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DETERMINATION OF CCT DIAGRAMS BY THERMAL ANALYSIS OF AN HSLA BAINITIC STEEL SUBMITTED TO THERMOMECHANICAL TREATMENT

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Introduction

CCT diagrams are broadly used to predict the microstructure and mechanical properties after thermal treatments. Most of these curves are determined by dilatometry with (1–4) or without (5–7) deformation prior to cooling. Dilatometry, however, even when straining is present, applies little deformation to the sample as compared to that imposed during an industrial process such as hot rolling. Here, an equivalent strain of approximately 5 is spread out into the several passes needed to reduce the thickness of a slab to that of a strip. Hence, dilatometry CCT curves may not be quite appropriate for the case of estimating transformation temperatures of hot rolling products. Trying to overcome this problem, Kaspar et al. (8) used plane strain compression testing to apply a higher strain to the sample during cooling and before the transformation temperatures were reached. By doing this, they could apply a few passes to the specimen, still in the austenite region and then use differential thermal analysis to determine the CCT diagrams. Although this approach is clearly better than dilatometry as far as deformation is concerned, the maximum uniform strain allowable in this technique is of the order of 0.8, much smaller than those usually found in rolling. An alternative and attractive technique, however, is torsion testing, and this has been successfully used to simulate industrial rolling schedules (9). The use of torsion testing and thermal analysis may yield cooling curves from a deformed austenite, which may be more suitable for the rolling conditions. Therefore, it seems preferable to apply the last technique to obtain information about the behavior of the austenite transformation after the samples had been deformed by torsion according to a rolling schedule.

Among the industrial rolling processes available for simulation, controlled rolling of microalloyed steels remains great technological interest because it results in a fine grain microstructure, providing a high strength and good material toughness. HSLA low carbon steels with bainitic or polyphase microstructure have been the subject of countless scientific works in the last decades. These steels are often used in the automobile industry, in the production pipe line for transport of gas and oil in areas of sub-zero temperature and in the naval ship construction, because they possess high strength, high toughness at low temperature and good weldability (10–12).

TABLE 1
Chemical Composition of the Steel (Weight%)

C	Mn	Si	P	S	Al	Nb	V	Ni	B	Ti	N
0.08	1.70	0.25	0.021	0.002	0.029	0.033	0.058	0.17	0.0024	0.026	0.0048

In this work, a CCT diagram is determined by analyzing the cooling curve of a sample of a Low Carbon HSLA Bainitic steel initially deformed by torsion simulating controlled rolling and then cooling down to room temperature.

Experimental Techniques

The steel used in this research contains Nb, Ti and V as microalloying elements and B (24ppm) plus Ni to enhance hardenability as detailed in the Table 1. This product has been recently developed by the industry as a HSLA low carbon-bainitic grade of the API X80 class to be used in the as hot rolled condition.

Tubular torsion specimens (16.5mm gauge length, 6.5mm outer and 2mm inner diameter) were machined from pieces cut longitudinally to the rolling direction so to keep the torsion axis parallel to the rolling direction. Tests were carried out in a servohydraulic torsion machine with a computerized MTS TestStar II^{TM} unit and Testware SX^{TM} 228 software for control of the hydraulic servovalve and data acquisition. The sample was heated up in an infrared furnace programmed by a digital temperature controller linked to a 1.5mm in diameter K type thermocouple with mineral insulation placed inside specimen. This thermocouple was also tied to a data acquisition interface installed in a microcomputer allowing control of the thermal profiles during thermomechanical processing and data collection of the cooling curves.

A simplified controlled rolling schedule was first established from the knowledge of the critical temperatures, Tnr = 971°C and Ar3 = 740°C, calculated from the empirical equation by Ouchi et al. (13). The samples were reheated at 1200°C for 900s and, while cooling down at a rate of 1°C/s, were given 9 passes of 20% of equivalent strain each, at a strain rate of $2s^{-1}$, being 5 passes above Tnr and 4 below. The final pass temperature was chosen as 810°C. Details of the temperature of each pass of the hot torsion experiments are given in Table 2 below.

After thermomechanical processing, the samples were cooled down in helium in a cooling system similar to that reported by Debray (9) at rates varying from 1 to 100°C/s measured as the average values for the temperature range of 800 to 500°C.

Samples for metallographic observation and Vickers hardness measurements were sectioned longitudinally producing a tangential plane to the gauge length of the torsion specimens. The pieces were ground with 600 and 1000 grit silicon carbide papers, polished in diamond paste of 9 to 1μm and then etched with nital 2%. The samples were observed by light and electron scanning microscopy. The Vickers microhardness was measured with a load of 4.905N.

TABLE 2
Temperature of Each Pass in the Simplified Controlled Rolling Schedule Employed in the Hot Torsion Experiments of This Work

Pass	1	2	3	4	54	6	7	8	9
Temperature (°C)	1170	1145	1115	1083	1053	903	872	842	810

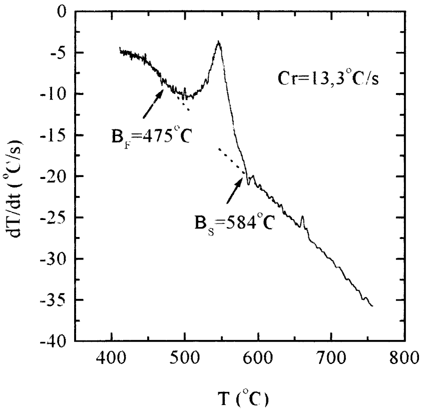

Figure 1. Cooling rate as a function of the temperature for a rate of 13.3°C/s. Arrows indicate how B_S and B_F temperatures were measured. The sample was subjected to multiple steps of torsional deformation at various temperatures prior to cooling for austenite transformation.

