Influence of Production Factors on Mechanical Properties of Ti-Bearing Steels

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The possibilities of using titanium-alloyed grades for the production of high-strength, low-alloy steels are widely described in scientific articles. However, the practical usage is difficult, since many production factors significantly influence the strengthening mechanism and structure formation of titanium-alloyed grades. This paper describes the influence of various technological factors on the properties of titanium-alloyed steels produced by the Compact Strip Production process.

While the possibilities of using titanium alloyed grades for the production of high-strength, low-alloy (HSLA) steels are widely described in scientific articles, the practical usage is difficult since many production factors significantly influence the strengthening mechanism and structure formation of titanium-alloyed grades. This paper describes the influence of various technological factors on the properties of titanium-bearing steels produced by the Compact Strip Production (CSP) process.

Steel produced by thin-slab rolling (TSR) technology or CSP has been on the market for more than 30 years. Despite the fact that these technologies were originally developed for the mass production of steel for non-critical applications, continuous process and equipment improvements combined with proper application of metallurgical knowledge make it possible to compete on an equal footing with traditional strategies for the production of HSLA steels. Actually, some features of the CSP technology can significantly improve the efficiency of the process. The greatest interest now is the technology of production of high-strength Grades 80/100. The use of titanium microalloying can significantly increase the strength characteristics of the material without a significant increase in the alloying cost. In addition, unlike traditional niobium microalloying, this strategy does not promote precipitation during hot rolling, which helps to reduce the load on the mill stands.

Discussion

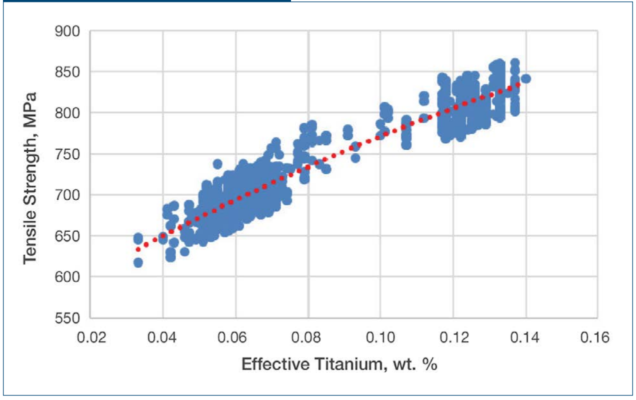
The first thing worth concentrating on during production of steel with Ti is the metallurgical processes in the meltshop, especially secondary metallurgy. It is critical to control the levels of dissolved nitrogen (N) and oxygen (O) in the melt. The stoichiometric ratio of Ti to N is well known – 3.42. However, looking at Ellingham for ladle metallurgy, it is likely that titanium nitride (TiN) will form along with titanium sulfide (TiS) at that process unless it tied up with something else previously. Eq. 1 is used to take this into account, where the atomic mass of [Ti] is 47.88 ~48; [N] is 14.01 ~14; [S] is 32.06 ~32. This makes it possible to calculate the effective content of Ti in steel and further evaluate its effect on mechanical properties (Fig. 1).

$$Ti_{eff} = (Ti\%) - \left(\frac{48}{14} * N\%\right) - \left(\frac{48}{32} * S\%\right)$$

(Eq. 1)

