

TECHNICAL BRIEFING

Thermomechanical Controlled Processing (TMCP)

Delivering the Advantages of Niobium Technology



The objective of this short document is to provide the reader with essential information about the basic metallurgical principles of thermomechanical controlled processing (TMCP) and its application in the production of plate and strip for the manufacture of high strength linepipe. The unique importance of niobium in the history of the development of such steels is thoroughly explained and the way in which lower carbon steelmaking has now opened the door to the more effective utilization of higher levels of niobium in high temperature processed (HTP) linepipe steels is also set out.

Although the principles and concepts presented in this document are described in the context of the manufacture of linepipe steels, they are, with minor modifications, also applicable in the manufacture of steels for other uses, for example, structural and shipbuilding.

High Strength Linepipe

To satisfy the increasing demands of the rapidly expanding global oil and gas distribution network, more than 20% of world ferroniobium output has been consumed by steelmakers producing plate or coil for the manufacture of high strength linepipe. The pipe required for such projects now also tends to be of larger diameter and of increased wall thickness because of the need to transport greater volumes of hydrocarbons at higher pressures. The market is constantly expanding and this is anticipated to continue, as portrayed in Figure 1 below. By 2035, the world is expected to consume about 36.5 million tonnes of high strength linepipe per year.

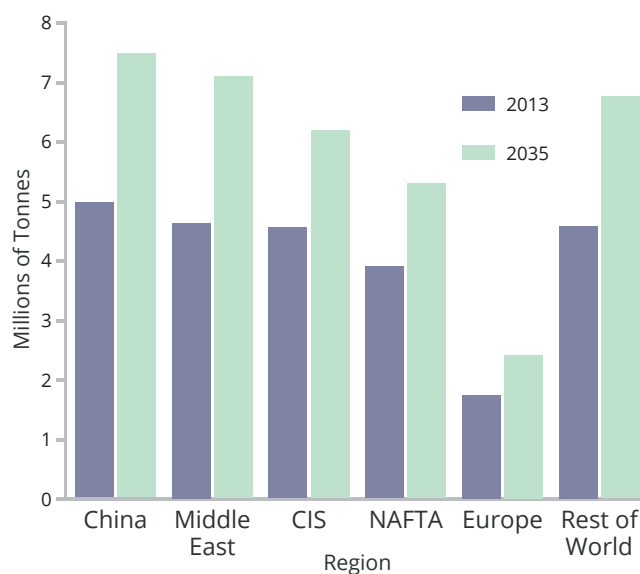


Figure 1. Projected linepipe growth – X60 or greater strength level.
(Source Metal Bulletin).



Figure 2a. Plate mill rolling. (Adapted from Corus-Namtec) [1].

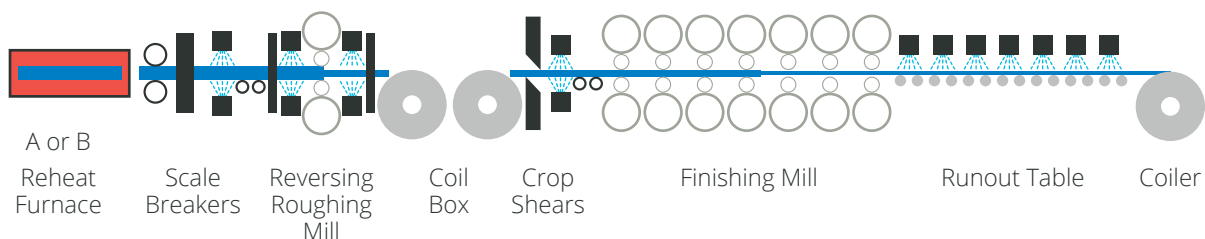


Figure 2b. Strip mill rolling. (Adapted from Evans, Kennedy and Thomas) [2].

Plate and Coil

High strength pipe is usually manufactured using either plate or coiled strip and Figures 2a and 2b schematically illustrate typical layouts for the two rolling processes.

Pipe is manufactured from plate in longitudinal seam, submerged arc welding (LSAW) mills (Figure 3a), or from coiled strip, in helical submerged arc welding (HSAW) mills (Figure 3b). For the thinnest walled pipes, and in certain circumstances, other options such as electric resistance welding (ERW) and high frequency induction (HFI) welding can also be employed.



