TMCP APPLICATIONS IN SECTIONS, BARS AND RAILS

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1. INTRODUCTION

Hot rolled steel is widely applied in modern structural applications. This success is justified by the intrinsic qualities of steel, combining resistance and ductility. These properties are recognised since time immemorial. But if steel remained so popular it is also because steel makers developed newer grades to the benefit of their customers in term of cost and optimised properties. In the field of long products, the use of thermomechanical control processes (TMCP) was for a large part responsible for these improvements. This paper will present these techniques highlighting three major families, namely the sections, the bars and the rails. The respective characters of the production devices will be detailed as well as the rolling schedules, steel grades, mechanical and users properties.

2. TMCP FOR SECTIONS

Figure 1 illustrates various types of hot rolled sections. The heaviest profiles are wide flange beams with a web size up to 1100 mm or flange thickness up to 125 mm.

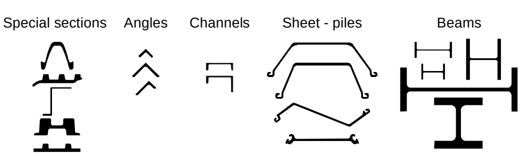

Figure 1 – Hot rolled sections

2.1 Mechanical properties

Sections are mostly applied in the structural steel market for a wide range of applications as buildings, bridges, offshore structures,… The main mechanical properties of structural steel grades are tensile properties and notch ductility. An example of specified mechanical properties is given at the Table 1 for thermomechanically rolled fine grain structural steel grades[1].

Table 1 - Mechanical properties of hot rolled sections

Grade	Tensile test			Impact test	
	Re MPa	Rm MPa	A5d min. %	Temp °C	Energy J
S275M	265	360 - 510	24	- 20	40
S275ML				- 50	27
S355M	345	450 - 610	22	- 20	40
S355ML				-50	27
S420M	400	500 - 660	19	- 20	40
S420ML				- 50	27
S460M	440	530- 720	17	- 20	40
S460ML				- 50	27

Yield strength is the basic character used in the design stage of a structure to guarantee its stability. Tensile strength is also of importance for some ultimate limit states. The use of higher strength for the erection of structural components offers substantial savings in terms of materials and fabrication costs[2].

A minimum elongation and maximum yield to tensile strength ratio may also provide a capacity of plastic deformation and hence a safety margin against fracture. A minimum Charpy V impact toughness is imposed to guarantee a resistance to brutal fracture. Other user's properties have also to be optimised. In particular weldability is important to allow the use of economical fabrication techniques of structural assembly.

Optimisation of one of these individual properties may be incompatible with other specifications. For instance, the use of higher strength is frequently advantageous for the erection of structural components as it offers substantial savings in terms of materials and fabrication costs[2]. Unfortunately, increased levels of tensile resistance through higher levels of C or Mn deteriorate weldability and fracture toughness. This is especially valid for thick products.

In the last decades, improvement of structural steel properties were mainly obtained by:

- restriction of the carbon content
- improvement of the internal cleanliness
- use of micro-alloyed grades combined with normalising and later thermomechanical rolling

This last development allowed to refine the microstructure and to produce stronger and tougher steels.

2.2 Conventional rolling of beams

As example, the Figure 2 schematises the rolling mill of the Stahlwerk Thüringen plant. The liquid steel production is based on the use of the electric arc furnace and continuous casting of beam blanks.

