenite grain boundaries and on transgranular deformation bands. Figure 4 directly compares the microstructure maps

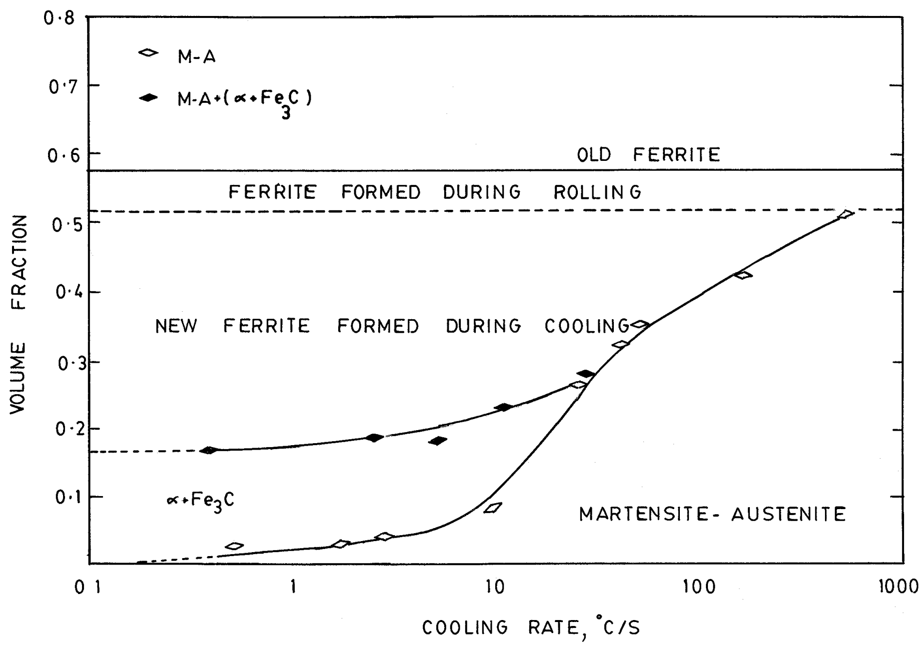

Fig. 3 Quantitative microstructure map showing the effect of cooling rates on the microstructure of the steel intercritical heat treatment at 780 °C with 48% reduction

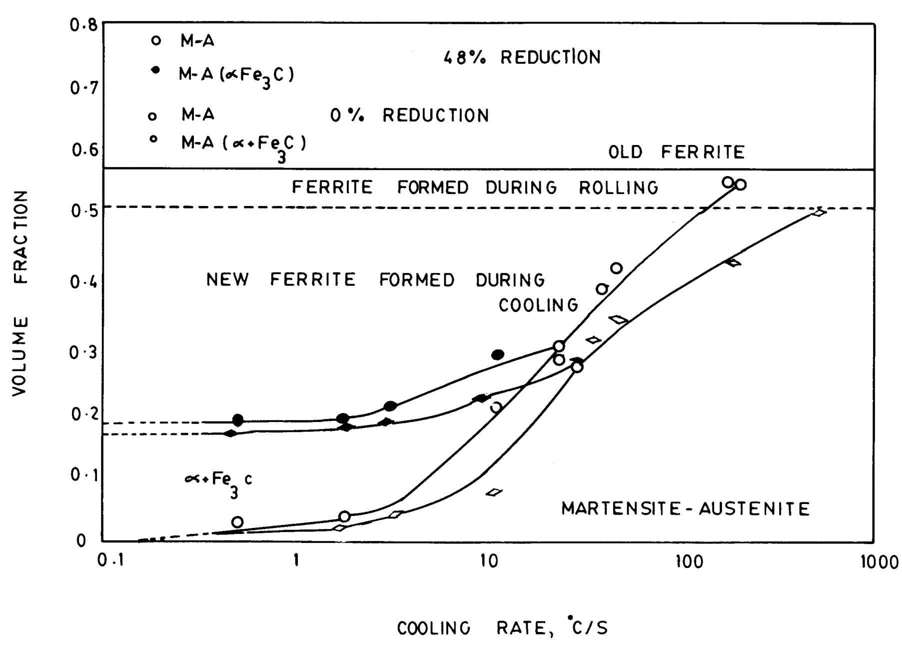

Fig. 4 Microstructure map showing the effect of cooling rates on the microstructure with 0 and 48% reduction

