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Production of Directly Quenched High-Strength Hot-rolled Strip Steels - Influence of Rolling and Cooling Conditions on Mechanical Properties and Flatness

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Abstract. The production of hot-rolled sheets of high-strength and wear-resistant special structural steels by direct quenching from the rolling heat is a cost effective and energy-saving alternative to traditional production via downstream quenching the previously cut-to-length plates. Reaching the required strength and toughness parameters in combination with best flatness of the sheets requires strict compliance with the pre-set rolling and cooling conditions over the entire strip width. Using two high-strength low-alloyed steels, plant trials have been carried out to study the effect of the cooling conditions and the coiling temperature on mechanical properties, impact toughness and flatness of cut-to-length sheets made of hot-rolled strip. The results showed that by applying optimized cooling pattern and low coiling temperatures, high-strength steel sheets with outstanding mechanical properties and good flatness can be produced.

Introduction

Demands regarding lightweight construction and cost reductions as well as the competition with other construction materials have prompted increased development of new grades of steel in recent years. Increased strengths and improved forming, application and processing characteristics distinguish the latest steel innovations.

The production of hot-rolled sheets of high-strength and wear-resistant special structural steels by direct quenching from the rolling heat is a cost effective and energy-saving alternative to traditional production via downstream quenching the previously cut-to-length plates, especially for sheet thicknesses smaller than 10 mm. The influence of rolling and cooling parameters during hot strip rolling on the microstructure development, mechanical parameters and flatness of cut-to-length sheets produced from direct-quenched strip of two types of high-strength special structural steels is described herein.

Composition and Processing

The materials used in this study are two types of high-strength low-allowed steels of nominal composition listed in Table 1.

Table 1: Nominal composition of the materials used in this study, in wt.% (bal. Fe) and equilibrium phase transformation temperatures in °C.

Steel	C	Mn+Si	Cr+Mo	Nb+Ti	Ni	B	A_{e1}	A_{e3}
1: BC	0.17	1.5	0.6	0.04	0.05	0.0030	718	830
2: BF	0.18	1.8	1.5	<0.01	0.50	0.0004	724	791

The first of the investigated materials is a boron-alloyed (named BC herein) steel with alloying additions of Cr, Mo and Nb and is commonly used to manufacture high-strength special construction steels for thin-walled structures with high rigidity, for example, in trucks or cranes. The second one is a boron-free wear-resistant steel (named BF herein) for wear-exposed structures with additional demands on weldability and formability. Typical areas of application are, for example, earthmoving and mining machinery, sliding plates and mixer-transport systems and other components which are subject to mainly abrasive wear.

The equilibrium phase transformation temperatures (bcc → fcc) were calculated using the JMatPro® software package [1] and are listed in Table 1 as well. Using JMatPro®, the TTT diagrams of the two steels were also determined, see Fig. 1, and used to select the appropriate rolling and cooling conditions in the hot strip mill. The shaded gray areas show the typical temperature cycles at coiling temperatures of 150 °C (a) or 500 °C (b), taking into account the inevitable temperature fluctuations over the strip thickness and width.

