API grades toughness analysis for thermo-mechanical rolling in QSP Thin Slab Rolling plants

M. Guagnelli, P. Bobig

A methodology for estimating the potentiality of the thin slab two step thermo-mechanical rolling technology for the API 5L grades production is described in this paper. The requirements on Ductile to Brittle Transition Temperature (DBTT) are considered the most important limiting factor for API 5L strip grades produced by Thin Slab technology because of the difficulties in achieving a refined and homogeneous microstructure. The results obtained by Danieli QSP layout, which are -60°C DBTT for X70M - 12.7 mm thick strips in OMK Vyksa mini-mill, are very promising. The limitation to thicknesses up to 12.7 mm is due to the product mix defined by the customer and not a limitation of the QSP layout. The relaxation in the requirement on DBTT is in fact potentially convertible in higher strip thickness and the quantification of such a conversion is the first modeling of the proposed approach. The limitations in the refinement achievable by thin slab rolling is considered in a second modeling which quantifies the effect of finishing rolling reductions on the Effective Grain Size of the final microstructure. The proposed methodology allows in particular defining the limiting thicknesses producible by a given QSP layout for each API 5L grade. It can be used as well for defining the slab size to be chosen for a given product mix.

Keywords: Thin Slab Rolling, API 5L Grades, DBTT, Thermo-Mechanical Rolling, Effective Grain Size

INTRODUCTION

The production of API 5L grades is of great interest because of the increasing demand of gas consumption and the forecast of new lines to be installed in the next future [1, 2, 3]. The economy of gas transportation via pipeline asks for high operating pressures and large pipe diameters. This in turns is reflected on the heavy thickness and/or high grade of the required pipes. A good toughness, both in terms of high Charpy V energy and low Ductile Brittle Transition Temperature, and an excellent weldability complete the requirements for the steels to be used for pipeline applications. API 5L grades production is, as a consequence, a promising as well as challenging field in the market development of steel strip producers.

Thin slab technology, on the other side, allows a reduction

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in energy consumption, with consequent benefits in terms of production costs and pollution reductions, and permits also a reduction in investment costs because of the compact layout. These features make the thin slab technology the preferred choice for new mill construction, but the limitation in the products which can be produced have to be considered because of the market requirements. Such requirements push the design of new mini-mills towards the production of high quality coils for demanding application. It is natural that high grade, heavy walled pipeline steels are more and more considered in the product mix of new plants.

It is therefore of great interest defining the potentiality of the present thin slab technology for the production of API 5L grades in term of both the mechanical properties and thickness of the strips. In the present paper an approach is described for defining such potentiality for the Danieli Minimill technology.

QSP MINIMILL LAYOUT

According to the Danieli Minimill concept, the so called Quality Strip Production (QSP) layouts, the whole hot

Fig. 1 – Typical QSP hot strip mill configuration.

Fig. 1 – Configurazione tipica di un impianto di laminazione nastri a caldo da bramma sottile QSP.
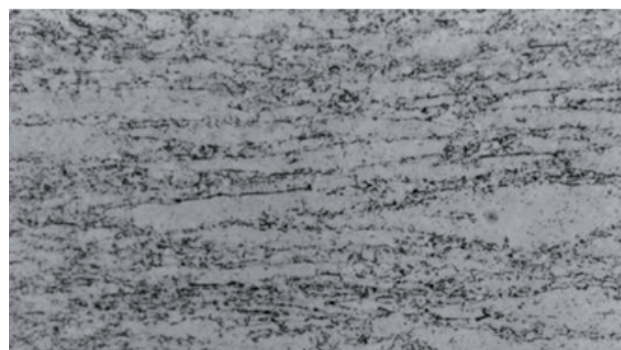

Fig. 2 – Examples of the microstructure evolution during hot rolling: a) recrystallized grains after roughing; b) pancaked deformed grains after finishing.

Fig. 2 – Esempi di evoluzione microstrutturale nella laminazione a caldo: a) grani ricristallizzati dopo sbozzatura; b) grani deformati (pancake) dopo finitura.

rolling process is divided in two differentiate steps (see Fig. 1). This concept corresponds to the two step thermo-mechanical rolling route which has been adapted to the typical thin slab conditions.

