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Materials

Effect of controlled rolling on the martensitic hardenability of dual phase steel

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Abstract: The C-Mn and C-Mn-Nb steels were thermo-mechanically processed to develop dual phase steel and to study the effect of controlled rolling on the martensitic hardenability of austenite. The steel specimens were intercritically annealed at 790°C, rolled at that temperature to the reductions of 10%, 23%, and 47% and immediately cooled at different rates. Quantitative metallography was used to construct the microstructure map, which illustrated that increasing deformation progressively reduced the proportion of new ferrite formed at all cooling rates and increased the amount of martensite at fast and intermediate rates. The martensitic hardenability of austenite remaining after all the rolling reductions was plotted as a function of cooling rates. It was observed that for the austenite-martensite conversion efficiencies greater than about 25%, controlled rolling increased the martensitic hardenability of austenite.

Key words: controlled rolling; dual phase steel; intercritical annealing; hardenability; phase transformation

1. Introduction

Dual phase steel has been developed to exploit the low proof strength and high tensile strength relative to high strength low alloy steel (HSLA) [1]. The microstructure of dual phase steel consists of 15vol%-20vol% martensite in a ferrite matrix. Dual phase steel can be produced by partial austenitization of a low carbon steel within the intercritical phase field, *i.e.* $\alpha+\gamma$, followed by quenching to convert austenite precipitates to martensite [1]. Cooling more slowly than a critical rate allows some of the austenite to transform back to ferrite, and at still slower rates, to pearlite or bainite, *i.e.* ferrite and carbide aggregate [1-2].

The effect of cooling rate on the constitution of the steel after intercritical annealing can be expressed in the form of a continuous cooling transformation diagram or microstructure map [2]. The fraction of the austenite that transforms to martensite is thus a function of cooling rate and is affected by the carbon and alloy content of the austenite, and the fineness of the dispersion of austenite particles [3-5]. Priestner [6] modeled the transformation of these austenite particles presented at the intercritical annealing temperature to martensite and suggested that small particles led to small volume fraction of martensite. Contrary to the Priestner [6] model, Erdogan [7] suggested on the basis of experiments that the fine dispersion of austenite at a lower temperature of intercritical annealing increased the martensite content.

The cooling of steel sheets from the intercritical phase field at a fast rate may lead to distortion and increases the production cost. Thus, a critical factor in the application of dual phase steel is the minimum cooling rate at which sufficient martensite is produced. Priestner and Ajmal [8] derived a hardenability diagram from the microstructure map in which the content of austenite, which transforms to martensite, is plotted *versus* cooling rates. This diagram represents the specific hardenability of the austenite produced by heating the steel in the two-phase region, that is, the hardenability of the austenite surrounded by ferrite. In the present study, the effect of controlled rolling on the martensitic hardenability of austenite surrounded by ferrite has been studied.

2. Experimental

The composition of the steel used in the present study is shown in Table 1. The material was supplied in the form of a hot rolled 25-mm thick plate. Metallographic observations showed that the steel consisted of banded ferrite and pearlite.

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Table 1. Composition of steels wt%

Steel	C	Mn	Si	Mo	Nb	S	P
Steel A	0.11	1.45	0.34	—	—	0.003	0.004
Steel B	0.11	1.43	0.33	—	0.102	0.003	0.004

2.1. Specimen preparation

The rectangular specimens with the dimension of approximately 50 mm×30 mm having three thicknesses as listed in Table 2, were prepared such that after rolling by 10%, 25%, or 50%, all the specimens will exit from the rolls at a common thickness of 5 mm. The longest dimensions of the test specimens coincide with the rolling direction of the original specimen. In each specimen, a 2-mm diameter hole was drilled 15 mm from one end on the centre line and through the width of the plate as shown in Fig. 1.

Table 2. Specimen thickness

Planned reduction / %	Starting thickness / mm	Average finishing thickness / mm	Average reduction applied / %
0	5.00	5.00	0
10	5.55	4.96 ± 0.006	10.28 ± 0.13
25	6.67	5.17 ± 0.02	22.64 ± 0.26
30	8.15	5.05 ± 0.03	29.73 ± 0.23
50	10.00	5.24 ± 0.02	47.29 ± 0.22

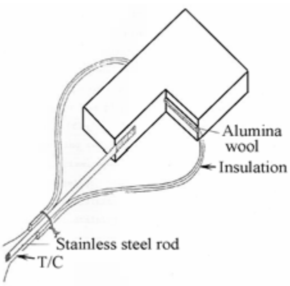

Fig. 1. Specimen diagram.