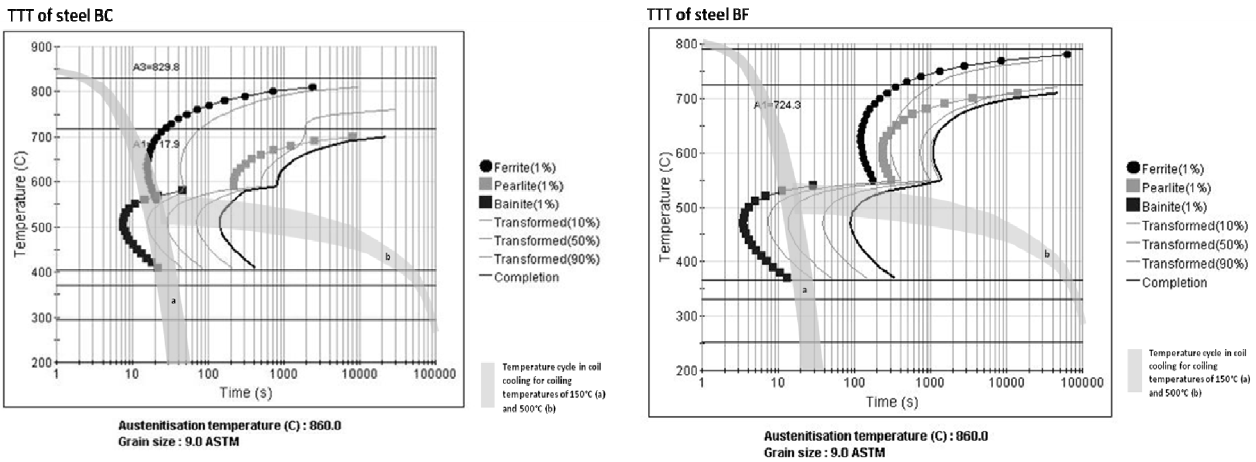


Fig. 1: TTT diagram of both steels

The examined steels were rolled on the hot strip mill at Salzgitter Flachstahl GmbH in regular operation from slabs of 250 mm thickness to hot-rolled strip in thicknesses of 5 - 8 mm. The final rolling temperatures were kept constant, respectively at 870°C, while the coiling temperatures were varied in the temperature range 150 – 500 °C. The finished hot-rolled strips were then cut to sheets on a hot strip cut-to-length line and finally tested.

Sample preparation for light optical microscopy (LOM) was performed with standard grinding and polishing procedures finishing with OPS polishing for several minutes. The samples were subjected to Nital etching, for SEM investigations just very slightly. Tensile tests were performed according to DIN EN ISO 6892-1 on two transverse specimens for each material condition. Due to the small sheet thickness, the impact tests were carried out using undersized samples and extrapolated to a test section of 80 mm^2 according to DIN EN ISO 148-1. The stated values are the mean values of three measurements.

Results and Discussion

Mechanical properties. The results of the tensile tests on samples of the two steel grades are shown in Fig. 1 and 2 as a function of the coiling temperature. The results show that high-strength sheets with the aspired properties can be produced by direct quenching on the hot strip mill with optimized coiling temperature depending on the steel grade. Using the steel BC, for example, by control of the coiling temperature, sheets meeting the requirements that apply to high-strength steels from S550QL to S1100QL may be produced. For most applications, it is sufficient to reduce the coiling temperature to a range of 300 - 350 °C, thus avoiding possible problems with further lowering the coiling temperature using higher amounts of water, such as "wet coils".