The two step thermo-mechanical rolling route has been successfully developed in plate mill rolling, by means of which have been realized linepipe up to X100M - 20 mm, X80M - 25 mm and X70M - 40 mm with a DBTT lower than -20 °C. This classical route for plate mills can be described as follow:

• In the first step the microstructure at the exit of the re-heating furnace is refined by subsequent pass rolling at high temperature: in the time between subsequent passes the microstructure, which has been deformed in the first passes, recrystallizes; by adjusting the alloying content (in particular Nb, Ti, C and N play the most relevant role) and the pass temperatures, the recrystallization process brings to a refinement (typical values of austenite grain sizes entering the finishing mill are in the range 20÷30 μm).

• In the second step the microstructure is refined by strain accumulation: when the temperature is lower than a typical value called No Recrystallization Temperature (TNR), the recrystallization process is retarded or fully stopped and pass after pass the strain is accumulated and the austenite is elongated and flattened (this feature is called pancake and the strain accumulation is referred also as "pancaking"); typical total reductions in finishing are in the range of 67÷75% and the pancaked thickness can reach values in the range 5÷7 μm (see Fig. 2);

• After the hot rolling the plate is artificially cooled at temperature in the range 650÷350 °C and the microstructure is transformed from austenite to the final type which, depending on the cooling rate, the finish cooling
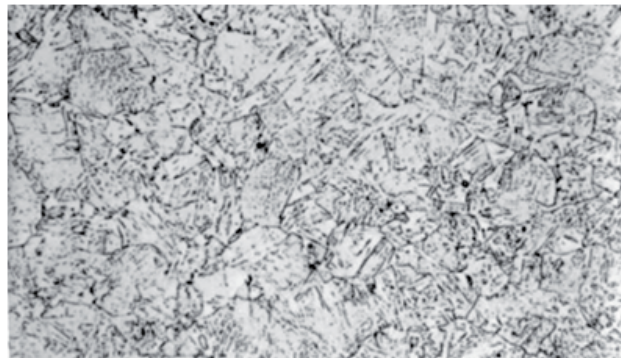
temperature and the steel composition, can be a mixture of polygonal ferrite (the classical form of ferrite in structural steels) acicular ferrite, bainite and also small amounts of martensite and retained austenite.

The Thin Slab Mill differs from Plate Mill and conventional Hot Strip Mill because of:

a. Lower slab thickness and consequently limited reduction available for a given final thickness.

b. Direct rolling after casting and consequently the coarser microstructure entering the mill.

c. Higher reduction that can be realized, particularly in the roughing step.

The Thin Slab Two Step Thermo-Mechanical Rolling can be described as follows (see Fig. 3):

1. In the first step the coarse microstructure obtained after the casting and the tunnel furnace is refined by two heavy roughing reduction passes at high temperature for a total reduction of about 50%.

2. After an artificial cooling to a proper temperature below TNR, the finishing stands accumulate deformations at each pass and a pancaked microstructure is achieved.