The purpose of keeping the common thickness of 5 mm after rolling was to ensure that the cooling rates in all rolled specimens were similar to each other. In the rolling experiments, the reductions applied were slightly different from those intended, with a consequent deviation from the planned finishing thickness indicated in Table 2.

For thermomechanical treatment, a chromel-alumel thermocouple was inserted through the hole with its junction situated in the middle of the specimen. The hole was packed with alumina wool. A long stainless steel rod was attached to the end of each specimen for convenience in handling the specimen during the thermo mechanical treatments.

2.2. Heat treatment and rolling

All the specimens were heated to 790°C for 15 min in a muffle furnace situated close to the rolls of the rolling mill with the furnace door facing the rolls. This temperature was selected to achieve a planned austenite content of 48vol%, based on the study of Priestner and Ajmal [8]. The specimen was inserted in the furnace with its handling rod placed between the rolls. The roll gap was set to the separation that was required for the planned reduction.

After 20 min, the door of the muffle furnace was opened and the specimen was drawn by its handling rod from the furnace and was fed directly into the rolls. After rolling, the specimen was immediately placed in one of the following cooling medias: (a) a quench tank containing iced brine at −8°C; (b) a quench tank with boiling water at 95°C; (c) a quench tank containing oil at room temperature; (d) forced air; (e) still air; (f) a box containing vermiculate;

Typical cooling rates in the centre line of the specimens are presented in Table 3.

Table 3. Typical cooling rates at the center line of the specimen

Cooling media	Cooling rate / ($°C·s^{-1}$)
Iced brine	700
Oil quenched	90
Hot air	45
Forced air	3.5
Still air	1.4
Vermiculate	0.75

2.3. Metallography

Long transverse sections were cut from the cooled specimens. These were mounted in plastic and polished conventionally to a 1-μm diamond finish. A number of phases were produced from the austenite after cooling at different rates. For this reason, martensite and ferrite carbide aggregates were distinguished by an appropriate depth of etching in nital or picral. Epitaxial or new ferrite was distinguished with alkaline chromate etch described by Lawson *et al*. [9]. Volume fractions of the constituents were determined by point counting. 1500 to 2000 points were counted to keep the standard error less than 1%.

3. Results and discussion

Fig. 2 shows the microstructure of a water quenched specimen after rolling to 47% reduction at the intercritical annealing temperature. The effect of alkaline chromate etch [9] reveals the epitaxial ferrite as white, old ferrite as gray, and martensite as black. The boundaries between the gray and white areas delineate the extent of the austenite pool formed during holding at the intercritical annealing temperature. Fig. 3 shows the microstructure of a specimen rolled to 47% reduction at the intercritical annealing temperature, brine quenched and etched with the same alkaline chromate solution. It shows old ferrite, new ferrite, and martensite but in elongated forms, indicating the effect of rolling after holding at the intercritical annealing temperature. The old ferrite and austenite pools formed during holding at 790°C become elongated as they are subjected to 47% reduction. Fig. 3 also shows that new ferrite is present in the specimen controlled-rolled to 47% reduction even when it is cooled at the fastest rate, *i.e*. brine quenched.

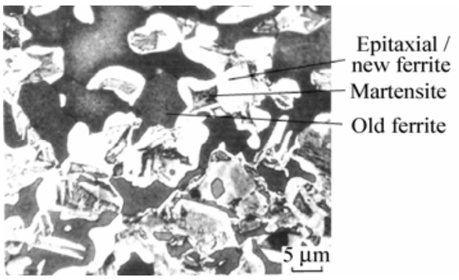

Fig. 2. Microstructure of the specimen rolled to 47% reduction at the intercritical temperature and water quenched.

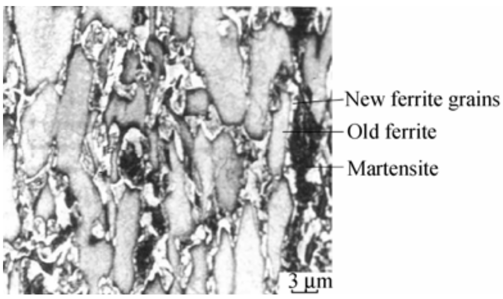

Fig. 3. Microstructure of the specimen rolled to 47% reduction at the intercritical temperature and brine quenched.

