INFLUENCE OF HEATING RATE ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF ANNEALED LOW CARBON STEELS

A. ARLAZAROV, G. Lujan BROLLO, C. MAGAR

ArcelorMittal Research and Development, Maizières-lès-Metz Cedex France, EU

Abstract

The influence of relatively high heating rates (100 - 300°C/s) and low soaking times (5s) on the microstructure and mechanical properties of a cold rolled low carbon steel was studied. Annealing treatments with different heating rates were performed on a 0.15C - 1.2Mn (wt.%) steel in order to study recrystallization, austenite transformation and growth of ferrite and austenite. Impact of heating rate was also analyzed in terms of mechanical properties: hardness and tensile tests were performed after different steps of annealing cycle. Influence of intermediate slow heating at high temperatures was also investigated. Increase of the heating rate leads to a partial recrystallization at the intercritical temperature, formation of high austenite fraction and lower ferrite grain size. The introduction of intermediate slow heating at high temperatures and a short soaking significantly reduce the effects of high heating rates. Finally, high heating rates promoted a slight increase in the ultimate tensile strength without any considerable changes in the other tensile properties.

Keywords: fast heating rate, intercritical annealing, phase transformation, low carbon steels.

1. INTRODUCTION

The heat treatment of cold rolled steels is usually used to obtain the desired microstructure with the mechanical properties appropriate for intended use of steel. The comprehension of the metallurgical phenomena occurring during annealing as well as their effects on the structure and final properties of steels are of great interest for the selection of best production parameters. The following thermally activated events occur during reheating and soaking of cold rolled steel: recovery, recrystallization, grain growth and phase transformation. These phenomena were largely studied in so-called "standard annealing conditions" - slow heating rates [1-3]. In the last years, the interest to the use of high heating rates (Rh) to increase the annealing line productivity or to improve the final product properties is more and more important [4].

Recent studies show that high heating rate has an important influence on recrystallization and phase transformation [5-11]. An increase in heating rate generates a delay of the recrystallization to higher temperatures. For some steels rich in C-Mn and alloying elements the recrystallization can be retarded to the temperatures superior than Ac_1 meaning that austenitic transformation starts before the full recrystallization occur. Such overlap between these two phenomena provokes an important interaction of them and results in very significant difference from the conventional and equilibrium conditions. Investigation of interaction between recrystallization and austenite transformation was done in the recent work of Chbihi et al. [11] and two interesting things were observed:

- kinetics of austenite formation depends intrinsically on both the heating rate and recrystallization state of the ferrite;
- high heating rates provokes an unusual behavior of austenite nucleation and growth.

It is also known that ferrite grain size is decreasing with the rise of heating rate [4, 5, 8].

In the present study the influence of high heating rates (100-300°C/s) and low soaking times (5s) on the microstructure and mechanical properties of a low-carbon steel was investigated. Cold rolled 0.15C - 1.2Mn (wt.%) steel was annealed with different heating rates. Effect of applied thermal treatment on recrystallization, austenite transformation and growth of ferrite and austenite was studied. Impact of heating rate was also analyzed in terms of mechanical properties: hardness and tensile tests were performed after different steps of annealing cycle. Influence of intermediate slow heating at high temperatures and a short soaking was also investigated.

2. EXPERIMENTAL PROCEDURE

Industrial steel with the composition presented in the **Table 1** was used in this study. The analyzed steel was hot rolled, coiled and cold rolled until the thickness of 1.2 mm.