3. After the hot rolling, the strip is cooled in the ROT and coiled as in the Conventional Hot Strip Mills.
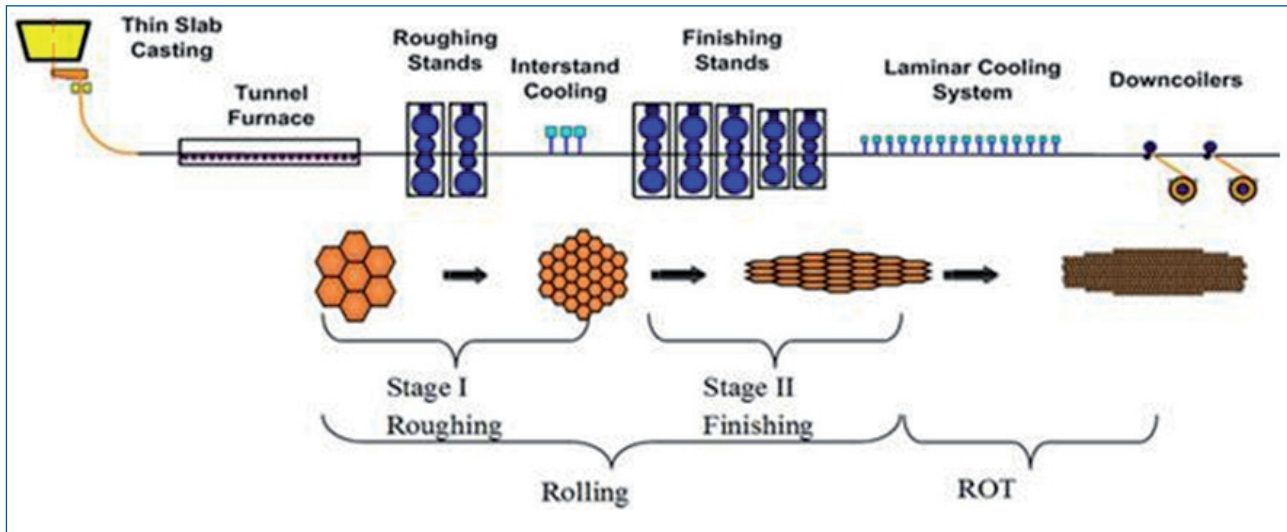
Fig. 3 – Schematic representation of the Danieli Minimill concept (QSP layout).

Fig. 3 – Rappresentazione schematica del concetto Danieli d'impianto di laminazione a caldo in bramma sottile (layout QSP).

MODELING THE DBTT IN THIN SLAB ROLLING QSP LAYOUTS

In the presented approach, the steel grade is defined by two main parameters which describe the strength and the toughness. The strength is represented by the yield strength, measured as the tensile stress under load at a total elongation of 0.5% (Rt0.5) while toughness is represented by the Ductile to Brittle Transition Temperature (DBTT), measured by the temperature at which the Shear Area of a specimen broken by a Drop Weight Tear Test (DWTT) is 85% (85%SATT – Transition Temperature at 85% Shear Area).
The API 5L standard states that the yield strength has to be measured and verified that it is inside a range specified as a function of the grade, the minimum value being reported in the grade name. Considering the toughness, the 85%SATT is not directly measured, but a DWTT has to be performed at a specified temperature (0°C or lower depending on the temperature at which the pipeline has to be installed and used) and the corresponding Shear Area should be at least 85%. This implies that in this case the 85%SATT of the pipe is lower than the specified test temperature.
The critical properties which limits the feasibility of API 5L grades is the toughness and in particular the DBTT. It is in fact possible to increase the yield strength by a number of ways, but for the toughness the grain refinement is the only way. The limitation of grain refinement in thin slab product is the consequence of the limitation in the hot rolling, in particular when the strip thickness increases.
The DBTT of thin slab strips produced by QSP layout has been modeled by a number of assumptions. Firstly the DBTT has been modeled in general as a function of the effective grain size, and then the effective grain size has been modeled for Thin Slab QSP as a function of a mini-

mum number of parameters. The obtained final modeling has been verified based on few industrial data available. Such model has been finally used to define the potentiality of QSP layout for producing API 5L steel strips.

MODELING THE DBTT AS A FUNCTION OF THE EFFECTIVE GRAIN SIZE

DBTT can be measured in several ways. In pipeline it is defined as 85%SATT on DWTT; DBTT definitions based on Charpy V test are ITT27J (Impact Transition Temperature for 27J), ITT40J (Impact Transition Temperature for 40J), and 50%FATT (50% Fracture Appearance Transition Temperature).
Charpy V test data have been extensively used to develop relationships between DBTT and microstructure [4, 5]. Even if no relationship has been developed for 85%SATT, it is assumed that the dependence of DBTT on the microstructure is independent on the particular definition of DBTT itself, provided that the effect of the specimen geometry has been taken into account.
The effect of the specimen geometry is mainly due to the specimen thickness. This effect is typical for fracture mechanics and is due to the fact that thicker specimens tend to promote a higher degree of triaxiality near the crack tip; the triaxiality increases the flow stress and it is consequently easier to reach the cleavage stress [6].
The effect of the specimen thickness is taken into account by an equation developed for describing the shift in DBTT for subsized (i.e. with thickness less than 10 mm standard size) Charpy V specimen [7]:

$$\Delta T = 51.4 \ln \left[2 \left(\frac{th}{10} \right)^{0.25} - 1 \right]. \tag{1}$$