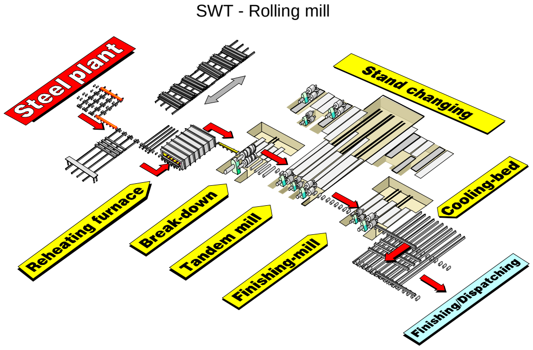

Figure 2 – Rolling mill of Stahlwerk Thüringen

In conventional rolling of sections, the semi finished products are generally reheated at temperature around 1250°C. The product is hot rolled in 15 to 20 passes. The reduction in the flanges range from 4 to 20 % per pass and the rolling end temperature is higher than 1000°C. Temperature is not homogeneous along the profile: hot points are observed in the web-flange connection and the coldest location is the mid-height of the web. The importance of this variation is related to the size of the profiles and can be as much as 100°C. With such a rolling schedule ASTM grain size in the flanges of 7 are usual for a 40 mm thick product.

2.3 Controlled rolling of beams

An improved combination of strength and impact properties can be obtained in sections if rolling can be controlled in such a way that a significant amount of deformation occurs in the lower austenite region. In this process the austenite is first deformed in a temperature range above 1050°C in order to refine the austenite grain size. If given a total deformation of around 70 % a fine austenite grain size is formed by static recrystallization after each pass.

This partially rolled section is then held until the temperature is below about 900°C when the finishing passes are given. Since recrystallization is sluggish the austenite grains become pancaked leading to significant grain refinement. This process is particularly efficient in niobium micro-alloyed grades. The improvement of the properties is also spectacular for steel with high free nitrogen contents as silicon killed steels produced by electric arc furnaces[3]. Lowering the rolling end temperature of C-Mn steel from 960°C to 870°C allows to refine the mean ferrite size to ASTM 9 instead of 7; this modification improves significantly the steel toughness (see Figure 3).

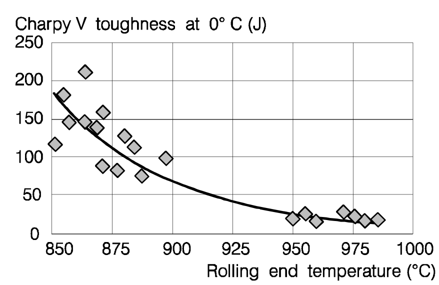

Figure 3 – Influence of the rolling scheme on toughness of silicon killed EAF steels

Following the extent of the rolling reduction given in the low temperature range, the controlled rolling process is defined as a "normalising rolling" or a " thermomechanical rolling". The normalising rolling is defined as a rolling process leading to a microstructure equivalent to that obtained after a normalising thermal treatment. The thermomechanical rolling is defined as a rolling process leading to a finer microstructure, which cannot be obtained by a heat treatment alone.

Although controlled rolling of sections leads to an attractive combination of strength and ductility it also includes substantial disadvantages. The reduction of the rolling temperature brings an increase of the rolling loads and many mills are not designed to resist the additional stresses. Because a waiting time is usually incorporated in the rolling schedule, controlled rolling can increase rolling time and reduce productivity.

Figure 4 shows the necessary chemical composition, carbon equivalent and niobium content, in order to obtain the required tensile properties of S355 in function of flange thickness.

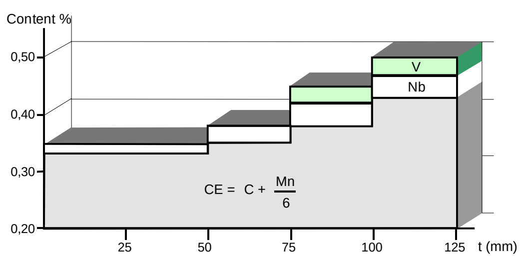

Figure 4 – Steel alloying contents for S355, controlled rolling

With higher thickness the rolling temperature increases and the cooling rate after rolling decreases what induces rougher microstructures. To reach the tensile properties the content of alloying elements has to be adapted. Due to weldability requirements and limit in equivalent carbon, beams in grade S460 are not produced for thickness higher than 50 mm (Figure 5).