The intercritical annealing temperature of 790°C was selected from the earlier study [8] with the intention of yielding approximately 48vol% austenite. The specimens used in the present study are considerably larger than those used in the previous study [8]. Although they were annealed for the same time period, the average volume fraction of austenite obtained in them was approximately 45%. Experimentally, the volume fraction of austenite obtained varied slightly among the specimens. Fig. 4 presents the data normalized to a constant volume fraction of austenite of 45% for the microstructure maps of 10%, 23%, and 47% reduction after the intercritical annealing temperature of 790°C for steel A.

It can be seen from Fig. 4 that even the fastest cooling yields some amounts of new ferrite in the rolled specimens. It is estimated that approximately 10vol% of the austenite present (*i.e.* from 45vol% to 40vol%) transforms to ferrite during rolling. It is noted that there is a temperature drop of 80°C during rolling. The amount of new ferrite produced during rolling can thus be attributed to the combined effect of a sudden drop in temperature and the stresses induced during rolling.

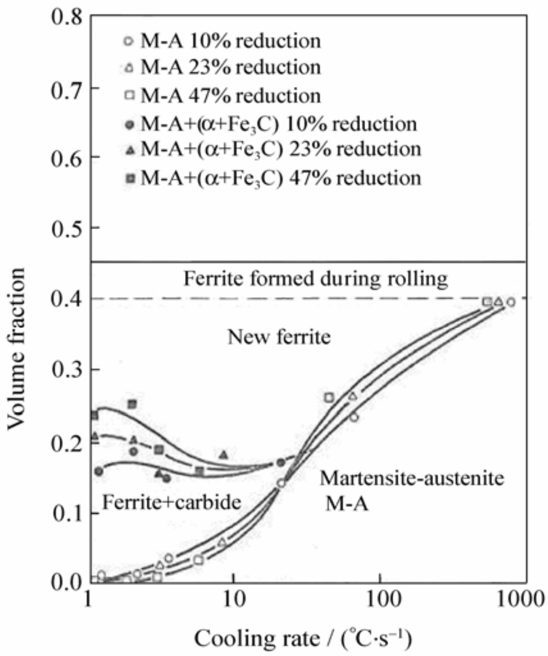

Fig. 4. Quantitative microstructure map showing the effect of cooling rate on the microstructure of steel A with 10%, 23%, and 47% reductions.

The most significant feature indicated by Fig. 4 is the progressively reduced amount of new ferrite with increasing deformation. This effect extends over the entire range of the cooling rates investigated. As a result, at the highest cooling rate at which few or no ferrite/carbide aggregates are formed, the reduction in the ferrite content leads to an increase in the martensite content. At a lower cooling rate, the reduction in the content of new ferrite leads to an increase in the amount of ferrite/carbide aggregates and a decrease in the martensite content. The presence of martensite even at the slowest cooling rate of 0.1°C/s (furnace cooling) has been reported by Erdogen [7]. This observation is also in agreement with the present study.

Several authors [10-13] have reported on the effect of hot deformation of fully austenitized steels on the subsequent transformation to ferrite. Without exceptions, the deformation of single phase austenite at relatively low temperatures in the austenitized phase field promotes its transformation to ferrite. However, in the present experiments, rolling in the intercritical temperature range has the opposite effect compared to the fully austenitized phase in ferrite formation. A possible cause of this behavior is the rotation of crystal structures of austenite and ferrite during compression that could have changed the relative orientation of the two phases such that the mobility of the interface is damaged. Novillo *et al*. [14] reported that deformation changes the Kurdjmov-Sachs relationship existed between ferrite and austenite suggested by other workers [15-16].

It is thought that large fraction of austenite formed during heating to 790°C in the present study, achieves the Kurdjmov-Sachs orientation relationship to the ferrite remained. On cooling, ferrite grows back into the surrounded austenite by maintaining the same orientation relationship as mentioned above. This can be observed in Fig. 3, where old ferrite grows into the austenite pool producing new/epitaxial ferrite. The destruction of the orientation relationship established between austenite and ferrite during the austenite growth, by crystal rotations during rolling, impairs the ability of ferrite to grow back epitaxially during subsequent cooling. This reasoning can be demonstrated in Fig. 4, which shows that small grains of new ferrite form in the elongated austenite pool at the interface of old ferrite instead of the growth of old ferrite into austenite. This formation of new ferrite grains through nucleation and growth rather than simple epitaxial growth of old ferrite may be a cause for the reduction of ferrite formation during cooling in the specimens that were rolled at the intercritical temperature.