Figure 3a. Longitudinal Submerged Arc Welding (LSAW) of High Strength Low Alloy (HSLA) pipe. (Image courtesy of Tata Steel).



Figure 3b. Helical Submerged Arc Welding. (Image courtesy of Welspun Corp).

In earlier decades, LSAW mills were very dominant for high strength linepipe but, in recent years, there has been a clear and progressive penetration of the market by mills employing helical (spiral) welding. This trend has primarily been driven by economics as it is significantly cheaper to purchase coil rather than plate and the capital cost of establishing a spiral pipe mill is about one quarter of that for an LSAW pipe mill. The approximate current global picture is shown below, where it can be seen that China and India, taken together, are leading the way in embracing this change (Figure 4).

The fundamental metallurgical principles are the same whether plate or strip is being produced, as set out below.

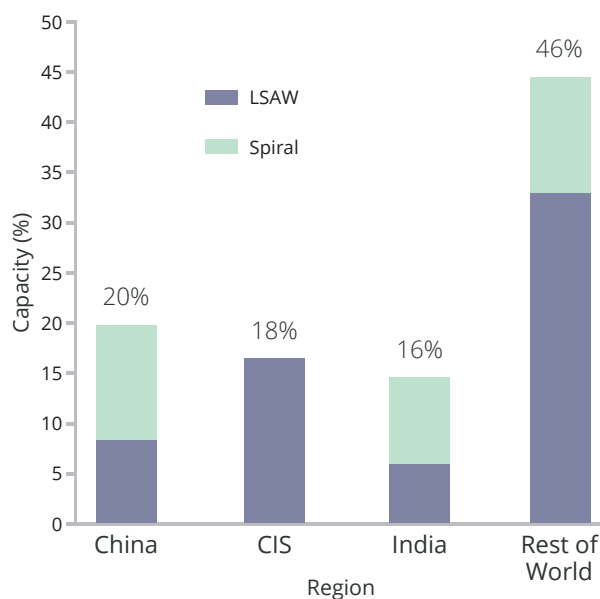


Figure 4. Approximate world capacity for the manufacture of HSLA pipe. (Compiled from ITI International data files).

Steel Hot Rolling Metallurgy in Perspective

Historically, the rolling of steel, like other hot deformation processes, was carried out primarily to achieve a specific external shape (in this case plate or strip) and the mechanical properties of the finished product were largely imparted by virtue of the effects of alloying elements and subsequent heat treatment.

Initially, therefore, hot rolling was usually carried out at temperatures as high as possible in the austenitic (γ) region, where the steel is softest and the upper limit tended to be governed by practical limitations, for example, operating at such high temperatures, costs, pressures on productivity, etc. Conventional hot rolling, e.g. of pre-World War II C-Mn steels, made little attempt to control the rolling conditions and usually **finished** in the range 1050-900 °C depending on product thickness (Figure 5a).

Following unfortunate instances of brittle failure of hot rolled plates in ships' hulls during the last world war, the 1950s witnessed many attempts to improve toughness, both by changes in steelmaking practices and, more interestingly, by the introduction of what we now call **'controlled rolling'**. At that time, it was beginning to be appreciated that the ductile to brittle transition temperature of steel could be greatly improved by the refinement of ferrite (α) grain size. This could be achieved either by the normalizing of aluminum treated steels or by controlled, lower temperature, hot rolling to further refine the austenite at temperatures still above the Ar_3 but down to 800 °C (Figure 5b).

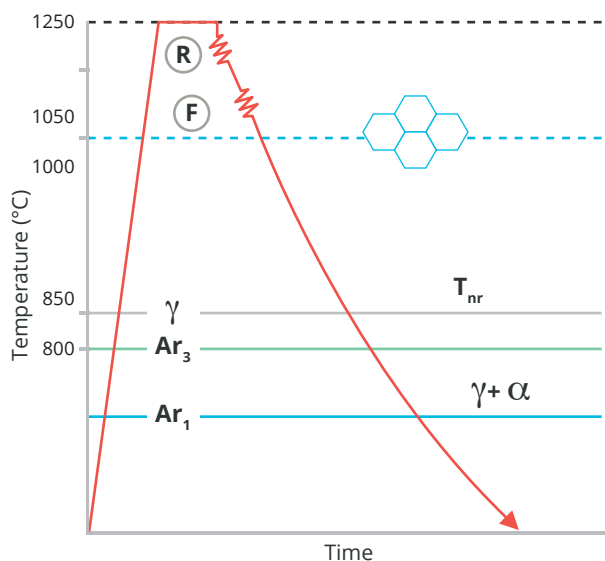


Figure 5a. C-Mn hot rolling [3].

