INFLUENCE OF CHROMIUM CONTENT ON THE MECHANICAL PROPERTIES AND HAZ SIMULATIONS OF LOW-CARBON BAINITIC STEELS

Tun Tun NYO, Antti KAIJALAINEN, Jaakko HANNULA, Mahesh SOMANI, Jukka KÖMI

Materials and Mechanical Engineering, CASR, University of Oulu, Finland, EU, tun.nyo@oulu.fi

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Abstract

During thermomechanically controlled processing (TMCP) of carbon steels, controlled rolling in no-recrystallization regime followed by directing quenching results in excellent mechanical properties, besides enabling cost-saving in respect of energy costs normally incurred during reheating and quenching procedure. The effects of three different combinations of Cr with 0.06 wt.% of Nb on the microstructures and mechanical properties of thermomechanically rolled and direct-quenched low-carbon (0.035 wt.%) microalloyed steel plates have been investigated to obtain balanced mechanical properties. Laboratory-scale ingots were cast, hot rolled and direct quenched into 12 mm thick plates as per an experimental plan. Tensile properties, impact toughness, hardness and hardenability were studied. In addition, coarse grained heat affected zone (CGHAZ) simulations were performed in a Gleeble simulator to evaluate the weldability of the investigated steels using cooling time from 800 °C to 500 °C ($t_{8/5}$) of 5 s and 15 s.

Keywords: CGHAZ, direct quenching, lower bainite, upper bainite

1. INTRODUCTION

In the last two decades there have been considerable advances in the theory and practice of accelerated cooling including direct quenching, following controlled rolling. Thermomechanical controlled processing (TMCP) has become the essence of processing low-carbon steel, particularly in combination with microalloying, in order to obtain the desired microstructures and properties [1]. In fact, TMCP represents the most effective manufacturing process to impart improved strength, ductility and low-temperature toughness in steels with reasonable hardenability, managed through controlled low carbon and alloy contents. The microstructure, which is the key to achieving a desired combination of mechanical properties in hot rolled steels, is greatly influenced by the quenching process following TMCP rolling. Hence, the microstructures and mechanical properties of particular low-carbon steel can be significantly improved by suitably designing the accelerated cooling/direct quenching process, following the hot deformation schedule [2]. Accelerated cooling may promote bainite formation with or without ferrite formation, depending on the alloy design and the cooling path. In this study, salient features of the successful development of a high strength, 0.035C low-carbon steel with yield strength on the order of 700 MPa in combination with good ductility and toughness are presented with a special emphasis on structure-property correlations. TMCP combined with direct quenching process was employed to produce three different types of high-strength low-carbon bainitic steels with a constant niobium level of 0.06 wt.%, but three different levels of chromium, (1.0, 2.5 and 4.0 wt.%). The aim of the study was to understand the effects of the combined additions of niobium and chromium on the microstructures and mechanical properties of 0.035C microalloyed bainitic steels. Besides, CGHAZ evaluation was planned to understand the occurrence of softening in welded structures and its effect on the microstructures and mechanical properties for different levels of chromium contents in the microalloyed steel.

2. EXPERIMENTAL PROCEDURES

The steel castings were procured from Outokumpu, Tornio, Finland as 70 kg vacuum-cast ingots. The chemical compositions of the three steels are listed in **Table 1.** 200 mmx 80 mm x 55 mm pieces of these castings were soaked at 1250 °C for 2 h and thermomechanically rolled to 12 mm thick plates as per an experimental plan comprising several hot rolling passes in recrystallization controlled regime followed by controlled rolling passes in no-recrystallization regime (T_{NR}). The temperature of the samples during rolling and direct quenching was monitored by placing thermocouples in the centre of the samples. The finish rolling temperature was controlled at around 880 °C and the final thickness was 12 mm at this temperature prior to quenching. After hot rolling, direct quenching in a water tank was used to achieve a high cooling rate (~40-50 °C/s) in the centre of the samples.

Table 1 The chemical compositions of experimental steels (wt.%).