for 0 and 48% reduction and shows that deformation increased the amount of epitaxial ferrite at the expense of martensite at all cooling rates. However, this apparent decrease in hardenability is small and is not due to increased nucleation rates on prior austenite grain boundary and deformation bands. This is because, in the partially reaustenitized microstructure, almost all the ferrite formed during cooling formed by the growth of existing ferrite back into the austenite.

The observation that rolling at the intercritical temperature reduced the amount of martensite formed on cooling over the whole range of cooling rates contradicts previous work by Priestner and Ajmal (Ref 5).

3.3 Hardenability of Austenite

In the traditional hardening heat treatment, where a steel is quenched from the single-phase austenite region of the phase diagram, the most important microstructural variables to influence the hardenability are the composition of the austenite and its grain size. The hardenability increases with increasing austenite grain size because the grain boundary area then decreases. This means that the number of sites for the nucleation of ferrite and pearlite is reduced, and the ferrite and pearlite reactions are slowed. Most alloying elements slow the ferrite and pearlite reactions and thus increase the hardenability of the steel. However in dual-phase steel, the volume of austenite formed during intercritical annealing is dependent upon the intercritical temperature. Thus, the hardenability of the austenite can be assessed more fundamentally in terms of the fraction that transforms to martensite rather than the fraction of the total volume of steel that transforms to martensite. Also, austenite present at the intercritical temperature contains few grain boundaries. The rate of ferrite formation is not controlled by ferrite nucleation rate but by the rate of growth of existing ferrite.

The microstructure maps in Fig. 2 and 3 are summarized in an austenite to martensite hardenability diagram in Fig. 5. Approximately 10% of the austenite present transformed to ferrite during rolling. In Fig. 5 the fraction of the austenite still present after rolling and just before quenching, and which transformed to martensite, is plotted. At a higher cooling rate than 6 °C/s, the volume fraction of austenite that transformed to martensite in the rolled material was less than in the nonrolled material. Data were obtained in a similar way by Priestner and Ajmal (Ref 6) for a steel containing 0.11% C, 1.5% Mn. It is clear that in the present work, rolling at the intercritical annealing temperature decreases the hardenability of the austenite remaining after rolling, whereas in the Priestner and Ajmal work, rolling increased the hardenability of the austenite.

The apparent effect of rolling on the austenite/martensite hardenability is complicated by the increase in ferrite by about 10% during rolling, accompanied by an increase in the carbon content of the remaining austenite. This would be expected to increase the hardenability of that austenite relative to the hardenability of the austenite present before rolling, quite apart from any direct effect of the rolling. The direct effect of rolling must, therefore, have been greater than that shown in Fig. 5.

At constant volume fraction of austenite particles, the interfacial area increases rapidly with decrease in particle size. Priestner (Ref 7) suggested that since epitaxial ferrite formed by regrowth of existing ferrite into the austenite, the volume that forms is the product of interfacial area, average growth rate during cooling, and the time taken to cool to the M_s temperature. Priestner found that the fraction of the austenite that remained at the M_s temperature and that then transformed to martensite strongly depended on the fineness of the dispersion of austenite particles. In his model, Priestner also suggested that warm rolling in the ($\alpha + \gamma$) phase field elongated austenite particles in the rolling direction, thus increasing their interfacial area without changing their volume. Warm rolling should, therefore, decrease the martensitic hardenability of the austenite. The present work is in agreement with Priestner's model.