Since we are interested in applying such equation for thickness higher than 10 mm the equation has been verified by comparing the temperature reduction given in the API RP 5L3 for testing pipes with wall thickness higher than 19 mm by means of specimen with reduced thickness with the estimation of same Temperature reduction given by equation (1):

$$Temperature\_reduction = 51.4 \ln\left[2\left(\frac{th}{10}\right)^{0.25} - 1\right] - 51.4 \ln\left[2\left(\frac{19}{10}\right)^{0.25} - 1\right]. \quad (2)$$

The comparison shown in Fig. 4 attests that the equation (2) gives acceptable results.

By means of the equation (1), the DBTT measured with DWTT can be related to the DBTT measured by Charpy V test:

$$DBTT_{DWTT} = DBTT_{CharpyV} + 51.4 \ln\left[2\left(\frac{th_{strip}}{10}\right)^{0.25} - 1\right]. \quad (3)$$

The DBTT measured by Charpy V shows a clear dependence by the grain size in ferritic steels. It has been recently shown that the same relationship can be found also in more complex steel microstructures like bainite and tempered martensite, once the concept of grain size has been conveniently redefined as an Effective Grain Size (EGS) which for ferrite is the grain size (FGS) while for bainite and tempered martensite is the packet size (PS) [8]. Such a relationship appears clearly when the DBTT values are depurated from the contribution of the Yield Strength.

In order to quantify the DBTT, the classical Gladman–Pickering equation [5] has been simplified (free nitrogen contribution is not considered, pearlite contribution is transformed in an equivalent carbon contribution) and integrated with the contribution of the Yield strength:

$$DBTT_{CharpyV} = 19 + 44[Si] + 275[C] - \frac{11.5}{\sqrt{EGS}} + k_y(YS - YS_{ref}). \quad (4)$$

The DBTT measured by DWTT can be consequently defined by rearranging the previous equations:

$$TT_{DWTT} = TT_0 + 44[Si] + 275[C] - \frac{11.5}{\sqrt{EGS}} + k_y YS + 51.4 \ln\left[2\left(\frac{th_{strip}}{10}\right)^{0.25} - 1\right]. \quad (5)$$

The term TT_0 is a parameter to be adjusted by fitting with experimental data.

MODELING OF THE EFFECTIVE GRAIN SIZE IN QSP LAYOUTS

The effective grain size of the final microstructure depends on a number of parameters. In the proposed approach we have:
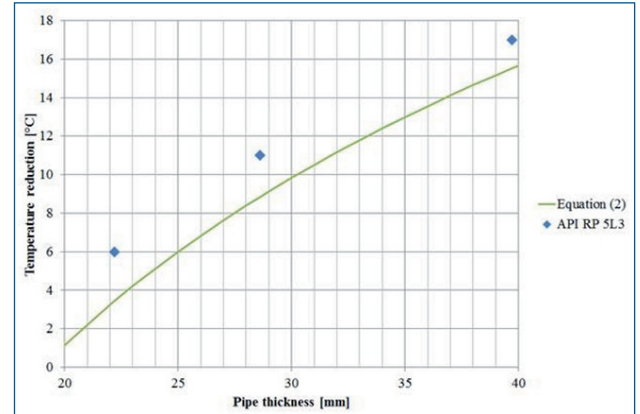• the austenite grain size entering the finishing stage (AGS);

Fig. 4 – Temperature reduction given in the API RP 5L3 for DWT testing pipes with wall thickness higher than 19 mm by means of specimen with reduced thickness.

Fig. 4 – Riduzioni di temperatura indicate dalla API RP 5L3 per la prova DWTT di tubi di spessore superiore a 19 mm per mezzo di provette a spessore ridotto.