Steel	C	Nb	Cr	Si	Mn	S	Al
4Cr	0.035	0.06	4.0	0.15	0.9	0.0034	0.037
2.5Cr	0.035	0.06	2.5	0.17	0.9	0.0030	0.045
1Cr	0.035	0.06	1.0	0.20	1.0	0.0030	0.045

A Gleeble 3800 thermomechanical simulator was used to conduct simulation of the coarse-grained region of HAZ (CGHAZ) using samples of the size 10 mm x 10 mm x 55 mm. Simulations were carried out in the Gleeble with the evacuated chamber and a free span of 10 mm. The following thermal cycle was programmed: heating at 100 °C/s to 1300 °C and continued heating at 50 °C/s to 1350 °C, holding at 1350 °C for 1 s to even out the temperature, followed by cooling corresponding to Rykalin-3D (thick plate) formulation based on conductive heat transfer, with a cooling time from 800 to 500 °C ($t_{8/5}$) of 5 and 15 s. After the simulation experiments, the Charpy V -notch tests were performed at temperatures of -40 °C and -60 °C. Besides, hardness profiles across the heat affected zones were determined with 0.5 mm spacing between the indentation as described below. The specimens used for microstructural evaluation, including optical microscopy and field emission scanning electron microscopy (FESEM), were mechanically polished and etched in a 2 % nital solution. Electron backscatter diffraction (EBSD) analyses were carried out using an accelerating voltage of 15 kV, and a step size of 0.2 μm and area of approximately 150 μm x 150 μm. Samples were polished with 0.04 μm silica as the final step for EBSD analyses.

Longitudinal tensile flat specimens with thickness of 11.7 mm, width of 20 mm and a parallel length of 120 mm were tested at room temperature using an MTS 810 mechanical testing machine fitted with a 100 kN load cell and the measurements were based on the SFS-EN 10002-1 standard with 3 tests carried out for each composition. For toughness evaluation, the standard Charpy V-notch impact test specimens were sectioned in the longitudinal and transversal directions of the rolled samples for testing in the temperature range between −120 °C and 20 °C using a 300 J Charpy testing machine. Hardness tests were done by using a DURAMIN A-300 Vickers testing machine for all the rolled samples. A representative hardness value was obtained from the mean of 5 sets of seven suitably spaced hardness impressions through the thickness.

3. RESULTS AND DISCUSSION

3.1. Microstructure

Due to the application of accelerated cooling, all the steel plates displayed various low temperature transformation microstructures, viz., granular bainite (GB), upper bainite (UB), coalesced bainite, lower bainite (LB), as well as, quasi-polygonal ferrite (QF). Examples of different microstructural constituents observed by metallography are shown in **Figure 1**. Grain boundary maps with image quality data of EBSD acquisitions are presented in **Figure 2**. Grain misorientation distributions and grain sizes were determined using the EBSD data and are presented in **Figure 3**. Effective grain and lath sizes were determined as equivalent circle diameter (ECD) values with low-angle (2°-15°) and high angle (>15°) boundary misorientations. Also the effective high-angle grain sizes at 90 percentile in the cumulative size distribution ($d_{90\,\%}$) were determined.

Based on the microstructural characterization and misorientation distribution measurements, clear differences between the three steels were apparent. With the highest Cr content (4Cr), microstructure consisted mainly lath-type structure such as UB and LB, which, therefore, had smallest grain sizes. As expected, decreasing the Cr content decreased the hardenability of steels and hence, resulted in more of granular bainite and ferrite in 2.5Cr and 1Cr steels. As the ferrite content increased, lath and effective grain sizes became bigger too, in comparison to that seen in steel 4Cr.