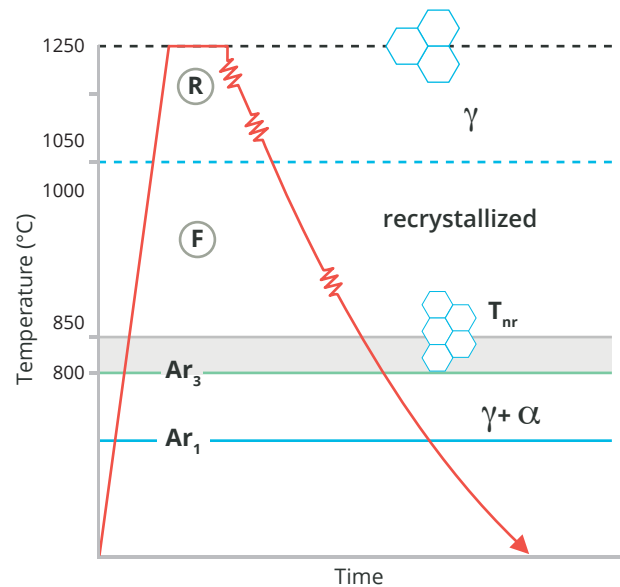


Figure 5b. Controlled rolling of C-Mn steel [3].

In both of the preceding diagrams, R indicates the initial deformation stages of the slab or **'roughing'**, whilst F denotes the **'finishing'** rolling stages.

T_{nr} is the temperature below which recrystallization does not occur.

Ar_3 is the temperature, during cooling, at which austenite begins to transform to ferrite.

Ar_1 is the temperature, during cooling, at which the transformation of austenite to ferrite is complete.

Terminology

It is easy to become confused by the plethora of different terms that are encountered in the literature, e.g. thermomechanical processing, controlled rolling, controlled processing and thermomechanical controlled processing. It is worth clarifying these before continuing.

We have already explained the origins of the term controlled rolling but thermomechanical processing, in its broader context, incorporates the harnessing of various techniques designed to improve mechanical properties. Thus controlled rolling, controlled cooling (such as accelerated cooling after rolling) or direct quenching are examples of thermomechanical processing. The common factor is that such processes may be able to eliminate the need for any subsequent heat treatment and they may permit a reduction in the total amount of alloying required, which, in turn, will

probably improve weldability and produce new and beneficial characteristics in the steel.

In recent years, it has become more common to utilize the term **Thermomechanical Controlled Processing** (TMCP), as incorporated in the title of this document. This usually implies the use of a combination of various features of controlled rolling, modifications to slab reheating and interpass holding temperatures, and some form of accelerated cooling following the completion of the rolling process.

We will revert to this later.

The Role and Unique Significance of Niobium

In very simple terms, it is necessary to appreciate that driven by the deformation process, and even as the temperature continues to drop, austenite is continuously recrystallizing during rolling. However, a temperature, dependent on steel chemical composition, is eventually reached, below which recrystallization becomes effectively impossible. This is referred to as

T_{nr} . In the controlled rolling of simple C-Mn steels, as in Figure 5b, the austenite grains are progressively refined by performing multiple passes between 950 and about 825 °C, this being the lowest temperature range in which significant recrystallization can still occur. This deformation results in a high density of sites for alpha (α) ferrite nucleation on subsequent transformation and this further refines the final grain size to improve properties, as illustrated in Figure 6.

Ideally it is beneficial to accumulate as much deformation strain as possible below T_{nr} , but above A_{r3} , and this is where the unique properties of niobium make the most dramatic contributions.