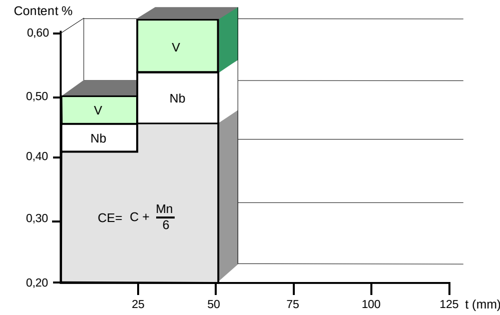

Figure 5 – Steel alloying contents for S460, controlled rolling

2.4 Accelerated cooling of beams

To overcome the limitations of thermomechanical rolling, accelerated cooling process of beams after rolling has been developed.

In the QST (Quenching and self-tempering) applied by ProfilARBED, an intense water-cooling is applied to the whole surface of the beam directly after the last rolling pass. Cooling is interrupted before the core is affected by quenching and the outer layers are tempered by the flow of heat from the core to the surface. Figure 6 illustrates schematically this treatment. At the exit of the finishing stand directly at the entry of the cooling bank, temperatures are typically at 850°C. After cooling over the whole surface of the section a self-tempering temperature greater or equal to 600°C is aimed for.

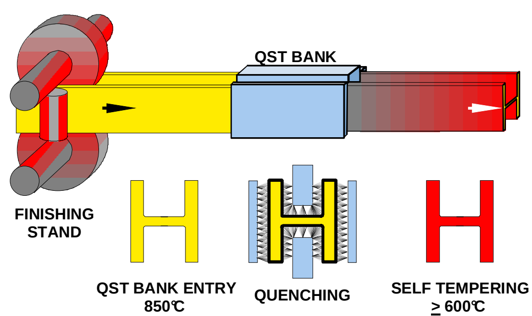

Figure 6 – QST process applied on beams in the rolling heat

The basic principles for the control of this device are sketched at the Figure 7.

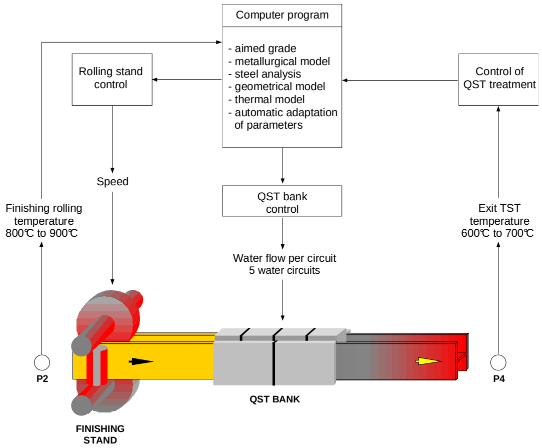

Figure 7 – Control of a QST process to produce a beam in an aimed grade

A prerequisite for a uniform QST treatment is a homogeneous temperature profile of the beam section before entering the cooling bank. The condition is fulfilled by applying a selective cooling during rolling to the hottest part of the beam, namely the flange-web intersection. Figure 8 gives a view of this process. By applying this selective cooling in the region of the flange web junction existing temperature difference can be eliminated as the comparison between typical temperature profiles over the flange width illustrates.

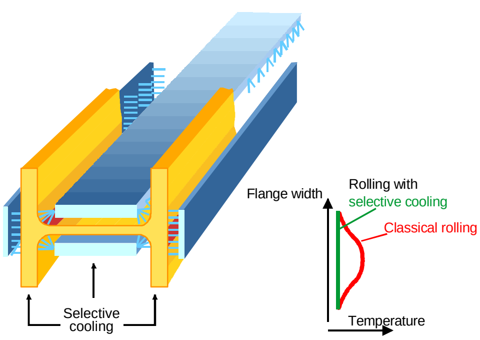

Figure 8 - Influence of selective cooling during rolling on the temperature profile of the flange width

Similar processes have been developed, as the Super OLAC S (Online accelerated cooling) by NKK at the large section mill of Fukuyama works. This system was derived from the OLAC device traditionally applied since 1980 in plate production[4]. The application to large shapes has been hampered by technical difficulties linked to the cross-section complexity of the shapes. Cooling without deformation due to heat distortion has been a challenge and achieving product quality has been difficult due to the wide diversity of sizes and grades.