Table 1 Chemical composition of studied steel (10^{-3} wt. %)

Composition	C	Mn	Si	P	S	N	Al
10^{-3} weight%.	153	1191	31	13	1	3,5	29

Six different thermal cycles were used to study the evolution of microstructure and mechanical properties with the increase of heating rate and some modifications in other annealing parameters (**Fig. 1.a-d**):

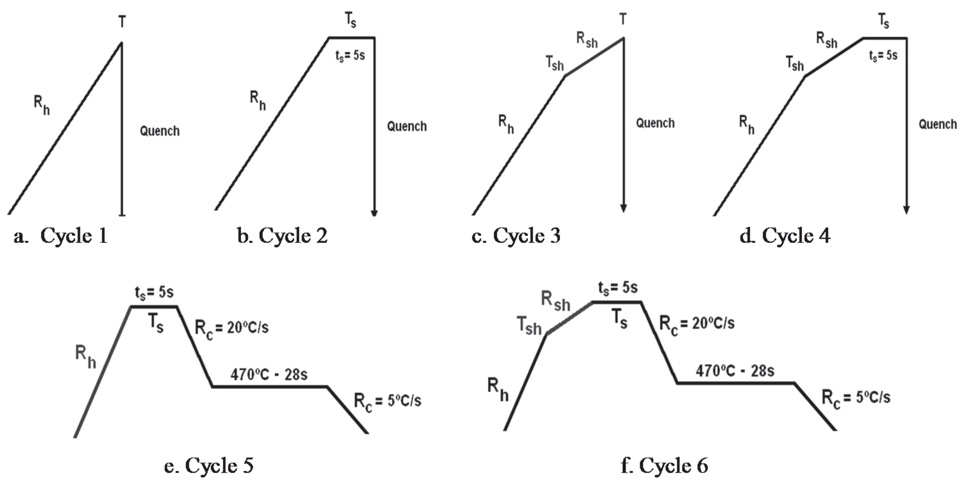


Fig. 1 Studied thermal cycles: (a) Fast Heating + Quench (FH + Q), Rh = 10, 100, 200, 300°C/s ; T = 600, 650, 700, 750, 800, 850 °C; (b) Fast Heating + Soaking + Quench (FH + S + Q), Rh = 10, 100, 200, 300°C/s ; Ts = 800 ; ts = 5s; (c) Fast Heating + Slow Heating + Quench (FH + SH + Q), Rh = 100, 200, 300°C/s, Tsh = 700°C, Rsh = 20°C/s, T = 800°C; (d) Fast Heating + Slow Heating + Soaking + Quench (FH + SH + S + Q), same as (c) but with soaking time of 5s; (e) Fast Heating + Complete Cycle (FH + CC), Rh = 10, 100, 200, 300°C/s, Ts = 800°C, ts = 5s, Rc = 20°C/s (470°C - 28s), Rc = 5°C/s; (f) Fast Heating + Slow Heating + Complete Cycle (FH + SH + CC), Rsh = 20°C/s from Tsh = 700° to Ts = 800°C

All thermal treatments were performed in a Gleeble 1500 machine. Samples for metallographic analysis were cut near the thermocouples and in the manner to observe the section parallel to the rolling direction. Then samples were mounted and mechanically grounded and polished. Different chemical etching were used for the detailed microstructure analysis: Marschall and Nital etchings were used for analyze of recristallisation and grain size quantification; LePera's [12] and/or Picral + Metabisulfite etchings - analyse of second phase (martensite and perlite); Picral + flash Nital - analysis using Scanning Electron Microscope (SEM). Microstructure observations were done with standard Optical Microscope (OM) and SEM. Estimation of ferrite grain size, recrystallized and second phase fraction were performed using "Aphelion" software. Mechanical behavior of the samples after the complete thermal cycles (e and f) and 3% skin pass was obtained from conventional tensile tests. Vickers hardness measurements were performed for complementary data.

3. RESULTS AND DISCUSSION

3.1 Influence of heating rate on the microstructure after heating and soaking

Recrystalization progress was evaluated using microstructure observations and microhardness measurements. An example of microstructure evolution obtained using cycle (a) with 300°C/s heating rate is presented at left in **Fig. 2**. At 600 °C the structure was only partially recovered, at 650 °C some small strain-free grains appeared, at 700°C the recrystallization increased a little bit (less than 10%). Going to 750 °C, the recrystallization was more advanced and growth of the newly formed grains occurs, but in the same time the intercritical domain was reached, leading to the austenite transformation. This means that there is an interaction between recrystallization and phase transformation. Finally, at 800°C the steel was totally recrystallized, but a high fraction of austenite was present.