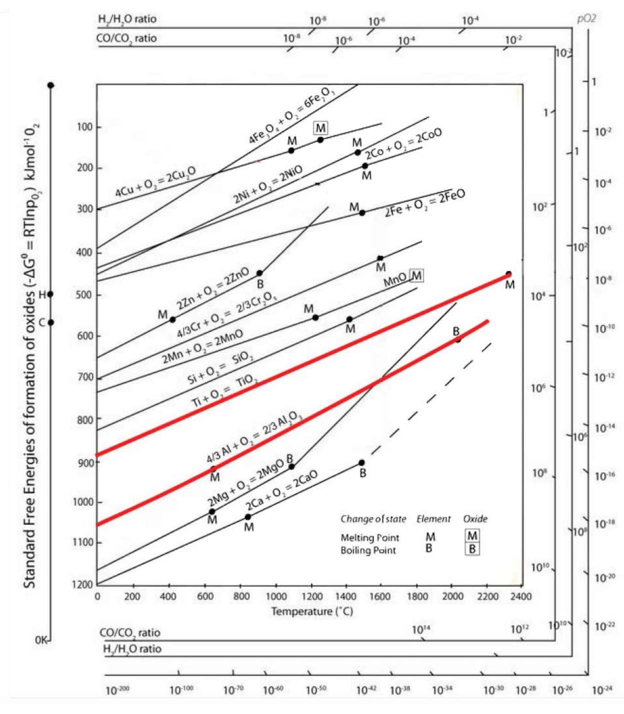
The effective titanium from Eq. 1 was derived with the assumption

Figure 1



Relationship between effective titanium and mechanical properties.

Figure 2



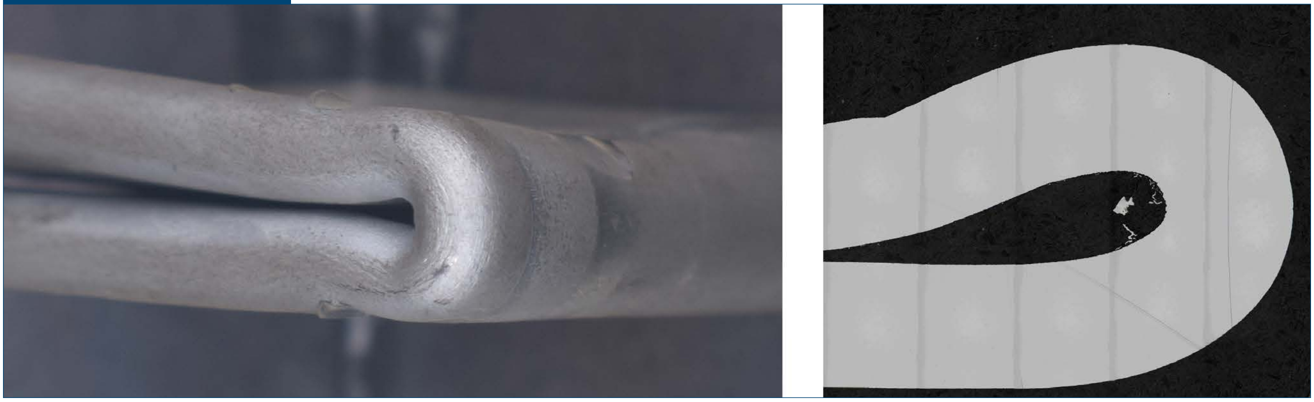
Ellingham diagram, oxide formation of Ti and Al.[3]

that Ti will tie up available nitrogen (N) and sulfur (S) during the secondary ladle metallurgy process before it precipitates as TiC in coil form. Calculating the remaining Ti that can precipitate later in the steelmaking process can help reduce mechanical property variation by providing a more consistent amount of TiC. The effective titanium equation removes the amount of TiN and TiS that could form during the secondary ladle metallurgy process. The atomic mass of Ti is 47.88 (~48), N is 14.01 (~14) and S 32.06 (~32). Removing the appropriate TiN and TiS mass ratios from the total Ti addition determines the remaining titanium or effective titanium.

However, it must not be forgotten that Ti interacts very actively with oxygen, which leads to the formation of TiO, Ti_2O_3 and TiO_2.[1,2] Ti oxides potentially could become a nucleation center for acicular ferrite. However, this interaction significantly reduces the strength and ductility of steel when subjected to aspiration of air during secondary metallurgy process. To minimize the effect of these conditions, it is proposed to apply additional treatment with aluminum before Ti additions (Fig. 2). Such treatment allows minimizing the formation of Ti-O inclusions by killing steel with additional Al, which contributes to the improvement of ductility, especially for steel strip ranging from 2.5 to 3.0 mm thickness (Fig. 3).