The development of an accelerated cooling device for wide flange beams is also reported by Nippon steel[5] .
Figure 9 illustrates the different types of rolling schedules applied and the microstructures of hot rolled products. As already said, typical ASTM grain size after conventional rolling are about 7. This value reaches around 9 with a controlled rolling procedure and 11 with the use of the accelerated cooling device.

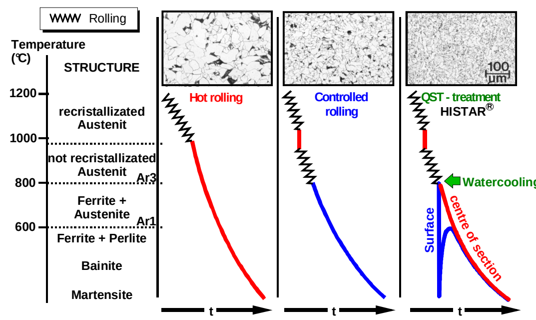

Figure 9 - Comparison of the different rolling process for beams

Such a fine microstructure allows to obtain toughness requirements at very low temperature: following the specifications of EN 10113, transition temperature at 27 J below –50°C are reached for a thickness up to 125 mm.

Figure 10 shows the necessary chemical composition, carbon equivalent and microalloying content, in order to obtain the required tensile properties with a flange thickness up to 125 mm.

The use of the QST process allowed to combine high strength, high thickness, high toughness and suitable carbon equivalent values. This latter character is representative of the weldability. Figure 11 sums up the evolution of the yield strength and carbon equivalent for various production processes.

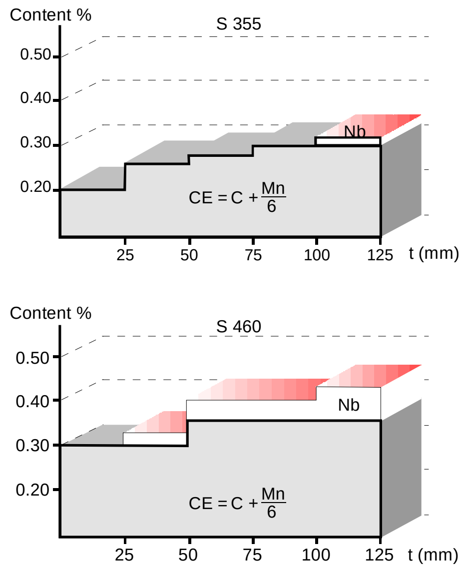

Figure 10 - Steel alloying concept for the production of QST structural shapes

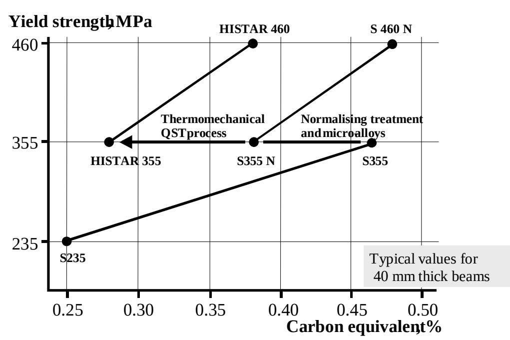

Figure 11 – Evolution of the yield strength in function of CE

In comparison with conventional low carbon steels hardened with micro-alloying elements, the QST steels also exhibit lower yield to tensile strength ratio as shown at the Figure 12.