As mentioned before, rolling in the two-phase region of the phase diagram would be expected to increase the interfacial area. This, in turn, should promote the formation of ferrite during cooling and thus decrease the martensitic hardenability of the austenite. The results presented here suggest that this is true for cooling rates faster than 6 °C/s.

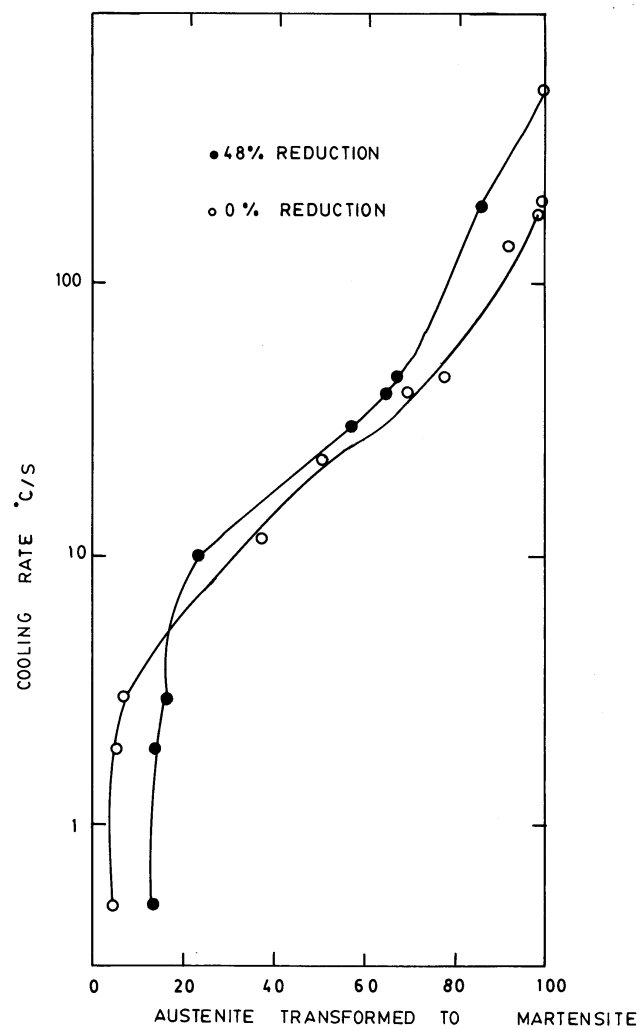

Fig. 5 Martensitic hardenability of austenite left after 0 and 48% reduction expressed as critical cooling rate for transformation of a percentage of austenite to martensite

4. Conclusions

When a low-carbon, low-alloy steel was intercritically heat treated and thermomechanically processed to study the martensitic hardenability of austenite, the following conclusions were obtained:

- The warm rolling of the two-phase ($\alpha + \gamma$) mixture reduced the hardenability of the austenite. For example, warm rolling increases the critical cooling rate for conversion of 80% of the austenite to martensite from 54 °C/s to 110 °C/s. Therefore the thermomechanical processing of a two-phase ($\alpha + \gamma$) mixture has the detrimental effect of increasing the quenching power needed to yield a specific amount of martensite.
- The warm rolling of the two-phase ($\alpha + \gamma$) mixture caused a useful increase in strength in the rolling direction if epitaxial ferrite was absent (Ref 5). This increase in strength was caused by flattening and elongation of austenite particles and consequent fibering of the resultant martensite particles in the rolling direction. The strength also increased with increase of volume fraction of martensite and was reduced by the presence of epitaxial ferrite. Ferrite grain refinement, substructure formation in ferrite, and improved stress transfer to the fiberized martensite probably all contributed to the improvement in strength. The addition of a rolling step during intercritical annealing is likely to be less expensive than the addition of extra heat treatments for improving the tensile properties of a dual-phase steel.

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