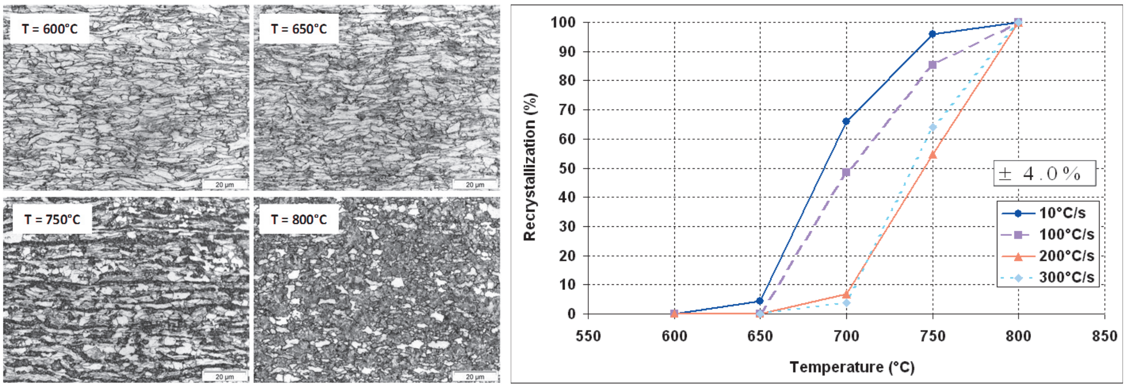


Fig. 2 At left an example of microstructure evolution obtained with cycle (a), Rh = 300ºC/s (ferrite is white and martensite and non-recrystallized ferrite are darker phases). At right is presented the recrystallization kinetics for different heating rates

Fig. 2 at right shows the recrystallization kinetics obtained with different heating rates. As it can be seen the recrystallization was delayed with the increase of heating rate. Such behavior was already observed in the previous studies [5-8, 10, 11]. The curves obtained with the heating rates of 200 and 300°C/s are very similar. This means that within this interval there is no relevant difference in the recrystallization behavior. At 800°C for all heating rates the samples were totally recrystallized. The confirmation of total recrystalization was done using backscattered images in SEM. Consequently, the temperature of 800°C was used as a standard for all further annealing treatments.

Influence of heating rate on the austenite fraction and ferrite grain size at 800°C is presented in **Fig. 3.A**. High heating rate leads to higher amount of austenite and surprisingly this amount is superior than the equilibrium one (grey line in **Fig. 3A**). Such important evolution of austenite fraction was also correlated to the hardness measurement that are shown in **Fig. 3B**. Similar observations were done by Huang et al. [7] and by Chbihi et al. [11]. This result shows that the fast heating provokes an excessive austenite formation and, hence, creating an extremely metastable state of steel. The observed phenomena may be explained as follows. High heating rate inhibits recrystallization kinetics, thus the intercritical domain is reached with more than 50% of non-recrystallized structure and probably it also hinders austenite nucleation due to the lack of time for diffusion. This deformed structure combined with the high temperature delivers a considerable driving force for austenite nucleation and growth, therefore resulting in the formation of huge austenite fraction.

High heating rates also brings the decrease in the ferrite grain size (**Fig. 3A**). This may be explained by the combination of two factors: 1) higher recrystallization temperatures which supposes that the number of strain-free ferrite nucleus will be more important, as the nucleation rate will be higher; 2) presence of high austenite fraction that inhibits ferrite boundaries migration and, consequently, limits ferrite grain growth.