Following secondary metallurgy, the next step in steel production at a CSP is the continuous production of cast slabs. The classical process path at integrated mills includes cooling down to ambient

Figure 3



Examples of 1T and 2T bend tests of Grade 100 coil 3 mm thick.

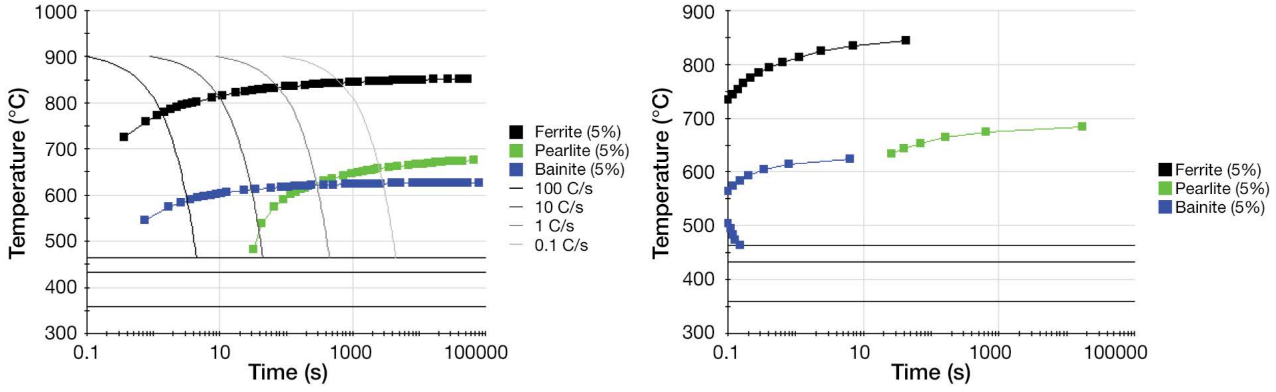
temperatures, enabling the assessment of slab surface quality. However, this practice leads to the formation of a large number of titanium nitrides in accordance with the stoichiometric ratio. On the contrary, under CSP conditions, the temperature of the steel never drops below the Ar3 temperature before hot rolling; therefore, the release of titanium nitrides is delayed, which leads to increased efficiency of Ti microalloying compared to integrated mills.

An experiment was conducted to assess the dependence of slab temperature on the mechanical properties of the final product (Fig. 4). Comparing the obtained results with the known data on the evaluation of effective Ti (Fig. 1), it can be noted that increasing the slab temperature by 100°F (≈55°C) is equal to an increase in effective Ti in a solid solution by 0.020–0.025%. In addition, the data shows the accelerated decline in strength properties with an approach to the temperature of transformation of austenite to ferrite.

Thus, the control of temperature and casting parameters becomes a critical factor in determining the consistency and stability of the mechanical properties of steels alloyed with titanium.

As noted, another important advantage of using Ti as the main microalloying component compared to niobium (Nb) is the fact that the titanium carbides