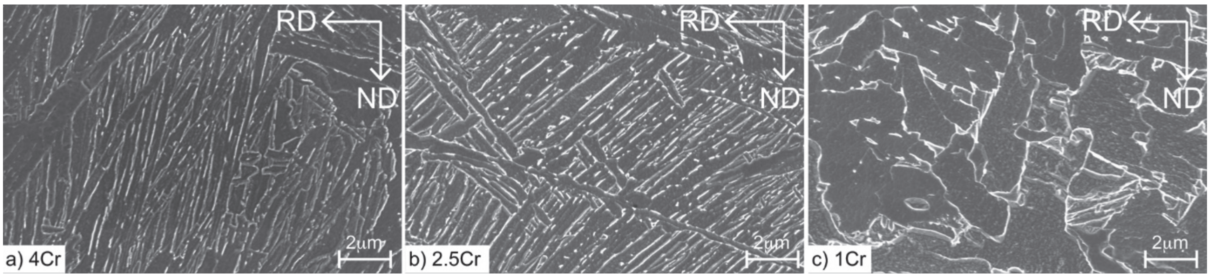

Figure 1 Typical microstructures of investigated steels. a) Upper bainite in 4Cr steel, b) lower bainite in 2.5Cr steel and c) quasi-polygonal ferrite and qranular bainite in 1Cr steel

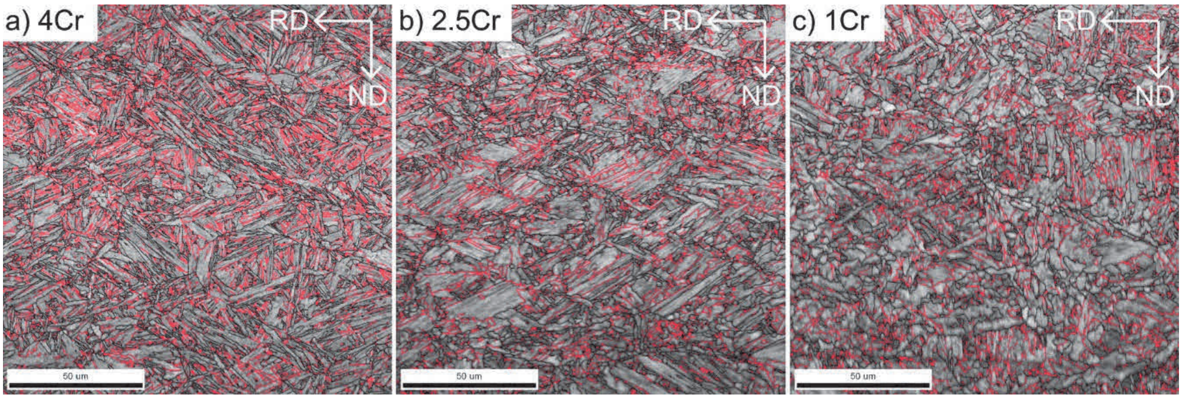

Figure 2 Grain boundary maps with image quality data of investigated steels. High-angle boundaries (>15°, black line) and low-angle boundaries (2°-15°, red line)

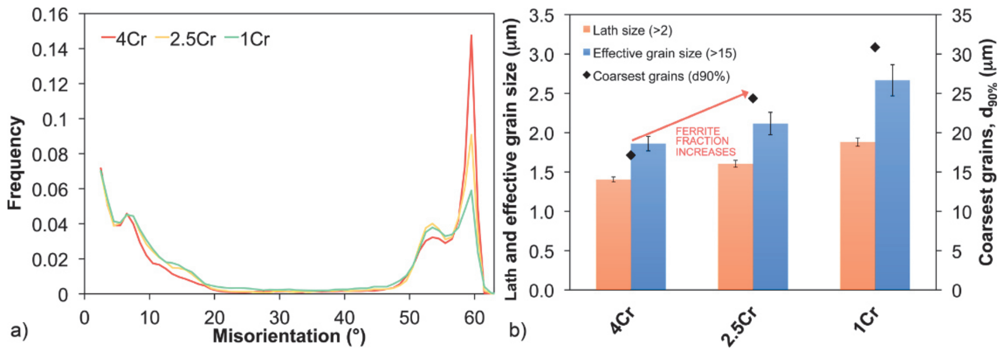

Figure 3 a) Grain boundary misorientation distributions and b) grain sizes of investigated steels measured by EBSD