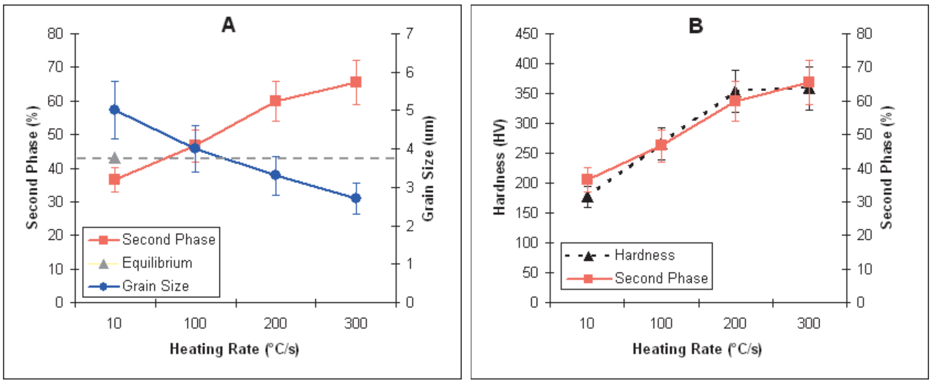


Fig. 3 Influence of heating rate (cycle (a) with T = 800°C): A - on the austenite fraction and the ferrite grain size; B - on the austenite and hardness.

Fig. 4 shows the effect of heating rate on the austenite fraction and the ferrite grain size with the introduction of small holding time (5s) and the intermediate slow heating at high temperatures. This figure represents the comparison of the microstructure parameters between the cycles (a), (b), (c) and (d). As it can be seen the application of short soaking tends to suppress the effect of heating rate: austenite fraction has decreased drastically and was close to the equilibrium value, and the evolution of ferrite grain size was also less important. However, the effect of heating rate was still observed on the ferrite grain size. As it was stated previously, using fast heating produces a microstructure at the beginning of soaking that contains a considerable amount of austenite. This structure is supposed to be in the state quite far from equilibrium, hence during holding the return to the equilibrium state is likely to happen, meaning that a part of the austenite will be transformed in ferrite. Such return to the equilibrium state from high austenite fraction was already described by Speich et al. [2] for the rather long holding times, but one can imagine that the same return can happens for the high heating rates.

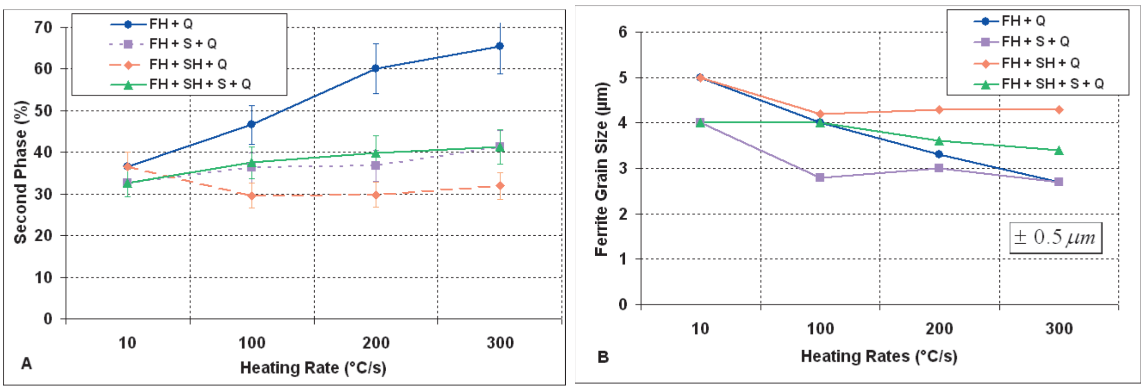


Fig. 4 Evolution of austenite fraction (A) and ferrite grain size (B) as a function of heating rate. Comparison between the cycles (a), (b), (c) and (d); T = 800°C.