Firstly, niobium in solution and in its precipitated state retards recrystallization and as demonstrated in Figure 7, effectively permits higher deformation temperatures. In effect, the presence of niobium raises the temperature below which recrystallization cannot occur by up to 100 °C.

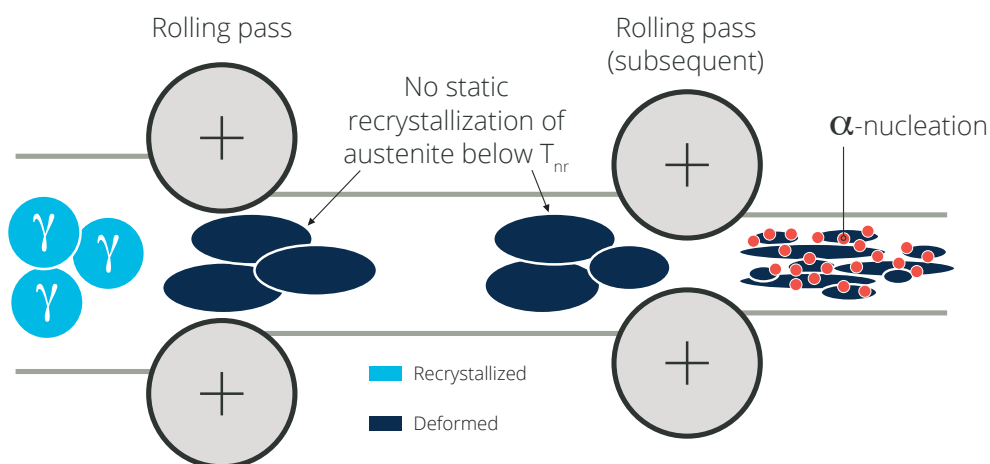


Figure 6. Illustration of deformation below T_{nr} producing pancaking and more sites for ferrite nucleation. (Adapted from Vervynck et al) [4].

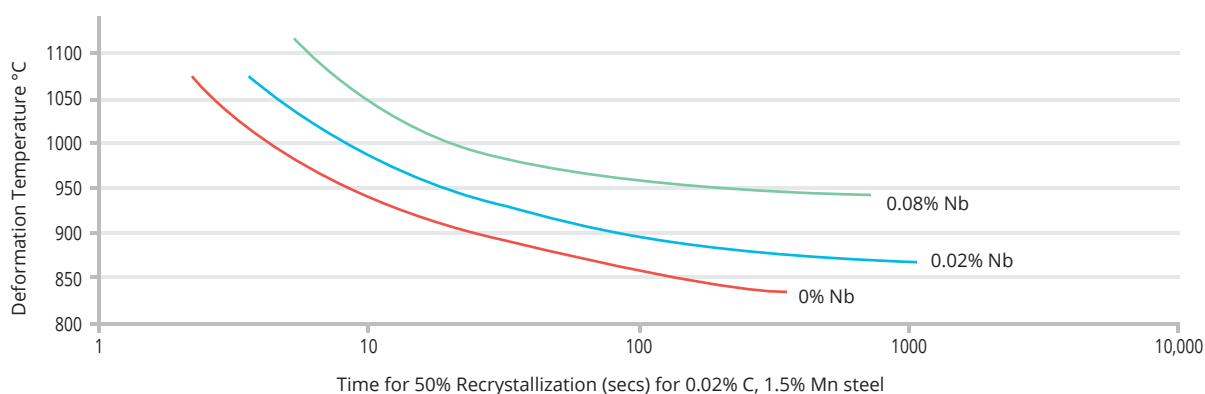


Figure 7. Simplified diagram adapted from Vervynck et al [5].

It should be noted that niobium also significantly reduces the A_{r3} temperature, the extent of the reduction depending on niobium level, cooling rate and carbon level. Figure 8 indicates the magnitude of this effect in a 0.05% carbon HSLA linepipe steel.