Figure 5



Grain size: 13 ASTM Austenitization: 910°C

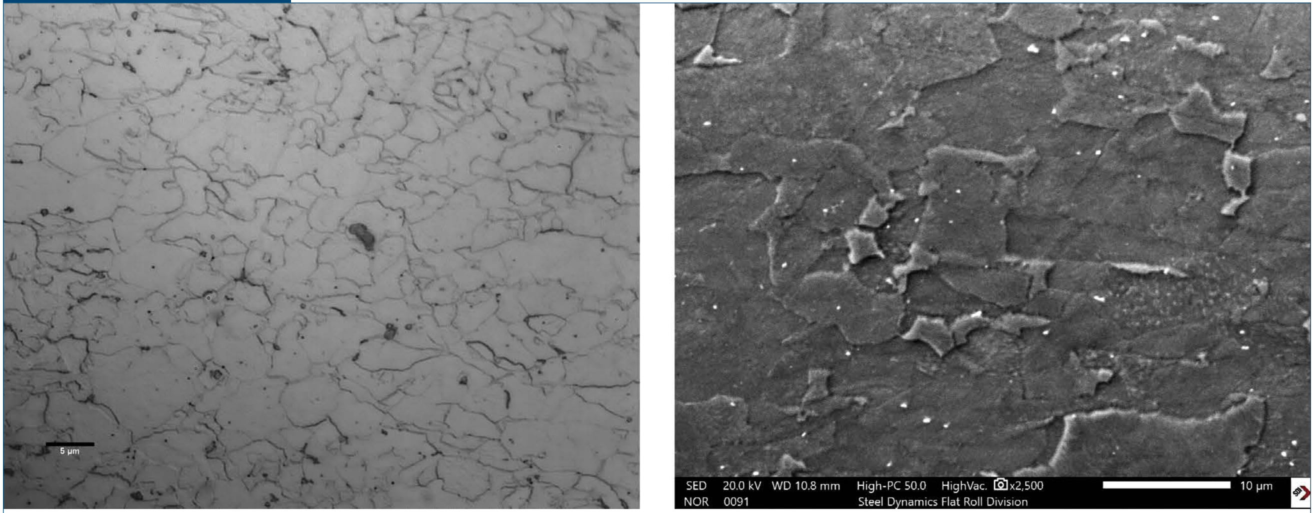
(a)

Grain size: 13 ASTM Austenitization: 910°C

(b)

Continuous cooling transformation (CCT) (a) and time-temperature-transformation (TTT) (b) diagram of the low-C high-strength, low-alloy (HSLA) (Mn-Si-Cr-Mo) steel with Ti microalloying, austenitized at 910°C calculated using the JMatPro software.