Influence of fast heating combined with the slow heating at high temperatures (cycle (c)) on the microstructure was also studied. The results in terms of austenite fraction and ferrite grain size are presented in **Fig. 4**. The addition of the slow heating at temperature lower than Ac_1 (before the start of austenite transformation) seems to eliminate completely the effect of fast heating rate. It appears that recrystallization was more advanced before entering in the intercritical domain equilibrium, thus lower driving force was available for the phase transformation and lower austenite fraction was obtained (**Fig. 4A**). The austenite amount for high heating rates was even slightly lower in comparison with the 10°C/s heating rate. Probably, fast heating hindered recrystallization till the high temperature where slow heating was applied, therefore recrystallization kinetics at high temperature (during slow heating) was more rapid in comparison with more continuous recrystallization process with 10°C/s heating rate. This explication was also supported by the values of ferrite grain size that are a little bit lower with the fast heating (**Fig. 4B**).

Finally, addition of short soaking to the treatment with the combination of fast and slow heatings (cycle (d)) was evaluated. Analysis of microstructure constituents is as well presented in **Fig. 4**. The obtained results are quite conventional in terms of soaking effect. As slow heating already reduced the impact of fast heating, the additional soaking just approached a little the microstructure to the equilibrium conditions. Austenite fraction was roughly at equilibrium value for almost all heating rates (**Fig. 4A**) and the observed decrease in the ferrite grain size was most likely due to the increase of austenite amount (**Fig. 4B**).

3.2 Influence of heating rate on the final microstructure and mechanical properties

In the today's industrial conditions after heating and soaking there are at least three more sections: cooling, overageing and final cooling. Such type of treatment will be called further complete cycle (CC) (**Fig. 1E** & **1F**). The final microstructure after complete cycle consist of ferrite matrix with pearlite islands and in some cases a small fraction of retained austenite (**Fig. 5A**). Influence of fast heating and fast heating followed by slow heating on the microstructure and mechanical properties of complete cycles was investigated. The evolution of the second phase fraction and ferrite grain size is presented in **Fig. 5B** and **5C**, respectively. Increase of heating rate has a limited impact on the final microstructure: pearlite fraction was slightly increased and the ferrite grain size decreased a little bit. Such evolution is consistent with the observations done in the first part of this work. Fast heating gives slightly higher austenite fraction that will be a little less stable, thus a bit higher fraction of pearlite will be formed.

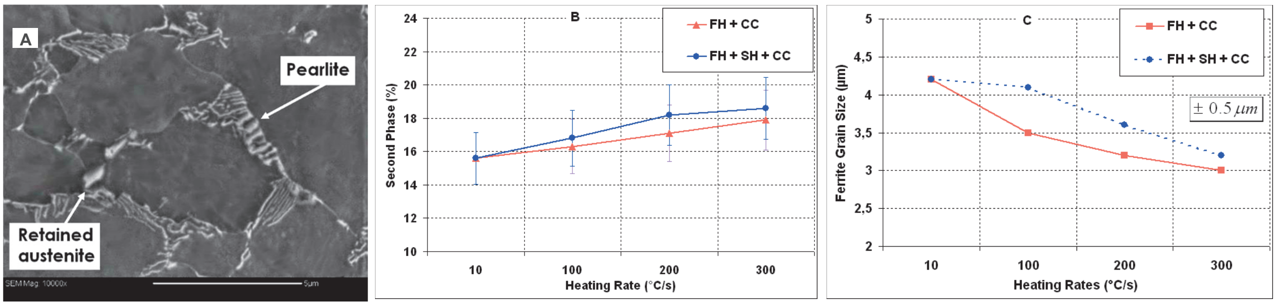
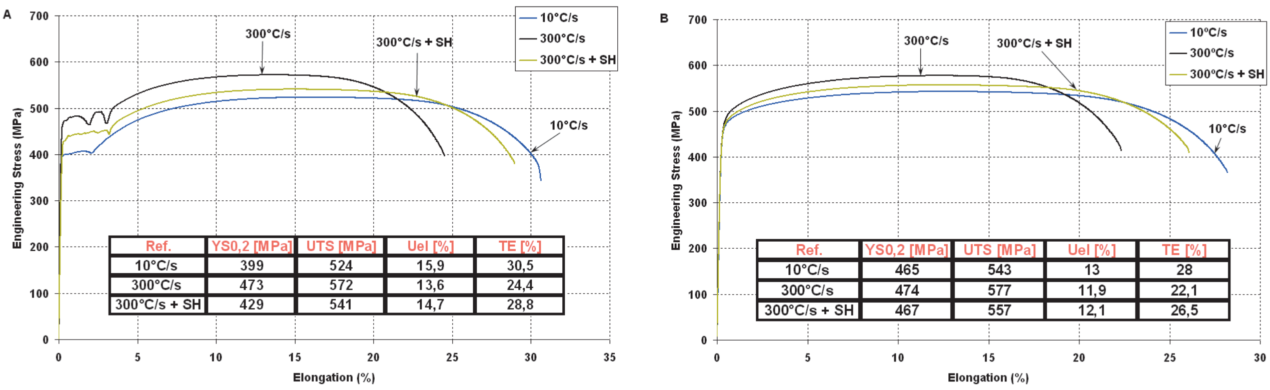