• the strain accumulated in the finishing stage (ε_{acc});
• the cooling rate in the ROT (CR);
• the type of microstructure (e.g. ferrite or bainite);

The austenite grain size entering the finishing mill is considered, in this calculation, to be the same independently of the slab thickness. This assumption is justified because of the two heavy reductions in the roughing stage (about 30% each) which allow the fully recrystallization of the austenite; the same reductions in the roughing passes are considered, independently from the slab thickness.

The bar thickness entering the finishing stand is as a consequence a half of the slab thickness and since the finishing is realized below the TNR, the strip accumulates the whole finishing reduction. This means that, for the same strip final thickness, different slab thicknesses give different finishing reduction and strain accumulation and the relationship can be described by:

$$\varepsilon_{acc} = \frac{2}{\sqrt{3}} \ln\left(\frac{T_{bar}}{T_{strip}}\right) = 1.1547 \cdot \ln\left(\frac{0.5 \cdot Th_{slab}}{Th_{strip}}\right). \quad (6)$$

The cooling rate in the ROT can be express as a function of the strip thickness by fitting experimental data:

$$CR = CR_0 \cdot \exp\left(-\alpha \cdot Th_{strip}\right) \quad (7)$$

where CR_0 and α are fitting parameters.

In the case of ferrite the grain size can be described equation (8) [9]:

$$FGS = \left\{4.5 + 3 \cdot CR^{-0.5} + 13.4\left[1 - \exp(-0.015 \cdot AGS)\right]\right\} \cdot \left(1 - 0.5 \cdot \varepsilon_{acc}^{0.47}\right). \quad (8)$$

In the case of bainite the Packet Size (PS) has been expressed as a half of the pancake thickness, which can be calculated by the AGS and accumulated strain in finishing:

$$PS = \frac{1}{2} Th_{pancake} = \frac{1}{2} AGS \cdot \exp\left(-\frac{\varepsilon_{acc}}{1.1547}\right) \quad (9)$$

Such an expression is based on the assumption that bainite grains nucleate at pancake grain boundaries and growth until impingement with other bainite grains occurs.
Buzzichelli and Mascanzoni (as quoted from [10]) determined the bainite packet size in terms of average grain size of the austenite grains; considering the pancake thickness instead of the average grain size we will found an alternative equation:

$$PS = 1.4\left[AGS \cdot \exp\left(-\frac{\varepsilon_{acc}}{1.1547}\right)\right]^{0.55}. \qquad (10)$$

From a numerical comparison of the two equations, the former gives higher values of PS for pancake thickness higher than 10 μm (see Fig. 5) resulting in a more conservative (higher) estimation of DBTT. Equation (9) has been consequently considered for calculating PS.
The EGS is the metallurgical feature which controls the DBTT; since for a ferritic microstructure EGS = FGS, and for bainitic microstructure EGS = PS, in the case of a mixed microstructure it has been assumed to be the average between FGS and PS:

$$EGS = f_F \cdot FGS + f_B \cdot PS \qquad (11)$$

where f_F and f_B are the volume fractions of ferrite and bainite respectively.
Even if in reality volume fractions of the micro-constituents depend on the chemical composition, the austenite grain size, the accumulated strain and the cooling rate, typical values for different steel grades are assumed, as described in the following Table 1.

API 5L Grade	f_F Ferrite Volume Fraction	f_B Bainite Volume Fraction
X60M	1.0	0.0
X70M	0.6	0.4
X80M	0.2	0.8

Table 1 – Reference volume fractions of main micro-constituents for different steel grades.

Tab. 1 – Frazioni volumetriche dei principali micro-costituenti di riferimento per diversi gradi di acciaio.

The final relationship is obtained by using equation (11) for the EGS in equation (5).