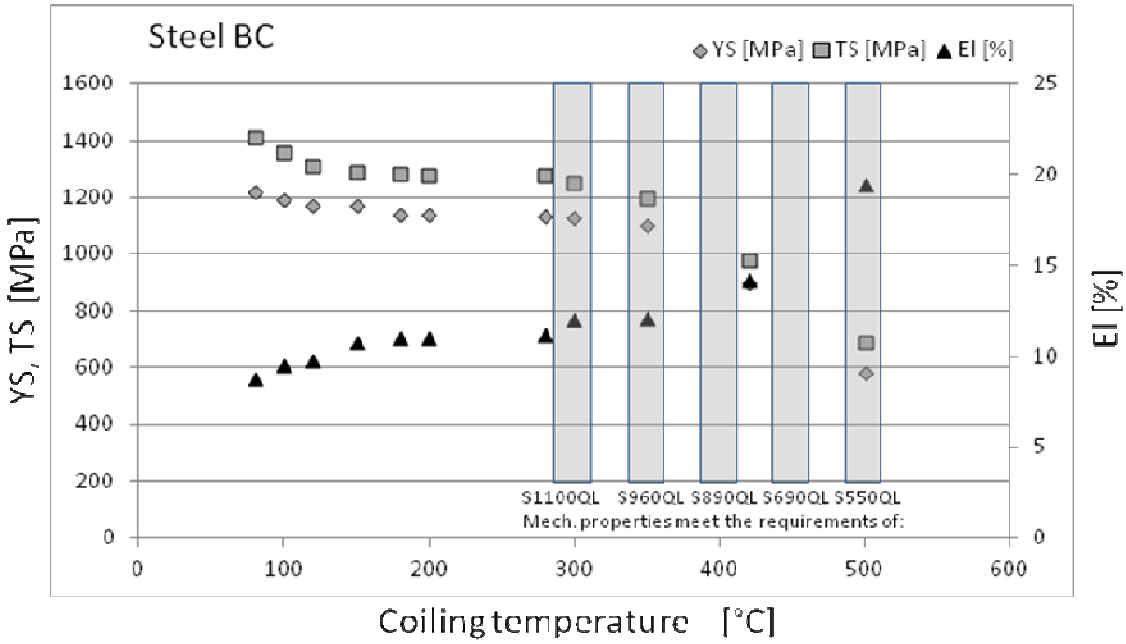


Fig. 2: Effect of coiling temperature on mechanical properties of steel BC

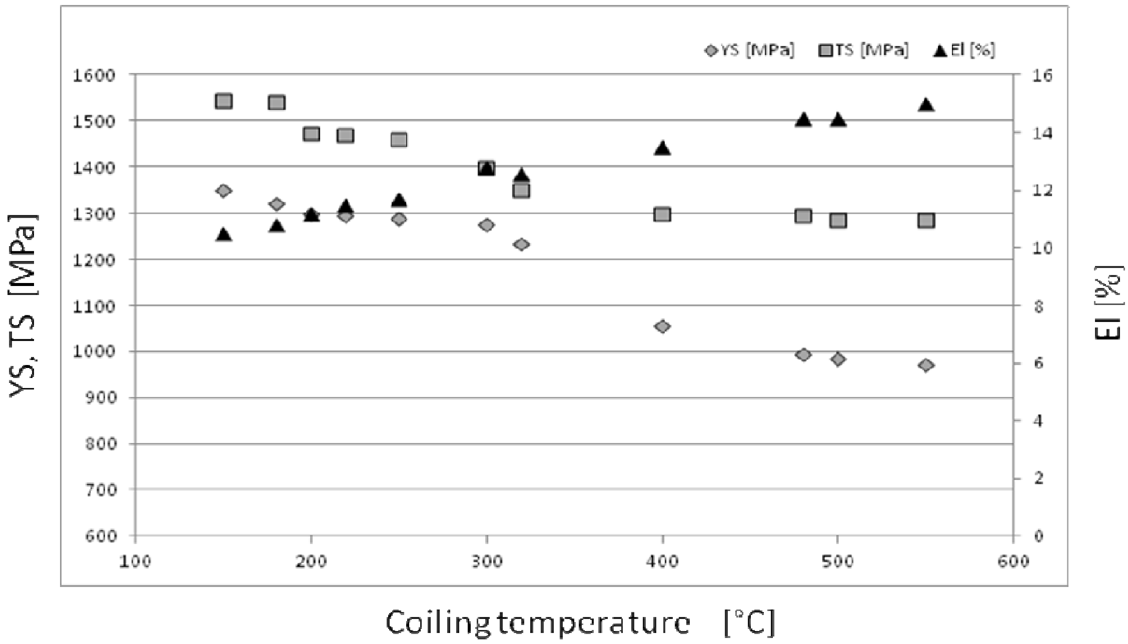


Fig. 3: Effect of coiling temperature on mechanical properties of steel BF

Impact toughness. The measured values of the impact energy depending on the process route for the steel BC sheets with thicknesses ranging from 5 to 8 mm are summarized in Table 2. Here, an only minor influence of the coiling temperature on toughness values is reflected. The toughness values reach the requirements for a S960QL steel according to DIN EN ISO 10025-6 even at low test temperatures of -40 °C.

In comparison, a strong influence of the coiling temperature on the notched impact strength was found for the BF steel, Fig. 4. In particular, at coiling temperatures above 500 °C, there is a rapid drop in the toughness values. The causes are discussed below on the basis of the results of microstructure investigations.