Fig. 5 Second phase fraction (a) and GS (b) of Complete cycles 5 and 6. Second phases present after complete cycles (SEM)

Fig. 6 presents engineering curves and mechanical properties obtained before and after skin-pass of 3% for the samples annealed with the complete cycles (e) and (f) and with two heating rates: 10 and 300 °C/s. It can be seen that fast heating increase slightly the strength (UTS and YS) and yield point elongation (YPE) before skin-pass. Of course the increase in strength was accompanied with the small decrease in elongation. This result is in agreement with the microstructure analysis: slight increase of pearlite fraction and decrease of ferrite grain size.



Ref.	YS0,2 [MPa]	UTS [MPa]	Uel [%]	TE [%]
10°C/s	399	524	15,9	30,5
300°C/s	473	572	13,6	24,4
300°C/s + SH	429	541	14,7	28,8

Ref.	YS0,2 [MPa]	UTS [MPa]	Uel [%]	TE [%]
10°C/s	465	543	13	28
300°C/s	474	577	11,9	22,1
300°C/s + SH	467	557	12,1	26,5

Fig. 6 Engineering curves and mechanical properties obtained by the tensile test before (A) and after skin-pass of 3% (B). The samples were annealed with the complete cycles (e) and (f) and with two heating rates: 10 and 300°C/s

Addition of slow heating at high temperatures decreased significantly the influence of fast heating and the obtained mechanical properties are very similar to ones obtained with 10°C/s heating rate. This is also in good agreement with the microstructure observations.

CONCLUSIONS

Influence of high heating rates (100 - 300°C/s), low soaking times (5s) and intermediate slow heating on the microstructure and mechanical properties of a cold rolled low carbon steel was investigated. Recrystallization, austenite transformation and growth of ferrite and austenite were analyzed. It was found that fast heating delays the recrystallization to the intercritical temperature, thus producing an important interaction between recrystallization and austenite transformation. Due to this interaction an excessive austenite fraction, much higher than the equilibrium value, was observed. Ferrite grain size was decreased with the high heating rate probably because of the recrystallization at higher temperatures and, thus, higher nucleation rate. Introduction of short soaking time and/or of slow heating at high temperatures tends to decrease or even vanish the effects of high heating rates: austenite fraction close to the equilibrium value and bigger ferrite grains. At last, the fast heating results in the minor increase of the strength (UTS and YS), yield point elongation (YPE) and slight decrease of elongation. However, using of slow heating at high temperatures reduces this effect considerably and, as consequences, the final mechanical properties were close to the standard condition (10°C/s).

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