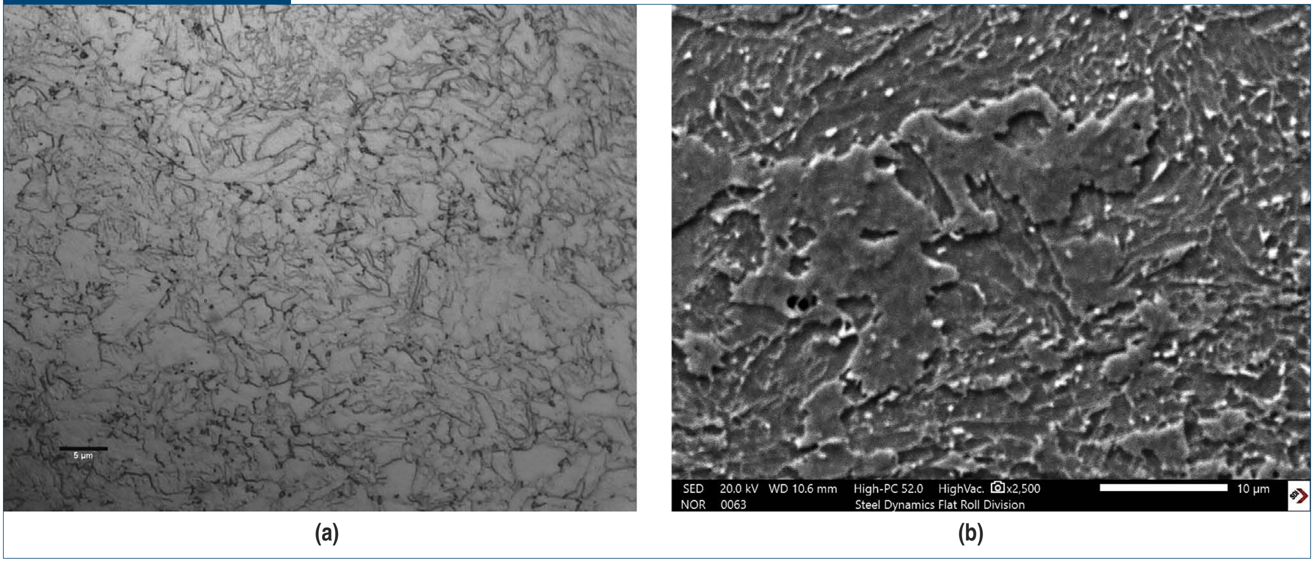
Figure 6



(a) **(b)**

Microstructure of Ti-microalloyed HSLA steel after hot rolling (a) and accelerated cooling to 650°C (b) — polygonal ferrite and granular bainite.

Figure 7



Microstructure of Ti-microalloyed HSLA steel after hot rolling (a) and accelerated cooling to 450°C (b) — upper/lower/granular bainite.

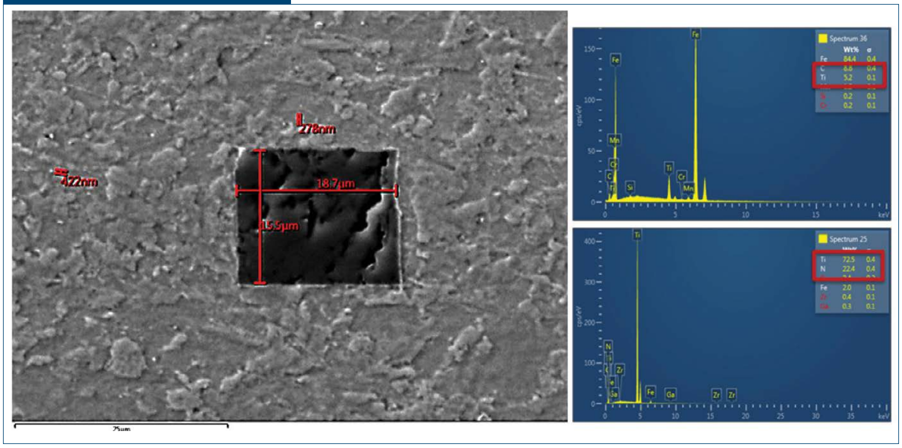
precipitate at temperatures significantly lower than hot rolling temperatures. This enables the production of HSLA steels such as Grade 80/100 for thicknesses as low as 2.5–3.0 mm at the hot rolling mill without significant overloads.

The greatest effect at this stage of production is achieved by controlling the transformation of austenite during accelerated cooling. Continuous cooling transformation (CCT) and time-temperature-transformation (TTT) diagrams for given chemical combinations was calculated by using JMatPro software (Fig. 5). The preferred microstructure is dependent on the desired set of mechanical properties, for example, a combination of high strength and ductility for ultrathin Grade 80/100 can be obtained by fine ferrite microstructure (Fig. 6), but in order to increase toughness it is important to form a bainitic microstructure (Fig. 7).

By reducing the intensity of cooling and making it uniform for the entire length of the runout table, mechanical properties become more stable and microstructures consisting of 90–95% ferrite are obtained. This has a positive effect on the ductility of steel and allows for an increase in elongation of 3–4% for the most critical thicknesses of 2.5–3.0 mm. As already noted in the literature[4,5] one of the most interesting and noteworthy processes occurring in the steels microalloyed by Ti is the precipitation of dispersed titanium carbides during cooling after hot rolling in the mill (Fig. 8).