Table 2: Effect of coiling temperature on the impact energy of undersized specimens of steel BC [J/cm²] * - according to DIN EN 10025-1

	Coiling temperature [°C]					S960QL*
Test temperature [°C]	**150**	**200**	**300**	**400**	**500**	**Min Impact Energy**
0	71	60	65	64	64	35
-20	63	52	52	54	53	30
-40	48	40	44	41	45	27

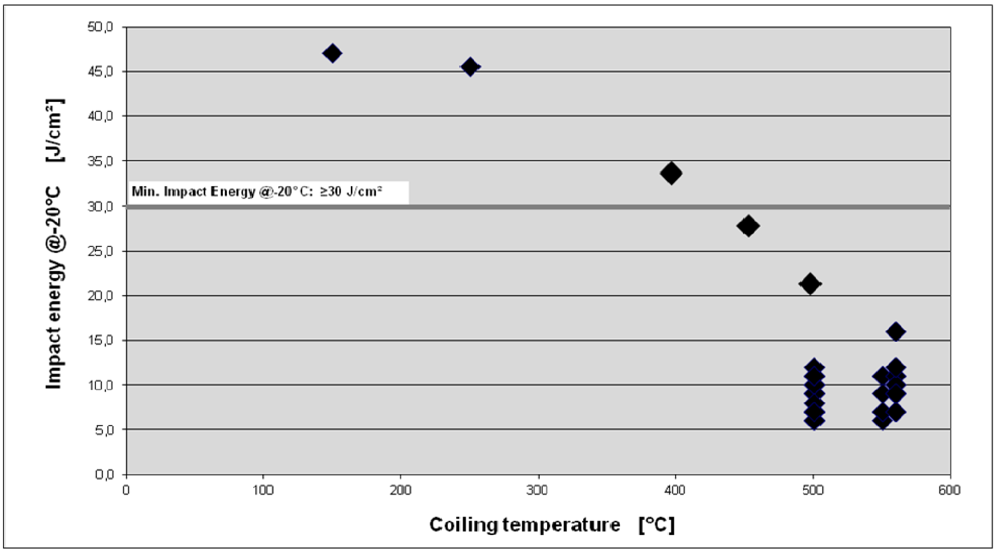
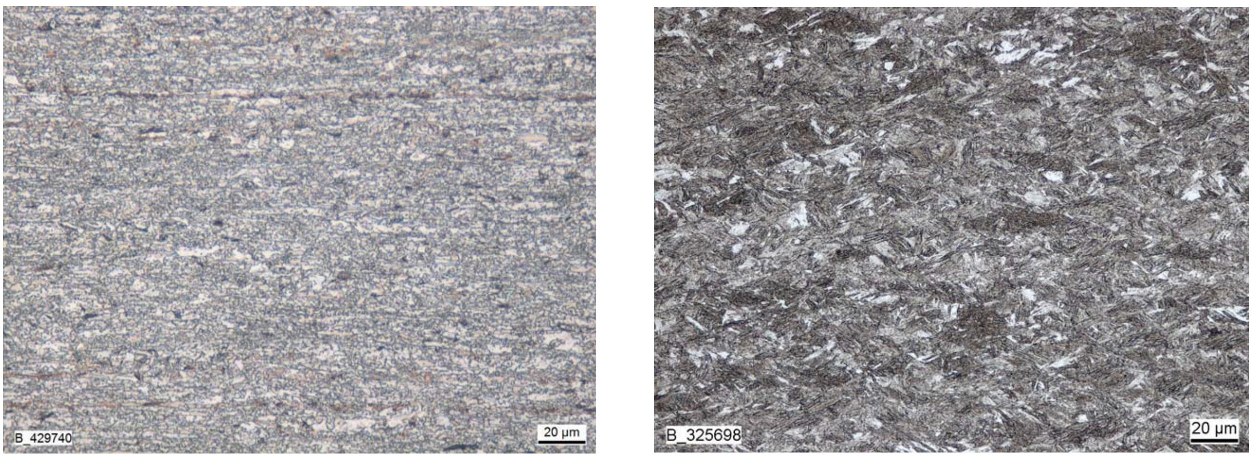


Fig. 4: Effect of coiling temperature on the impact energy of steel BF at -20°C test temperature (on undersized specimens)

Microstructure. The microstructures after direct quenching on the run-out table of the hot strip are given in Fig. 5 for the steel BF for two different coiling temperatures.