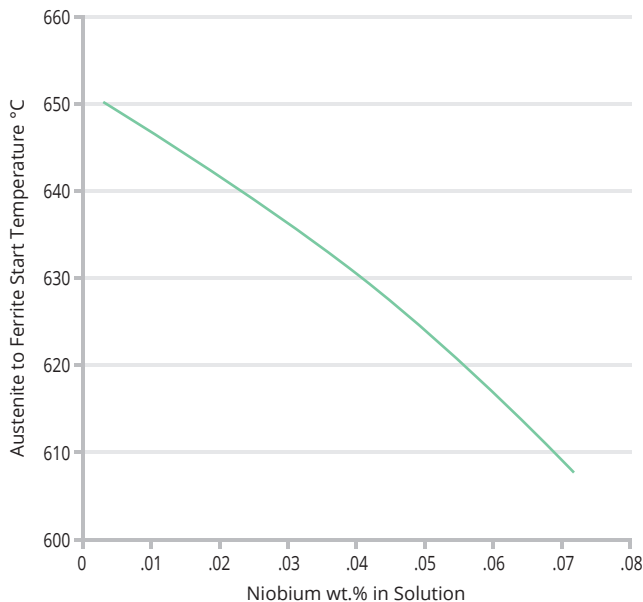


Figure 8. Theoretical effect, from kinetic theory, at a cooling rate of 20 °C/sec adapted from Pei and Bhadeshia [6].

The combination of these two effects as portrayed in Figure 9 significantly widens the operational window for optimum austenite processing, the full implications of which are beyond the scope of this document. It is however, for example, possible even with reduced slab reheating temperatures (allowing the process to start with a smaller slab austenite grain size), to achieve significant austenite grain size reductions through deformation-induced recrystallization in a higher temperature range 1000 to 950 °C during **roughing**. This in turn provides the opportunity for further rolling reductions at temperatures below T_{nr} down to A_{r3} , i.e. in the range in which recrystallization does not occur, but the austenite grains can be flattened (pancaked).

Additionally, as illustrated in Figure 9, there is scope in such steels to extend the **finishing** of rolling into the two-phase ($\gamma + \alpha$) region as this sometimes has the potential to further increase strength and affect the ductile to brittle transition temperature. Through this approach, in niobium treated steels, the pancaked austenite grains can be further deformed introducing new microstructural features such as deformation bands and a significant further increase in ferrite nucleation sites.

This is **controlled rolling** in the more widely understood sense of the term. However, as will be appreciated later, the reliance on intercritical rolling to enhance mechanical properties can bring with

it significant disadvantages and best practice in the modern era tends to avoid this, where possible.

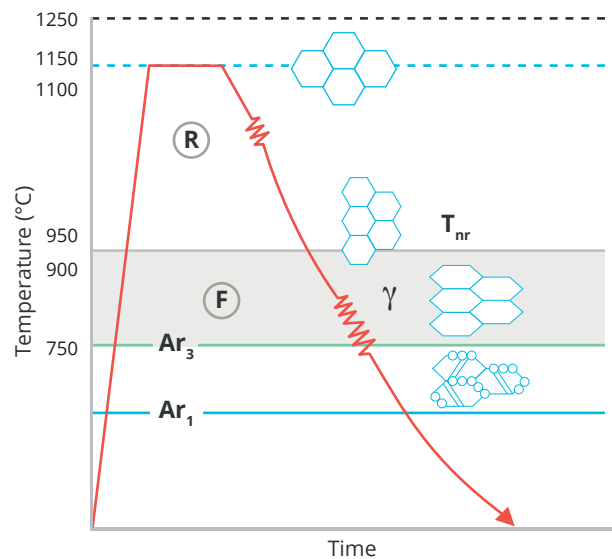


Figure 9. Controlled rolling of a C-Mn-Nb steel. (Adapted from Tamura et al) [3].

Note - T_{nr} is increased and A_{r3} is decreased with cross reference to Figure 5b.

The Constraints of Higher Carbon

Although the importance of low carbon in improving properties and weldability has been appreciated for many years, the vast majority of high strength linepipe produced in the last four decades has relied on alloying designs based on carbon levels around 0.1% or above. There have been important exceptions to this general statement that we will elaborate on later.