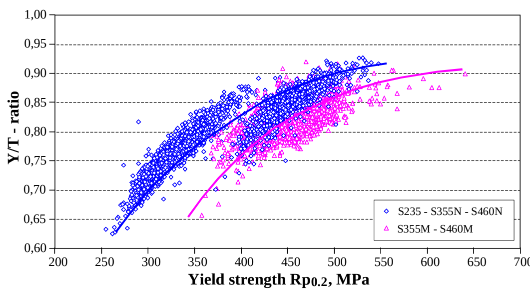

Figure 12 – Re/Rm ratio in function of the yield strength and rolling process

2.5 Accelerated cooling: other sections

TMCP processes based on QST devices have also been applied on other section geometry. For instance the Figure 13 shows its application on mining support sections.

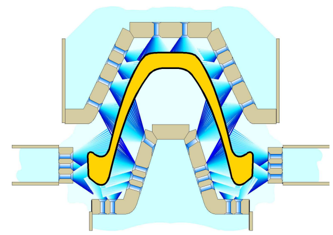

Figure 13 – Zores cooling in QST bank

Table 2 shows the improvement of the mechanical properties obtained with the QST process with a similar chemical analysis.

Table 2 – Steel qualities

DIN 21544 NF A 35256	31 Mn 4 (U) TH 350	31 Mn 4 (V) TH 520 QST
Yield Strength	≥ 350 N/mm²	≥ 520 N/mm²
Tensile Strength	≥ 520 N/mm²	≥ 650 N/mm²
Elongation (5D)	≥ 18 %	≥ 19 %
Impact test (DVM in aged condition 10%)	≥ 18 J	≥ 60 J

3. TMCP FOR BARS

The first major application of TMCP in long products was the implementation of the TEMPCORE process[6]. TEMPCORE has found a world-wide expansion for the production of high quality reinforcing bars (Figure 14).

Figure 14 – TEMPCORE reinforcing bar

The cooling efficiency of the system, installed at the exit of the last rolling stand, is such that a surface layer of the bar is quenched into martensite, the core remaining austenitic (Figure 15).

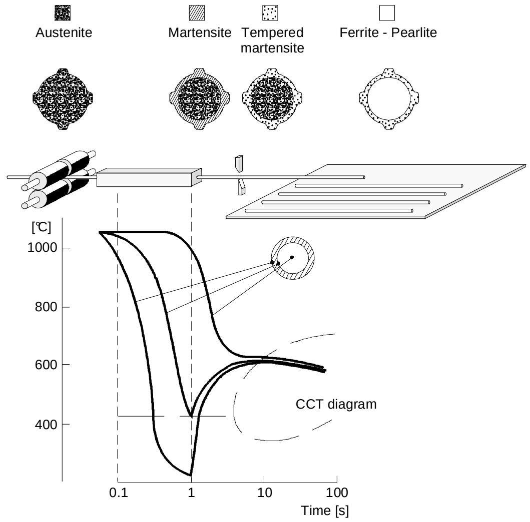

Figure 15 – Tempcore process and relationship with CCT diagram

When the bar leaves the high rate cooling section, the temperature gradient established in the cross section causes heat to flow from the centre to the surface. This results in a self-tempering of the martensite. Finally, during slow cooling of the bar on the cooling bed, the austenite core transforms to ferrite and pearlite.

The high strength steels obtained with the TEMPCORE process shows an improved combination of properties when compared to classical as rolled C-Mn bars (figure 16, table 3). Economical advantages were also remarkable in comparison with other hardening means as micro-alloying or cold deformation.

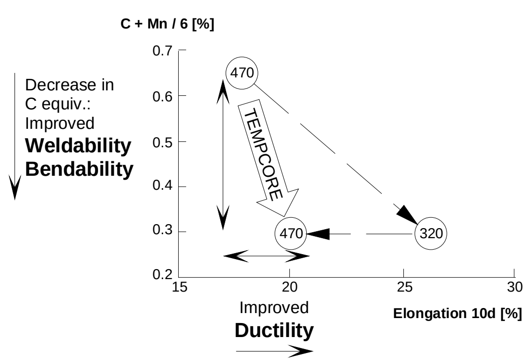

Figure 16 – Weldability and ductility properties of Tempcore rebars

Table 3 – Bendability of Tempcore rebars

Bending tests	Typical *D* values Conventional C_{eq} = 0.61 %	Typical *D* values Tempcore C_{eq} = 0.30 %
180° bending	3	0.5
90° bending and rebending after ageing	6	3.2
90° bending after electrical butt welding	15	4.0
90° bending after electrical cross welding	> 20	7.0