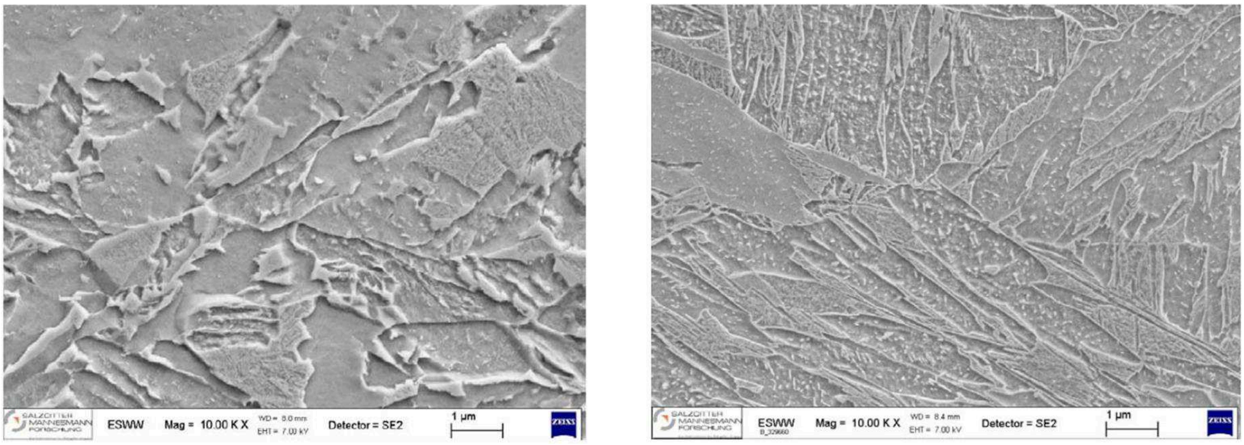


500 °C **150 °C**

Fig. 5: Effect of coiling temperature on microstructure of steel BF (LOM)

The steel BF is of particular interest in relation to the microstructure since in this case, as can be seen in the TTT diagram above (Fig. 1), at elevated coiling temperatures at around 500 °C, the formation of pearlite cannot be excluded, particularly in the center areas of the strip where the temperatures are slightly higher and the temperature gradients smaller compared to the surface. This would affect in particular the impact strength of the material. While a coiling temperature of 150 °C results in a martensitic-bainitic structure, the microstructure of the material coiled at 500 °C actually contains pearlite colonies.

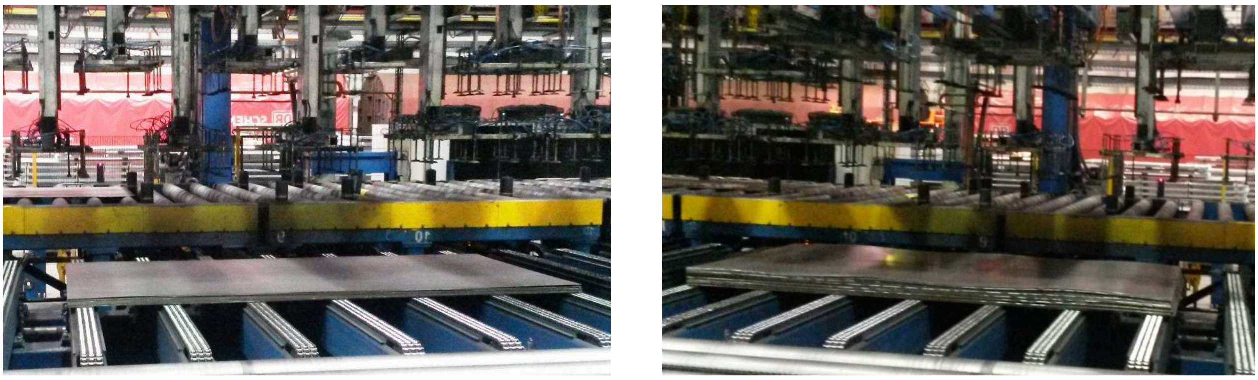
The SEM study of the material structures shows a finer structure and less sharp-edged microstructural components at a coiling temperature of 150 °C, Fig. 6, which is also favorable for the notched impact strength of the material [2].