Results and Discussion

The cooling curves were differentiated with respect to the time so to enhance the deviations due to the heat generated while the transformation was going on. Prior to differentiation, the experimental scatter inherent to measurements in temperature during cooling was filtered by a procedure described elsewhere (14). The start of austenite transformation was measured at a point on a dT/dt versus T curve where there was a deviation from the main curve as pointed out by the arrows in Fig. 1. This figure indicates the temperatures for the start and finish of bainite formation, B_S and B_F, respectively. The CCT diagram obtained as described here for the steel of this study is then presented in Fig. 2. The diagram also indicates the cooling rates employed in the experiments as well as the measured values of Vickers microhardeness.

In order to validate the CCT diagram, metallography of the samples cooled at 1, 6.3, 33 and 100°C/s was carried out. Fig. 3a-d show the photomicrographs of SEM for the 4 different cooling rates. It can be seen that for cooling rates up to 33°C/s the microstructure is predominantly bainitic. For a rate of

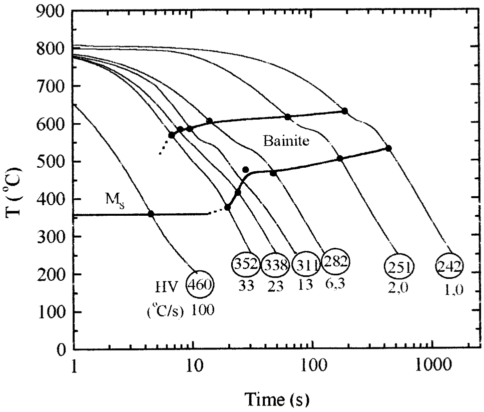

Figure 2. CCT diagram of an HSLA bainitic steel subjected to multiple steps of torsional deformation at various temperatures prior to cooling for austenite transformation.

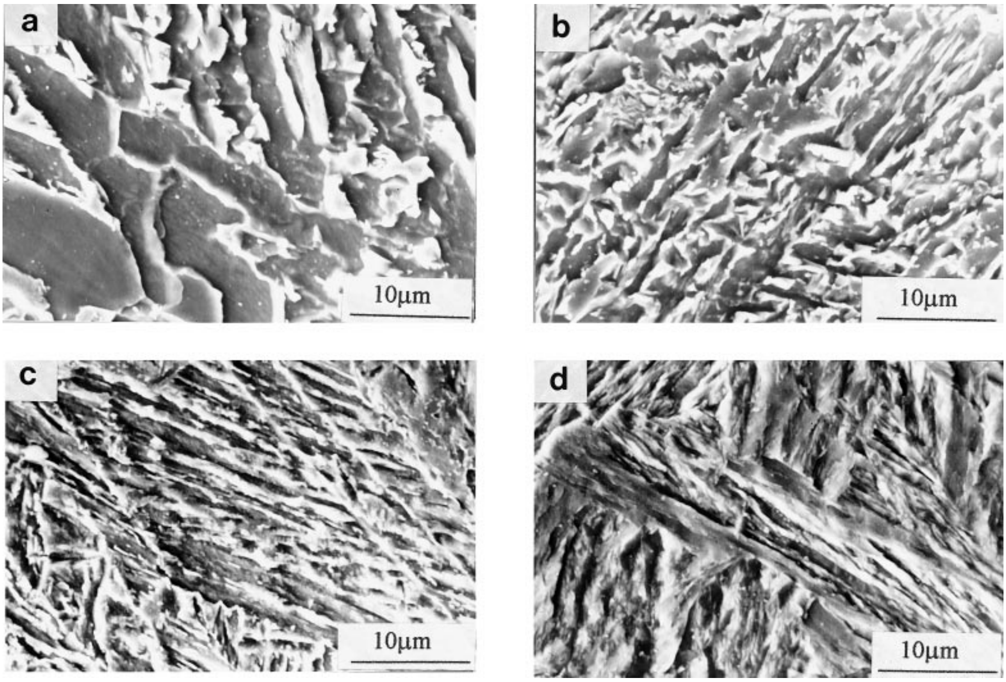

Figure 3. SEM photomicrographs (2000X) for samples cooled at rates of (a) 1, (b) 6.3, (c) 33 and (d) 100°C/s.

1°C/s, the microstructure is ~15% of polygonal ferrite, ~5% of MA constituent (martensite and retained austenite) and 80% of granular bainite. For 6.3°C/s, the microstructure is essentially bainitic with a small amount of MA constituent. As the cooling rate increases to 33°C/s, the microstructure transforms to fine laths of bainitic ferrite. Finally, as expected from the CCT diagram, a typical microstructure of low carbon martensite laths was obtained for a cooling rate of 100°C/s.

Conclusions

Torsion tests simulating a simplified thermomechanical treatment typical a HSLA bainitic steel were carried out in order to measure the temperatures of start and finish of austenite transformation from the cooling curves. Cooling rates up to 100°C/s were employed and the values of the transformation temperatures on cooling were obtained from dT/dt versus T curves. The CCT diagram built in this way was validated by metallographic results. This leads to the conclusion that a CCT diagram for steels thermomechanically processed and accelerated cooled can be obtained with the technique described in this paper.

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