Bendability expressed in terms of minimum bending diameter *D*
(*D* is the ratio of the minimum possible bending diameter to the rebar diameter

Another applications of bars produced with the TM process is found in cryogenic steels. The design of LNG storage tanks (Figure 17) uses a concrete confinement wall. This containment may be subjected to high peak stresses under low temperature conditions in case of an accident (earthquake, blast, external impact,…) leading to the failure of the inner tank. It is well known that for standards reinforcing steels, as used in day-to-days jobs, toughness and ductility deteriorate with decreasing temperature to a point where brittle failure will occur.

Figure 17 – Reinforcing steel for concrete reinforcement of LNG storage

The concrete reinforcing bars used in LNG storage must therefore, in addition to the normal range of properties, fulfil supplementary conditions at the low design temperature[7]. Table 4 shows the properties obtained with TMCP bars down to –165°C (KRYBAR steel).

Table 4 – KRYBAR properties at – 165 °C

At room temperature

Tensile strength	Yield strength	Elongation A 5d	Bend test
min. 1.1 x yield strength	460 min. N/mm²	18 % min	5 d (d ≤ 16 mm) 7 d (d > 16 mm)

At design temperature -165°C
- unnotched bars
  uniform elongation Ag min. 5 %
- notched bars
  uniform elongation Ag min. 1 %

Notch sensitivity ratio (NSR) > 1
NSR = Tensile strength of notched bar/0.2% proof stress of unnotched bar

4. TMCP FOR RAILS

Since the advent of railways, rail materials have been challenged by the rising speed and weight of traffic, resulting in a higher rate of rail deterioration. The response of the steel metallurgist has been to produce rails with greater hardness and ultimate tensile strength. The microstructures of the rails used presently are still generally a pearlite based on a carbon/manganese composition. Strength and related wear resistance may be improved by decreasing the interlamellar spacing of the pearlite.

An alternative bainitic microstructure has been also proposed recently.

These microstructures can be obtained by increasing the alloying contents (i.e. chromium addition). Another approach has been found with the introduction of TMCP, namely accelerated cooling.

The cooling process can be off-line or in-line. In the off-line process, rails (some parts or the entire rail) are reheated into the austenite region and subsequently accelerated cooled. In the in-line process, the rail is treated directly with an accelerated cooling after rolling.

In-line systems are preferred by rail manufacturers because the cooling process can be designed to match the rolling mill capacity, hence they achieve a high productivity rate. In contrast, the off-line systems are relatively slow and energy intensive.

Different technologies have been used aiming at the in-line hardening treatment of pearlitic rails (forced air-cooling, cold water cooling, dipping in synthetic quenching medium, etc…).

Among them, the in-line water spray cooling technology called CHHR[8] (Continuous Head Hardening Rails) has been applied for the production of rails at ARES, in Corus UK and Pennsylvania Steel Technology. The cooling technology is based on water sprays (Figure 18).

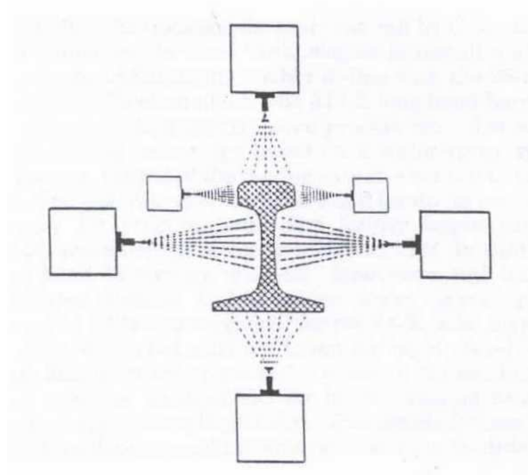

Figure 18 – Spray configuration in rail cooling system

The development of these new pearlitic and bainitic rails allows to decrease the wear rates[9] (Figure 19).