500 °C **150 °C**

Fig. 6: Effect of coiling temperature on microstructure of steel BF (SEM)

Flatness. In the course of the plant trials, a whole range of factors influencing the flatness of hot rolled and directly quenched strips was found and investigated. The cooling process of the rolled strip between finish rolling and coiling is known to be of particular importance for the strip flatness [3,4], above all, the homogeneity of the temperature distribution over the strip width. In particular, a rapid cooling of the strip edges may have the result that the edge areas reach the Ae_3 onset temperature of the γ-α-transformation earlier than the strip center, leading to thermal stresses and excessive thermal contraction in the over-cooled strip edges, and therefore to poor flatness of the strip after decoiling [5]. Therefore steels with a higher Ar_3 temperature should be especially prone to strip flatness deviations. Our plant tests showed that actually the boron-alloyed steel BC with an Ae_3 temperature of 830 °C is significantly more susceptible to flatness deviations than the B-free steel BF. To avoid this problem, a lower coiling temperature is required so that the phase transformation completes before the strip enters the pinch rolls at the coiler entry. Another factor influencing the flatness of the strip is the uniformity of the heat flux from the hot strip surface. As known, the heat transfer coefficient of a hot surface is strongly influenced by the surface roughness. According to [6], the heat flux from the hot surface during water cooling in the temperature interval of interest (150 - 500 °C) sharply intensifies with increasing roughness due to interaction between the surface roughness elements with the liquid-vapor interface. In the plant trials described herein, differing surface roughness has been measured in different surface areas of one and the same strip in dependence of the amount and type of the scale layer in this strip area. Since the two examined steels contain about 0.20 % Si, a fayalite-containing red scale is formed on the surface already in the oven or during roughing. In these scale-covered areas, the roughness of about 6µm is significantly higher than in scale-free areas with about 1.5 µm, resulting in significantly different heat fluxes from the strip surface leading to fluctuations in the strip temperature in the width and length directions and, finally, to strip flatness deviations. Therefore, care must be taken in rolling high-strength steels with high Si contents regarding the as full as possible descaling of the rolled material after roughing. By optimum application of water on both sides of the strip, a best combination of desired mechanical properties and best flatness can be achieved [7]. This was confirmed in the plant trials described here, in which cut-to-length sheets of very good flatness have been obtained after hot rolling with appropriate process conditions in the hot strip mill, while in non-optimum process conditions the flatness was insufficient, Fig. 7.



Good flatness with proper cooling pattern   Insufficient flatness due to non-optimum cooling pattern

Fig. 7: Effect of cooling pattern on flatness of sheets made of direct-quenched hot rolled strip

Summary

Reaching the required strength and toughness parameters in combination with best flatness of the sheets requires strict compliance with the pre-set rolling and cooling conditions over the entire strip width. Plant trials have been carried out to study the effect of the cooling conditions and the coiling temperature on mechanical properties, impact toughness and flatness of cut-to-length sheets made of hot-rolled strip of two high-strength low-alloyed steels. The results showed that by applying optimized cooling pattern and low coiling temperatures, high-strength steel sheets with outstanding mechanical properties and good flatness can be produced. By setting appropriate coiling temperatures, sheets meeting the requirements that apply to high-strength steels of different strength classes may be produced using the same steel composition.

References

[1] JMatPro® developed by Sente Software Ltd. http://www.jmatpro.com

[2] X. Wu, Y. Wang, The Development of X120 Line Pipe Steel Hot Rolled Coil, AISTech 2013, Proceedings of the Iron & Steel Technology Conference, May 6 - 9, 2013, Pittsburgh, PA, US, pp. 2165-2173.

[3] H. Briunsma, Shape and Profile Throughout the Strip-Mill Processing Line, EUR 13628 EN (1992).

[4] P. Gevers, H.W. Tamler, Internal Stress and Flatness Evolution after Hot-Strip Mill, EUR 19874 EN (2001)

[5] E. Nikitenko, B.C. Gris, A Mechanism of Post-rolling Deterioration in Hot Band Flatness during Coiling, AISTech 2009, Proceedings of the Iron & Steel Technology Conference, May 4 - 7, 2009, St. Louis, MO, US, pp. 107-111.

[6] J. Sinha, Effects of Surface Roughness, Oxidation Level, and Liquid Subcooling on the Minimum Film Boiling Temperature, Experimental Heat Transfer: A Journal of Thermal Energy Generation, Transport, Storage, and Conversion, 16 (2003) 1, 45-60.

[7] S. Kraemer, A. Sprock, Efficient Strip Cooling to Meet the Requirements of Advanced Steel Grades, Millennium Steel 2014, pp. 105-109.