Processing of niobium microalloyed high-strength steel on a thin-slab plant

The use of thin-slab casting and direct hot rolling is well-suited to the production of low-carbon high-strength linepipe grades. The slabs have excellent surface quality and the high strength, ductility and toughness of the hot strip rely on a very fine-grained microstructure attained by niobium microalloying, high total rolling reduction, low finish rolling temperature and rapid laminar cooling.

Key technical and economic drivers in the steel industry are the need for better weldability and reduced weight via use of higher strength steels, better toughness, particularly at sub-zero temperatures in structural steels, as well as better cold formability and surface quality, especially for the automotive industry.

The use of thin-slab casting followed by direct rolling is well-placed for the production of low-carbon niobium microalloyed steels. In this process thin slabs of between 52 and 90mm thickness are cast and directly hot rolled to hot strip between 1 and 12mm thick.

Figure 1 gives a schematic view of a typical plant layout. On plant start up after commissioning, a basic product range comprising non-microalloyed steel grades for use as general structural steel and mild unalloyed steel for cold rolling is often produced (see Table 1). After a short run-up phase, however, thin slab producers often turn to the production of higher value-added steel grades.

### Table 1

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>C max Mn max YS [MPa] UTS [MPa] El min [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild unalloyed steel for cold rolling</td>
<td>0.12 0.60 170–340 ≤ 440 28</td>
</tr>
<tr>
<td>DD12</td>
<td>0.10 0.42 170–320 ≤ 420 30</td>
</tr>
<tr>
<td>DD13</td>
<td>0.08 0.35 170–310 ≤ 400 33</td>
</tr>
<tr>
<td>General structural steel</td>
<td>0.15 0.90 185 290–510 18</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>C max Mn max YS [MPa] UTS [MPa] El min [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>X52 trial</td>
<td>0.05 1.2 0.006 0.002</td>
</tr>
<tr>
<td>X52</td>
<td>0.28 1.25 0.03 0.03</td>
</tr>
<tr>
<td>X60</td>
<td>0.26 1.35 0.03 0.03</td>
</tr>
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### Metallurgical Aspects of Microalloyed Steel Production

Table 2 shows the chemical composition of grades X52 and X60 according to the API 5L specification. Lowering the carbon content will improve toughness, decrease the transition temperature and enhance surface quality and welding behaviour. The carbon equivalent CE (IIW) is typically 0.24, fulfilling the requirements for safe welding without preheating. Low carbon content also has a positive influence on segregation behaviour.

The typical impact of different microalloying elements on strength and toughness properties is given in Figure 2. Grain refinement is the only mechanism that simultaneously increases strength, toughness and ductility, making niobium the most effective element, even if added in small quantities.
These combined effects lead to a particularly fine-grained transformation structure. Niobium also contributes to precipitation hardening. In order to make optimum use of its metallurgical potential niobium has to remain in solid solution while the slab moves through both the casting machine and the tunnel furnace.

Figure 3 relates the precipitated fraction of initial niobium content to the available nitrogen content after holding at various temperatures [3,4,5].

The figure shows that niobium precipitation is completely suppressed above around 1050°C by lowering the nitrogen content to about 53 ppm, even when thermal equilibrium is reached. Thus niobium stays in solid solution, promoting grain refinement during thermomechanical hot rolling. For this same reason, it is necessary to avoid any supercooling of the strand below this temperature (including the edges of the thin slab), in the secondary cooling section of the casting machine before entering the soaking furnace [6].

When producing API grade steel the tramp element concentration, in particular that of segregating elements such as sulphur and phosphorus, is reduced to the low levels illustrated in Table 2. Low nitrogen content positively affects ageing stability and toughness in the heat-affected zone of the weld seam, as well as resistance to intercrystalline stress-corrosion cracking.

After deoxidation, FeNb is added gradually in batches to the ladle, ensuring that the slag does not trap the FeNb lumps, while soft bubbling with argon gas enhances the homogenisation and cleanliness of the melt. This way, maximum recovery of niobium is achieved.

An important preparatory stage for thin-slab casting is calcium treatment to improve the castability of the melt, prevent nozzle clogging and to raise toughness by inclusion control.

The best mechanical properties are attained when the soaking furnace is operated at temperatures at or above 1,100°C, with the residence time in the furnace being about 20 minutes. This enables hot rolling to start at a temperature that is high enough to ensure complete recrystallisation in the first stand of the mill.

Direct rolling starts with the entry of the as-cast thin slab into the first stand of the finishing mill without any previous roughing pass. To obtain optimum strength and toughness, hot rolling has to compact the dendritic as-cast microstructure and achieve a fine-grained microstructure.