3.2. Mechanical properties

A summary of the tensile test results for the three steels and the corresponding 28J transition temperatures (T_{28J}) estimated from the impact tests are displayed in **Table 2.** Plots of through-thickness hardness profiles, representative engineering stress-strain curves and impact transition curves of the investigated steels are presented in **Figure 4**. In respect of the desired level of 700 MPa yield strength, both the 4Cr and 2.5Cr steels were able to demonstrate similar tensile properties as in the industrial production [3], but the 1Cr steel showed lower yield strength (560 MPa) obviously as a consequence of the formation of quasi-polygonal ferrite, though the total elongation (A) was relatively higher. The presence of quasi-polygonal ferrite and granular bainite with M/A islands seem to have significant effect on the impact toughness of 1Cr steel, which is better than the higher 2.5Cr and 4Cr steels, both in respect of higher upper shelf energy as well as lower T_{28J} temperature, as displayed in **Table 2** and **Figure 4c.** A good toughness is known to be associated with a massive ferrite structure like quasi-polygonal ferrite [4]. On the other hand, thin films of martensite-austenite (M/A) constituents present in lath-like granular bainite might adversely affect the impact toughness [5]. Anyhow, the highest tensile properties and correspondingly, somewhat higher transition temperatures were achieved with the low-carbon (0.035C wt.%) Nb-microalloyed, 4Cr TMCP rolled sample with the FRT controlled at 880 °C, essentially due to the formation of fine bainitic structure and the absence of ferrite in the microstructure. In essence, steel with the yield strength of about 780 MPa in direct quenched condition with the T_{28J} transition temperature of around -80 °C can be considered as extremely good and meets the desired expectations.

Table 2 Mean tensile properties in longitudinal direction and corresponding T_{28J} transition temperatures

Steel	YS (MPa)	UTS (MPa)	A (%)	HV10	YS/UTS	UTS*A (MPa*%)	T_{28J} (°C)
4Cr	780	982	12.5	312	0.79	12238	-78
2.5Cr	699	909	14.1	293	0.77	12852	-93
1Cr	560	756	17.2	251	0.74	13034	-118

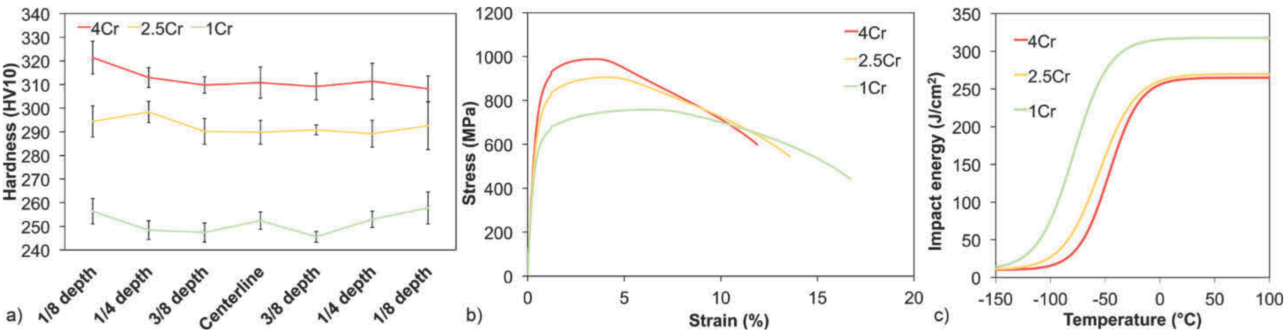

Figure 4 a) Through-thickness hardness profiles,
b) stress-strain curves and c) Charpy V transition curves of investigated steels