COMPARISON WITH EXPERIMENTAL DATA

The developed relationship can be applied to the available rolling data. The results of this calculation are shown below (Fig. 6).
As can be seen in Fig. 6, the experimental values are close to the respective theoretical curves. More data should be needed in order to better validate this approach; in particular care has to be used as Strip Thickness increases
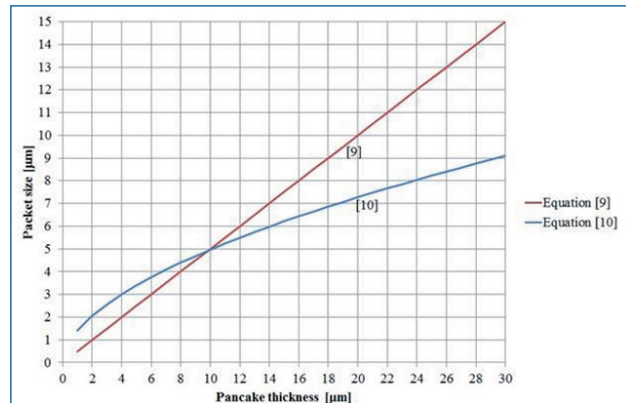

Fig. 5 – Comparison of the equations (9) and (10) for the calculation of the bainitic packet size.

Fig. 5 – Confronto tra le equazioni (9) e (10) per il calcolo della dimensione del pacchetto bainitico.
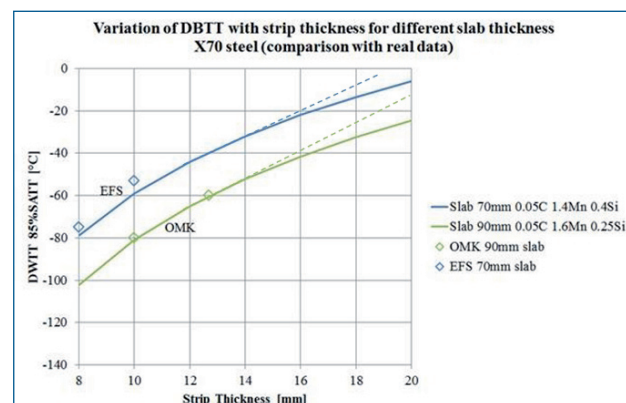

Fig. 6 – DBTT as a function of the Strip Thickness for different Slab Thickness with different chemical composition and comparison with experimental results.

Fig. 6 – DBTT in funzione dello spessore del nastro per diversi spessori di bramma (con diverse composizioni chimiche) e confronto con i dati sperimentali

beyond 13 mm. In the absence of further data the relationship is considered reasonable up to 13 mm and for higher thickness a linear relationships corresponding to the tangent at 13 mm is suggested for more conservative estimation (dashed lines in the picture). In any case it is possible to see that a DBTT of -60°C for a 12.7 mm strip corresponds to a DBTT of -20°C for a strip thickness of about 19 mm starting from the same slab thickness of 90 mm.

ANALYSIS OF THE POTENTIALITY OF THIN SLAB FOR API 5L GRADES PRODUCTION

In the next Fig. 7 three curves are shown for different slab thickness and the same steel grade and a reference chemical composition (the grade is X70 and the chemical composition results from an optimization based on the industrial data).
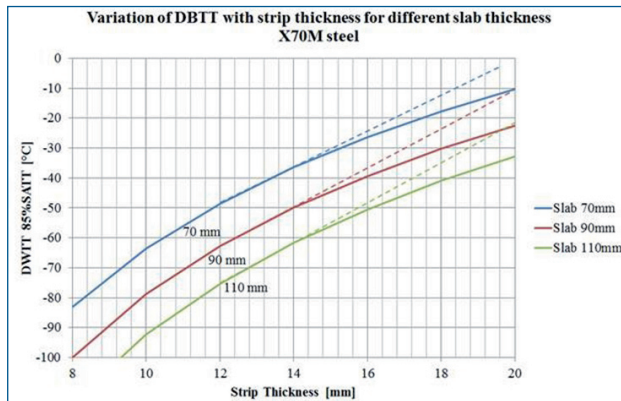
Fig. 7 – DBTT as a function of the Strip Thickness for different Slab Thickness of the same composition