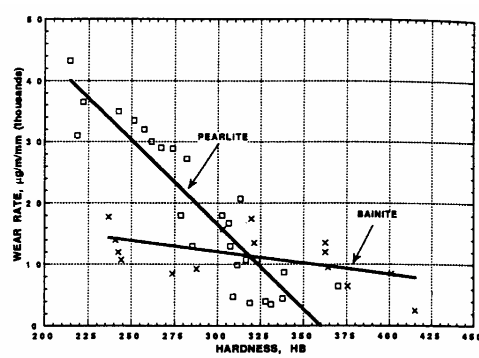

Figure 19 – Wear rates vs. hardness for pearlitic rail steels (open square) and bainitic steels

Another important character of rails is the resistance to rolling contact fatigue (RCF). Repeated high stresses combined with creepages (predominant in curves) are the main cause of rolling contact fatigue. Hence, new rail steels offering longer life need better resistance to RCF in addition to improved wear resistance.

In this field also, TMCP allows to elaborate suitable microstructure with superior initiation time for fatigue cracks due to RCF[10] (Figure 20) or superior toughness and resistance to the propagation of the cracks (Figure 21).

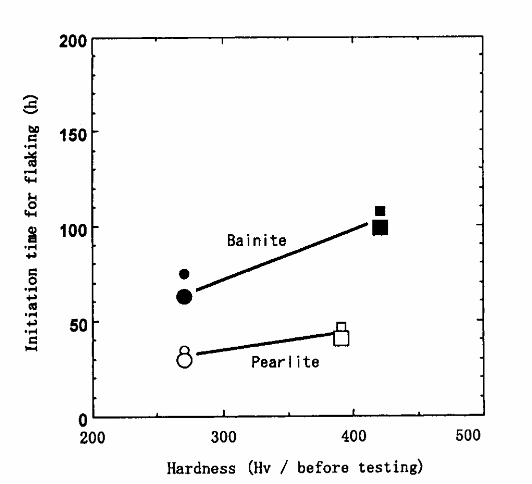

Figure 20 – Initiation time for RCF damage as a function of hardness

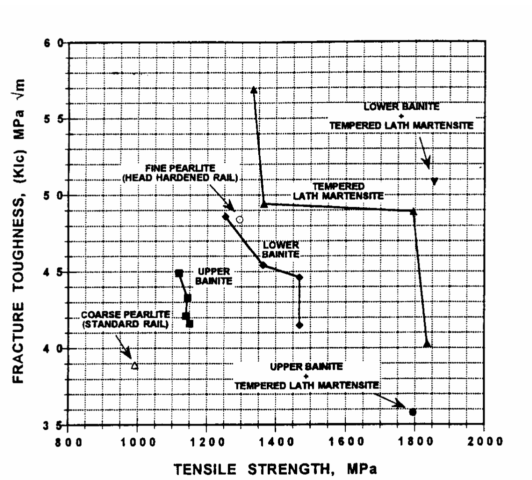

Figure 21 – Fracture toughness/tensile strength plot of rails

5. CONCLUSION

TMCP has been successfully applied for the elaboration of long products. In term of quality or economy, the performance of this production route compares advantageously with alternatives as increased alloying or off line processes as normalising.

For the steel producer, TMCP has allowed to rationalize the number of grades at the steelshop, to increase the productivity and to decrease the cost of the alloying.

For the steel user, TMCP brought on the market products with an improved combination of properties as tensile resistance, toughness, ductility, wear resistance, weldability for a wider range of thickness.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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