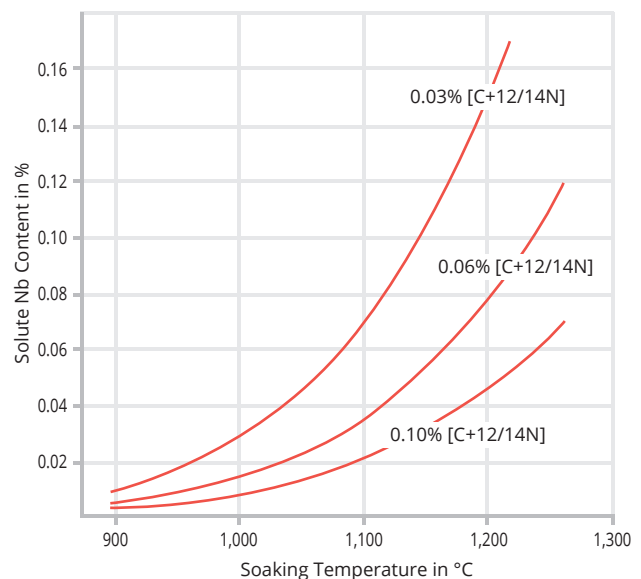


Figure 10. The effects of carbon and temperature on the solubility of niobium [7].

The solubility of niobium in austenite during slab reheating is determined by the carbon level, as illustrated in Figure 10. It can be appreciated therefore, that the earliest niobium treated linepipe steels, which contained about 0.05/0.06% niobium, were unable to take full advantage of the presence of the element because the carbon level was frequently 0.1% or greater.

From Figure 10, and with cross reference to Figure 9, it is clear that with slab reheating temperatures of around 1150 °C and with carbon levels in excess of 0.1%, it will only be possible to take around 0.03% of the niobium into solution. This places restrictions on the potential benefits to be realized by niobium's unique effects on austenite recrystallization, transformation and precipitation strengthening of ferrite.

Niobium and Vanadium in Controlled Rolled Linepipe Steels

Because of the reluctance of many producers to consistently embrace lower carbon steelmaking, linepipe strengths in excess of X60 have been (and still are) frequently achieved using combinations of niobium and vanadium. Vanadium nitride and vanadium carbide are more soluble than niobium carbide or nitride in both austenite and ferrite and therefore, even if slab-reheating temperatures were reduced, there would be more scope to derive increased strength through precipitation hardening. However, on a pro rata basis, more vanadium than niobium is required to achieve such benefits and other aspects of performance such as weldability suffer in consequence. This resulted in steels with compositions and processing details along the lines set out in Table 1 (after Tamura et al) [3]. Note the reversion to higher slab reheating temperatures to ensure maximum solution of all microalloying elements.

Steels of the general type described above have historically been used for most X65 strength transmission pipe. They were frequently quite heavily controlled rolled into the temperature region between Ar_3 and Ar_1 to guarantee the strength level required. Such steels have a traditional ferrite-pearlite microstructure with carbon levels of up to 0.12%.

As transmission gas pressure increased and the demand for X70 pipe gradually materialized, this strength level could also be achieved by using C-Mn-Nb-V controlled rolled compositions, though the chemical composition was occasionally modified by using additions of molybdenum or other alloying elements such as nickel or chromium.

Mill Type	Plate Mill	Hot Strip Mill
Standard	API-5L-X65	API-5L-X65
Plate Thickness	14.3 mm	11.7 mm
Chemical Composition	0.1%C, 0.25%Si, 1.4%Mn 0.04%Nb, 0.06%V	0.1%C, 0.25%Si, 1.35%Mn 0.04%Nb, 0.04%V
C+ Mn/6	0.33	0.32
Slab Reheating	1250 °C	1250 °C
Final Roughing	1050-1000 °C	1000 °C
First Finishing	910 °C	980 °C
Final Finishing	720 °C	830 °C
Coiling	Not relevant	630 °C

Table 1. Typical Steel Compositions Employed for API-5L-X65 for Alaska in 1969 [3].



The overall process was also frequently augmented by accelerated cooling, following rolling (Figure 11), to enable adequate properties and enhanced weldability to be realized with slightly lower carbon levels. By the year 2000, pipe plate and coil for

strengths up to X70 were regularly being produced with steel compositions not dissimilar to those in Table 1, but more sophisticated processing had enabled carbon to be reduced to the 0.06/0.07% level.