Fig. 7 – DBTT in funzione dello spessore del nastro per diversi spessori di bramma di medesima composizione chimica.
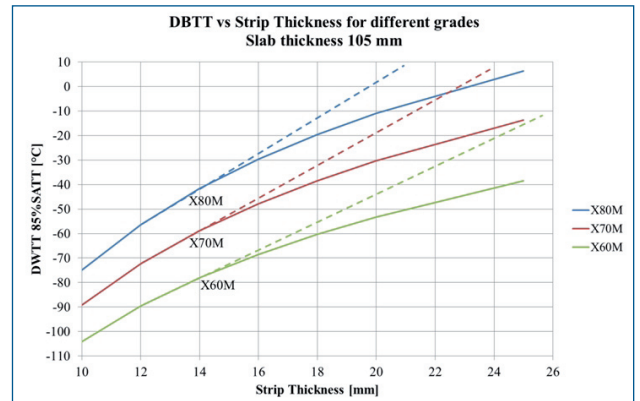

Fig. 8 – DBTT as a function of the strip thickness for different steel grades and a 105 mm slab thickness.

Fig. 8 – DBTT in funzione dello spessore del nastro per diversi gradi di acciaio per una bramma di spessore 105 mm.

From the picture it can be understood and quantified the effect of the Slab Thickness on the DBTT. In particular the theoretical curves have to be interpreted in two ways:

• For a given steel grade, chemical composition, Slab Thickness and Strip Thickness, the curve gives the minimum temperature at which DWTT Shear Area is expected to be higher than 85%: for example, considering a 14 mm Strip Thickness, the expected DBTT is lowered from –36 °C to –50 °C and –62 °C passing from a slab Thickness of 70 mm to 90 mm and 110 mm respectively.

• For a given steel grade, chemical composition, Slab Thickness and DWTT 85%SATT requirement, the curve gives the maximum Strip thickness: for example, considering a requirement for DBTT of –60 °C, the maximum Strip Thickness is increased from about 10.5 mm to about 12.4 mm and 14.2 mm passing a slab Thickness of 70 mm to 90 mm and 110 mm respectively.

Considering the slab thickness of 105 mm, the expected DBTTs as a function of the Strip Thickness are shown in Fig. 8 for the three API grades X60M, X70M and X80M.

Based on such results the QSP with a slab thickness of 105 mm is able to produce API grades up to the thickness summarized in the Table 2.

In order to design the mill configuration based on the product mix defined by the customer, a further development of the model is useful. This is possible, for example, considering the ways by which the strip thickness influences the DBTT:

• affecting the value of the accumulated strain (together with the slab thickness);
• affecting the cooling rate in the ROT;
• directly affecting the DBTT which is sensitive to the specimen thickness.

Among these effects, the effect of the cooling rate is the weakest: even if passing from 10 to 20 mm the CR is reduced from 18 to 9 °C/s, the effect on the DBTT is only 2 °C. The direct effect of the specimen thickness is the second being in the same case about 16 °C while the effect of the strain accumulation is the strongest being about 35 °C.

If only this last effect is taken into account, the two variables Slab Thickness and Strip Thickness can be considered together via their Ratio. The diagram which results from such assumption is shown in Fig. 9; the colored regions around the curves remember the average nature of this graph.
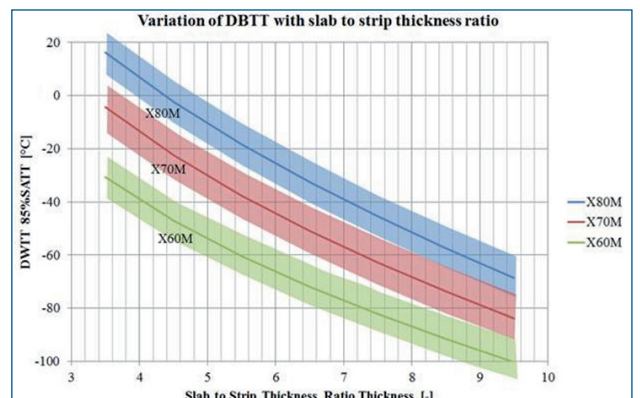
Reference DBTT [°C]	0	–20	–40
API 5L grade	Strip thickness [mm]		
X60	26	24	20
X70	22	19	16
X80	19	16	14

Tab. 2 – Potential application of QSP in terms of strip thickness for different DBTT values for a 105 mm thick slab.