Through-thickness hardness profiles made on the rolled samples are depicted in **Figure 4a** and the corresponding mean hardness values are summarized in **Table 2**. The adverse effect of the quasi-polygonal ferrite on hardness in 2.5Cr and 1Cr steels can be seen in **Figure 4a**. The hardness dropped significantly in the case of 1Cr steel, where a fairly significant amount of QF did form in the microstructure (**Figures 1c).** Though Cr is a strong ferrite-stabilizing element, an increase in Cr content contrarily reduced the amount of ferrite (except for the increased solution hardening) due to the increased hardenability of the high chromium steels, 2.5Cr and 4Cr, which therefore displayed enhanced hardness values, as shown in **Table 2** [6]. A higher Cr addition resulted in less ferrite formation, thus facilitating an increased bainite fraction in the microstructure. It is reported that an increase in Cr content in the steel causes a separation of the bainite C-curve from the ferrite C-curve (more clearly in the presence of Mo) and extends the bainite phase field [7]. The dilatometer studies did confirm a similar effect, further supporting the higher hardenability of high Cr steels [8]. The addition of Cr decreased the B_s and M_s, which not only contributed to the higher fraction of bainite at a given cooling rate, but also promoted fine lath-type structure with enhanced strength and toughness. Moreover, due to higher hardenability of high-Cr steels, the hardness seems to be fairly uniform through the thickness (**Figure 4a)** besides, the better stability and uniformity of the microstructures. Therefore, more undercooled austenite can transform into lath-like bainite in the Cr-added steel, which may impart better properties, though the casting practice should be thoughtfully designed (both in respect of superheat and appropriate Cr-content) to prevent Cr- microsegregation bands in the microstructure.

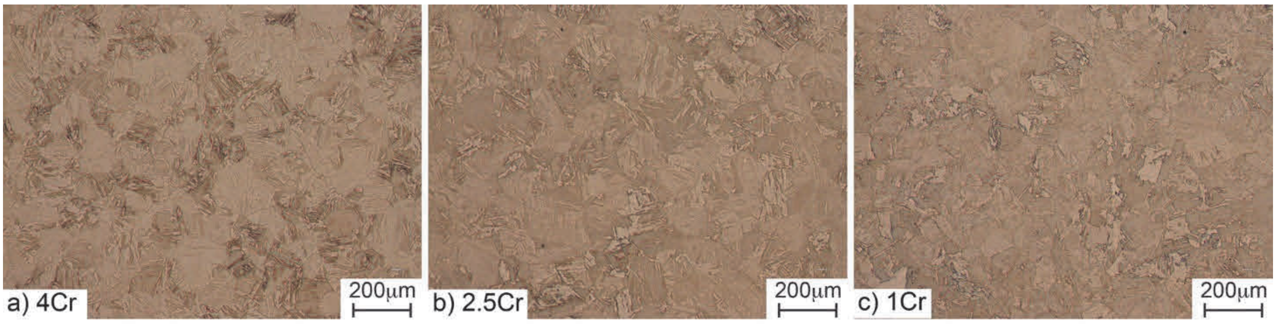

Figure 5 Representative microstructures of CGHAZ simulation samples using $t_{8/5}$ =15 s cooling cycle

3.3. HAZ simulation

The microstructures of CGHAZ simulated samples with $t_{8/5}$=15 s cooling cycle are presented in **Figure 5**. Microstructures essentially consisted of mixtures of different bainite types, and also with small fractions of quasi-polygonal ferrite in 2.5Cr and 1Cr steels. Hardness measurements performed across the simulated CGHAZ samples are presented in **Figures 6a** and **b**. The highest softening occurred in 1Cr and 2.5Cr steels at the CGHAZ regions with more softening occurring in samples with longer $t_{8/5}$ -time (15 s) (**Figure 6a**).