This affords a two-stage rolling strategy. Rolling starts above the recrystallisation stop temperature where temperature and deformation in the first stand should be as high as possible to remove the initial as-cast microstructure by complete recrystallisation [7,8].

Finish rolling is completed below the austenite non-recrystallisation temperature where the austenite grains remain flattened. The final ferrite grain size depends on the size of the final austenitic grains, the accumulated strain in the non-recrystallisation temperature region and the cooling rate in the laminar cooling section. Maximum grain refinement is achieved by applying an early fast-cooling mode in the laminar cooling section.

These solid-state reactions, and thus the final ferrite grain size, are closely linked to the macroscopic deformation of the slab during hot rolling. API pipe steel grades require both high strength and toughness. Figure 4 illustrates the relationship between toughness, given in terms of the ductile to brittle fracture transition temperature (FATT) and the total thickness reduction during hot rolling of microalloyed steel. It can be seen from this diagram that in the case of the X70 grade steel a transition temperature of ~50°C can only be achieved when the slab thickness is ≥70mm for a 10mm thick hot strip.
An example of an X52 is given in the literature [99]. The chemical composition used is shown in Table 2. The steel was produced from 90% direct-reduced iron (DRI), 10% scrap. The use of a high percentage of DRI combined with foaming slag technology results in very low N and S contents. The slab dimensions were 52mm thick by 1,500mm wide.

In the course of this trial 6mm and 10mm thick strip was produced and examples of the rolling parameters of two coils are given in Table 3. In spite of high pass reductions, particularly in the first stands, no overloads in rolling forces or torque were observed. All strips were cooled in early fast-cooling mode in the laminar cooling section and were coiled at 575°C.

The average ferrite grain diameters were 4.6 microns (ASTM 12.6) and 2.7 microns (ASTM 14.1) for the 10mm and 6mm strip, respectively. Transmission electron microscopy (TEM) revealed homogeneously distributed Nb precipitates having diameters between 2 and 5nm, contributing to this fine-grained ferritic microstructure.

The effect of the finish rolling temperature on the yield and tensile strength of the 10mm strip is given in Figure 5. Lowering the finishing temperature to below a critical temperature of about 880°C results in an increase of both yield and tensile strength because of the greater work-hardening of the austenite and the more intensive microstructure refinement during \( \alpha \) and \( \gamma \) transformation.

To get stable process results and further improved toughness by grain growth prevention in the lower austenite region, the finish rolling temperature may need to be below 870°C.

Table 4 summarises the mechanical properties of the 6mm and 10mm thick X52 hot strip. Due to the pronounced texture after thermomechanical rolling, transverse samples show slightly higher strength compared to longitudinal samples. Both, strength and elongation at fracture reliably meet the API specification. Strength and elongation of the 6mm strip is higher than the 10mm due to the greater amount of deformation and hence finer microstructure.

The excellent toughness properties are further underlined by the notch-bar impact results. Figure 6 shows that for both longitudinal and transverse samples the upper shelf level is about 170–180J. The transition temperature is around -50°C and even at -100°C impact energy is still 60–80J.

**FUTURE DEVELOPMENTS**

Table 4 indicates that API X52 and X65 strength can be achieved with 10mm and 6mm thick hot strip, respectively from direct rolled 52mm thin slab. It has been reported that some plants have already successfully produced X70 and that current development is for X80. The limiting factor will be toughness as it is impaired by the strength increase. To compensate, the total deformation of the slab will have to increase in order to reach the minimum reduction as illustrated in Figure 4. Accordingly, higher strength API grade steel will be limited to a strip thickness...
range that is dependent on the thickness of the thin slab. Improving liquid metallurgy by reducing impurities and tramp elements such as sulphur, lowering the carbon content, as well as further efforts towards producing an even more homogeneous fine grain structure may lower the minimum reduction for X70 grade steel to about 80%. This would enable production of, for instance, X70 as 10mm strip from a 52mm thin slab.

**SUMMARY**

The use of low-carbon, Nb-microalloyed steel is well adapted for the production of API grade high strength hot strip on a thin slab direct rolling plant. The cast slabs have excellent surface quality, and the high strength, ductility and toughness of the final hot strip rely on a very fine-grained microstructure that has been attained by niobium microalloying and adapted processing parameters. The best results are obtained after high total rolling reduction, low finish rolling temperature and fast laminar cooling.

Strength and toughness are linked with reduction ratio, and data indicates 10mm thick X70 is producible from 52mm slab. 

Christian Klinkenberg, Niobium Products Company GmbH, Düsseldorf, Germany

**CONTACT:** ck@niobium.de

**REFERENCES**