Tab. 2 – Potenziali applicazioni del QSP in termini di spessore nastro massimo producibile da una bramma da 105 mm di spessore per diversi valori di DBTT.

Fig. 9 – DBTT as a function of the Slab to Strip Thickness Ratio for different steel grades

Fig. 9 – DBTT in funzione del rapporto tra spessore bramma e spessore nastro per diversi gradi di acciaio.

As an example of application, let's consider the X80M blue curve in Fig. 9: the production of X80M strips for standard application (DWTT SA ≥ 85% at 0 °C) results possible only for slab to strip thickness ratio higher than 4.4; this means, for a 12 mm strip, a slab thickness higher than 53 mm. In the case of X80M for low temperature applications (e.g. –40 °C DBTT) the ratio between slab and strip thickness should be higher than 7.1, which means a slab thickness higher than 85 mm for the same 12 mm thick strip.

It is anyway to be clearly stated that such a graph represents an average best estimation based on the actually available knowledge and should be used mainly for qualitative analysis of the DBTT which can be obtained in a Thin Slab Mini-mill.

CONCLUSIONS

A model for DBTT has been developed for high grade API 5L strips from Thin Slab QSP mill layouts. The proposed model is based on the assumption that two roughing passes at high temperature with a total reduction of 50% is able to refine and homogenize the as cast microstructure. The finishing passes at low temperature, below the TNR, provide further refinement which can be quantified as the final thickness of the pancaked microstructure. The effective grain size of the final microstructure can be consequently be determined as a function of the pancake thickness, the cooling rate on the ROT and the typology of microstructure. The effective grain size is then used to calculate the DBTT in terms of DWTT 85%SATT.

By means of such a model, the potentiality of QSP technology for API 5L production have been assessed. Based on this assessment, X80 grade strips can be produced up to 19 mm thickness, starting from a slab thickness of 105 mm; X70 and X60 grade can be produced from a 105 mm thick slab up to 22 mm and 26 mm strip thickness, respectively.

It has been also show how it is possible to use this methodology for defining the slab thickness required for producing a given product mix.

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ANALISI DI TENACITÀ DI GRADI API PER LA LAMINAZIONE TERMO-MECCANICA IN IMPIANTI A BRAMMA SOTTILE QSP.

Parole chiave: Bramma sottile - Laminazione termo-meccanica - Linepipe - Transizione Duttile-Fragile

Il presente articolo descrive una metodologia per stimare la potenzialità della laminazione termo-meccanica in due stadi da bramma sottile per la produzione di nastri per tubazioni API. I requisiti sulla temperatura di transizione duttile fragile (DBTT) sono considerati il più importante fattore limitativo per la produzione di nastri per gradi API da bramma sottile; questo a causa delle difficoltà a ottenere una microstruttura fine e omogenea. I risultati ottenuti nel layout QSP Danieli, quale la produzione di nastri di spessore 12.7 mm di grado X70M con DBTT di –60°C nell'impianto OMK sito in Vyksa (Russia), sono molto promettenti. La limitazione allo spessore massimo di 12.7 mm è in questo caso dovuta al mix produttivo definito dal produttore e non una limitazione del layout QSP. Il rilassamento del requisito sulla DBTT è, infatti, potenzialmente convertibile in un aumento di spessore e la quantificazione di tale conversione rappresenta la prima modellazione proposta nel presente approccio. La limitazione all'affinamento microstrutturale ottenibile in un impianto in bramma sottile è invece considerato in un secondo modello che quantifica l'effetto della deformazione effettuata nella laminazione al finitore sulla dimensione del grano effettivo della microstruttura finale. La metodologia proposta permette di definire i massimi spessori producibili in un impianto in bramma sottile con un dato layout QSP per ciascun grado API. Lo stesso può anche essere usato per definire lo spessore di bramma da scegliere per la produzione di un determinato mix produttivo.