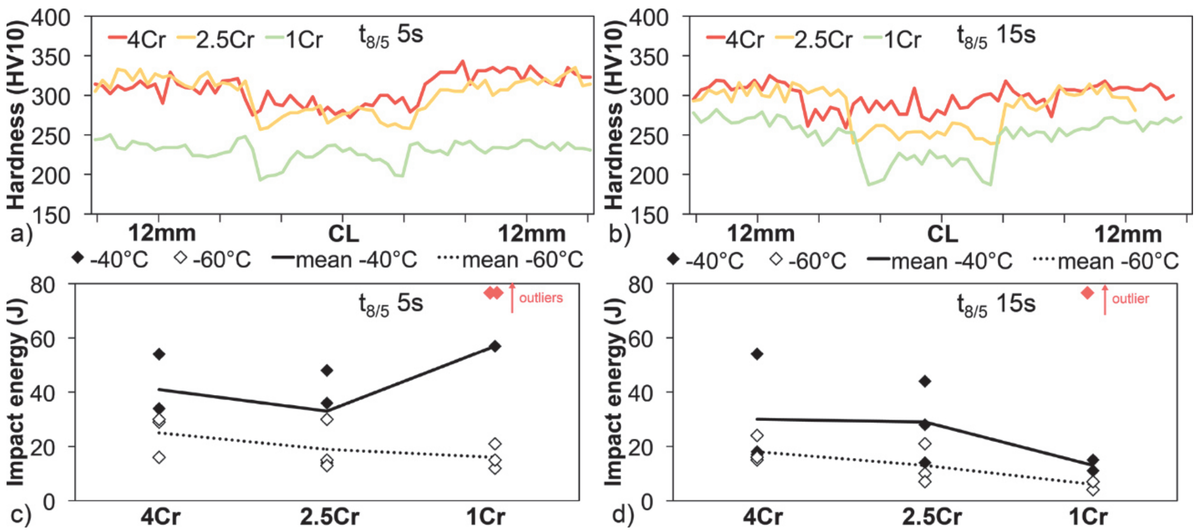

Figure 6 Hardness profiles across HAZ samples with $t_{8/5}$ times of (a) 5 s and b) 15 s; and corresponding Charpy V impact toughness energies at -40 °C and -60 °C for $t_{8/5}$ times of c) 5 s and d) 15 s. The CGHAZ regions in some Gleeble simulated samples of 1Cr steel were not clearly identifiable to correctly machining the notches and led to scatter in the results, marked as outliers (red coloured solid diamonds).

Higher Cr content (4Cr) decreased the amount of softening in the HAZ region, especially with longer (15 s) $t_{8/5}$ -time due to increased through-thickness hardenability (i.e. larger ideal critical diameter). The average hardness of 4Cr steel in direct quenched condition was 312 HV, whereas the CGHAZ simulated samples with $t_{8/5}$ = 15 s showed a marginally lower hardness of 287 HV. This suggests that even with a longer $t_{8/5}$ time of 15 s, it should be possible for the HAZ area to achieve mechanical properties nearly similar to the base metal.

The Charpy V impact test data for CGHAZ samples at -40 °C and -60 °C are plotted in **Figures 6c** and **d** for both the cooling cycles corresponding to $t_{8/5}$ = 5 and 15 s. As can be seen in the figure, the CGHAZ simulated samples of 1Cr steel has displayed largest scatter in impact energy values (11 J - 212 J) at -40 °C, but the impact energies are lowest of all at -60 °C. In all, 4Cr steel had the highest impact energies at both cooling cycle conditions ($t_{8/5}$ = 5 and 15 s). As expected, shorter $t_{8/5}$ time (5 s) corresponding to the higher cooling rates (**Figure 6c)** gave better impact toughness properties compared to the longer duration $t_{8/5}$ = 15 s samples (**Figure 6d**).

4. SUMMARY AND CONCLUDING REMARKS

The main aim of this report was to understand the effect of chromium on the microstructures and mechanical properties of Nb-microalloyed 0.035C low carbon steel processed through TMCP rolling followed by direct quenching. The study also included weldability aspects of these Cr-alloyed steels through Gleeble simulations. The programme envisaged high yield strength of the order of 700 MPa in these steels with good ductility and improved low temperature toughness in direct quenched condition. Three laboratory-scale experimental steels with different Cr levels were processed through laboratory rolling simulations and evaluated in respect of mechanical properties and microstructures. A Gleeble 3800 thermomechanical simulator was employed to conduct the CGHAZ simulations with two different cooling cycles. The typical microstructures consisted of mainly mixtures of different type of bainite in all the three steels with the exception of 1Cr steel, which displayed significant fractions of quasi-polygonal ferrite, too. An increase in Cr content resulted in an increased hardness owing to an enhanced hardenability during direct quenching. A decrease in Cr content, however, promoted formation of quasi-polygonal ferrite, which in turn increased the impact toughness and elongation, but the required yield strength of ≥700 MPa could not be achieved. CGHAZ simulation of 4Cr steel showed negligible softening and the impact toughness at -40 °C was quite reasonable at about 45 J/cm^2. Thus, the 4Cr steel emerges as the potential candidate for 700 MPa grade steel envisaged in this program owing to its high properties both in direct-quenched as well as welded conditions.

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