At high cooling rates at which martensitic transformation directly follows the cessation of ferrite formation, the effect of increasing deformation is to increase the amount of martensite in the structure. This is simply due to the martensite replacing austenite as the growth rate of ferrite decreases. It shows that martensitic hardenability of the austenite, which is surrounded by ferrite after rolling, is increased. It can be deduced that thermomechanical processing, in which a major amount of reduction is applied by controlled rolling to a two-phase mixture, has the beneficial effect of reducing the quenching power needed at the end of processing in order to obtain suitable conversion efficiency. Therefore, it is also expected to avoid distortion in the production of dual phase steel.

The result of a study [17], in which methodology similar to the present study was used on a material similar to steel B (Table 1), is shown in Fig. 5. These results support the conclusions of the present study that controlled rolling reduces the formation of ferrite at all cooling rates. However, the reduction in the formation of new ferrite was reported to be considerably larger than that found in the present study on steel A. In order to determine the reason for this discrepancy, further experiment was carried out as follows.

i) Some of the experiments of the study in Ref. [17] were duplicated on steel B. The volume fractions of various constituents were measured. The results are presented in Table 4 and also superimposed in Fig. 5.

ii) Some of the analyzed specimens were obtained from the researcher of Ref. [17] and quantitative metallographic recounting for various phases present was performed. The recounted fractions of the phases are presented in Table 4 and also superimposed in Fig. 5.

Table 4. Volume fractions of the constituents in steel B at different cooling rates and reductions

Cooling media	Cooling rate / (°C·s^{-1})	Reduction / %	Epitaxial ferrite/vol%	Martensite / Austenite	Ferrite / Carbide
Forced air	2.72	10	25.62	1.56	19.73
Forced air	2.48	23	19.93	0.75	26.16
Forced air	3.10	47	21.34	1.06	24.56
Hot water	7.57	10	31.28	9.08	6.57
Hot water	10.48	23	32.79	6.36	7.72
Hot water	12.10	47	31.90	5.40	9.70
Oil quenched*	59.46	23	17.67	29.34	—
Oil quenched*	59.46	47	8.99	17.94	—
Iced brine*	1930	23	6.80	40.12	—
Iced brine*	1930	47	5.22	41.77	—

Note: *recounted results of the specimens studied in Ref. [17].

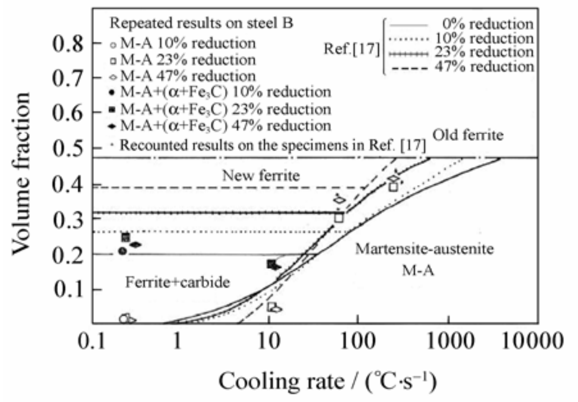

Fig. 5. Quantitative microstructure map showing the effect of different reductions in Ref. [17].

After an analysis of Fig. 5, it can be stated that there is an effect of controlled rolling on the retested specimen of the study [17]; however, it is not as great as that reported. We believed that the fine phases produced after reduction may not have been resolved in the study [17] due to poor etching and/or low magnification. This may have led to the reported increased volume fraction of various constituents.

The duplication of some of the experiments on steel B and recounting of the volume fraction of different constituents of the specimens, suggest that the effect of controlled rolling on steel B is similar to the results for steel A presented in this study.

4. Conclusion

High strength low alloy steels were controlled-rolled in the two-phase region to study the martensitic hardenability of austenite in connection with the production of dual phase steel. It is concluded that the martensitic hardenability of austenite, which is surrounded by ferrite after rolling, is increased. This results in a marked decrease in the quenching power needed at the end of processing. Thus, a dual-phase steel with 15vol%-20vol% martensite in the ferrite matrix can be attained at a slower cooling rate by avoiding distortion in the steel plate.

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