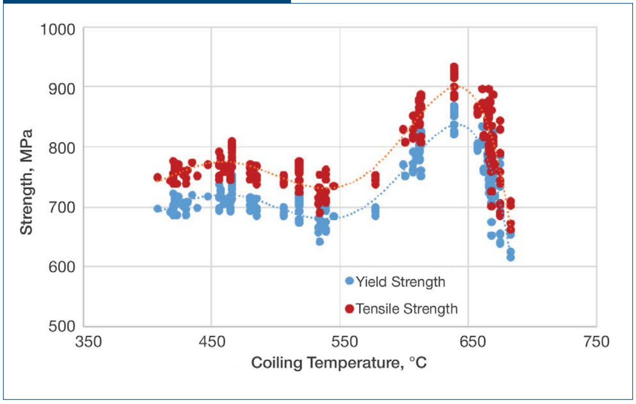
Technical papers usually describe effects of TiC based on laboratory-scale data;[4–6] the experiments with production equipment confirmed described strengthening effects and showed the ability of CSP mills to control mechanical properties of Ti microalloyed steels by utilizing its accelerated cooling capacity. The relationships between the strength properties and the temperature of the cooling end is shown in Fig. 9. As can be noted, the classic approach "Lower Coiling → Higher Strength" does not hold true with Ti microalloyed

Figure 8



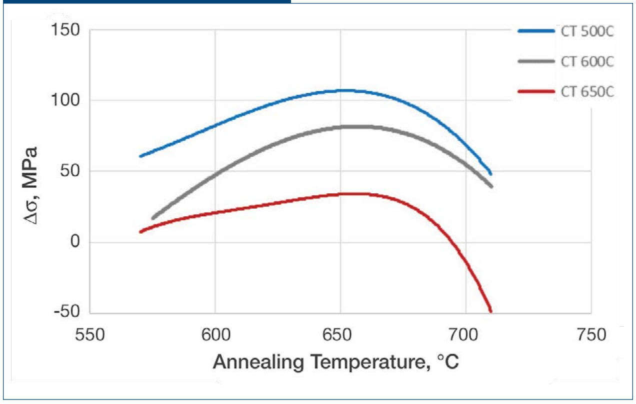
TiN and TiC with in the ferrite matrix.

Figure 9



Influence of coiling temperature on behavior of mechanical properties.

Figure 10



Mechanical properties improvements after annealing.

steels. Moreover, as the coiling temperature rising, the maxima for strength was able to be determined, which is in line with literature data. However, after reaching 670–710°C, a catastrophic drop in strength occurs. This is most likely due to the excessive increase in the size of carbides to 300–500 nm (clearly distinguishable using optical microscopy magnified at 1,000X) and the loss of coherence within the ferrite matrix (Fig. 8). Microstructure analysis showed that lower coiling temperature promotes more complex bainitic structures, including lower and upper bainite (Fig. 7). Formation of hard phases would explain the slight yield/tensile bump around 450°C (Fig. 9).

In addition, the industrial experiments also confirm the possibility of significantly improving the strength characteristics through subsequent heat treatment.[6] Subsequent heat treatment enhances additional Ti precipitation and it appeared that bainitic structures which formed at the lower coiling temperatures promote much higher precipitation input.

As noted by the authors, the effect of additional precipitation of titanium carbides can reach 100–150 MPa, depending on the amount of effective titanium in a solid solution on that stage of production (Fig. 10). No significant microstructural changes, in terms of grain size or phase transformation, are observed after heat treatment.

Conclusions

The use of titanium microalloying for the production of HSLA Grades 80/100 seems to be the most promising for the CSP route, compared to a Nb or vanadium microalloying strategy. The advantage is from not only a cost-effective perspective, but is also based on complex mechanical properties achieved: increased strength combined with high ductility on ultrathin material (2.5–3.0 mm).

The greatest efficiency from Ti microalloying can be obtained by preserving most of it in solid solution up to post-rolling transformation from austenite to ferrite. The titanium carbides that precipitate during cooling or during subsequent heat treatment can increase strength by 100–150 MPa without introducing a negative effect on the ductility of steel. No significant microstructural changes are observed in terms of grain size or phase transformation.

Technological methods presented in this article allow for stabilizing the mechanical properties of steel and improving its overall quality.

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