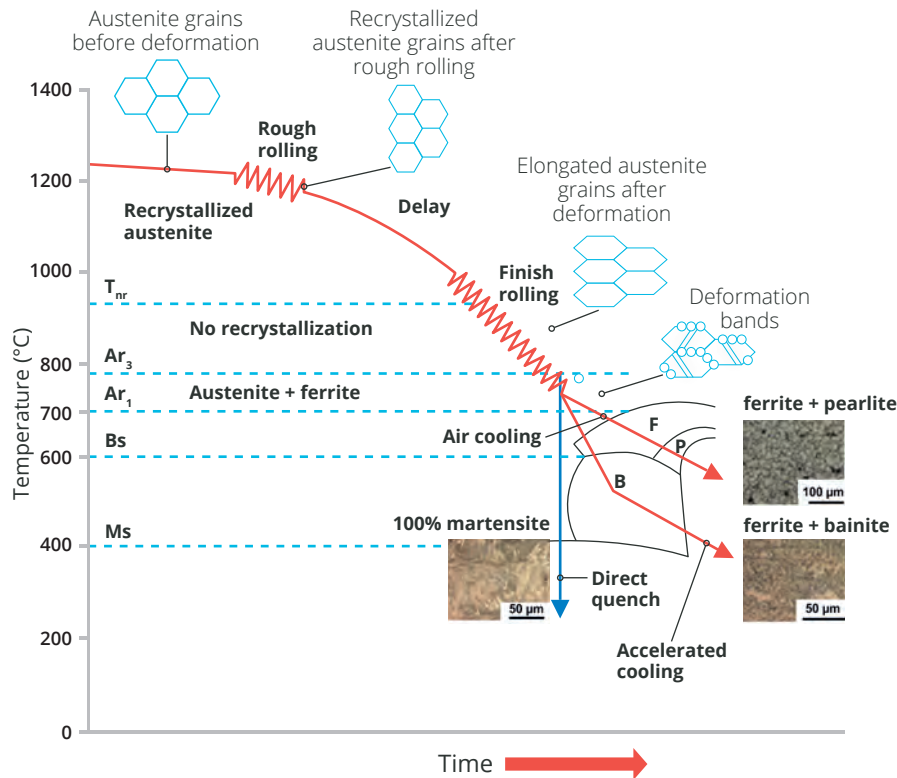


Figure 11. Key features of TMCP options for higher strength linepipe. (Adapted from Vervynckt et al) [4].

Limitations of the Niobium-Vanadium Approach

As the technical requirements of end users have continued to evolve, demanding ever increasing low temperature toughness and even better weldability at all strength levels, from X65 upwards, the necessity to decrease carbon levels has intensified. This trend is not compatible with the presence of vanadium and greatly reduces its ability to contribute effectively to strengthening.

As the carbon level decreases, Ar_3 progressively increases and, since vanadium nitrides and carbides exhibit increased solubility in ferrite compared with the corresponding niobium precipitates, they are unable to precipitate effectively in ferrite, which has been formed from austenite at a higher temperature. This, in effect, seriously limits the extent to which carbon and carbon equivalent (CE) can be reduced, without a corresponding decrease in strength. Thus, even with accelerated cooling and heavy controlled rolling in the intercritical temperature range, there are limits to what can be achieved.

Additionally, there is considerable evidence in the literature to suggest that certain combinations of niobium and vanadium are detrimental to HAZ [8] and weld metal toughness [9] and, at a given carbon level, will not provide the best possible resistance to hydrogen induced cracking following welding [10]. This situation is exacerbated in the higher nitrogen steels that some steelmakers have attempted to use to make vanadium strengthening more effective.

There is no doubt that the niobium-vanadium approach to seeking optimum strength, toughness and weldability for higher strength linepipe no longer represents the best way forward.

Furthermore, the excessive controlled rolling in the intercritical temperature range, which is usually required to enable V-Nb combinations to achieve X70 or greater, is now known to introduce undesirable texturing which results in the appearance of 'separations' on the fracture surfaces of Charpy test pieces used for the assessment of toughness

in plate or strip materials [11]. Unfortunately, while strength and even the ductile to brittle transition temperature can be improved by this low temperature processing, the through thickness (Z direction) properties often suffer and the behavior of such steels in full-scale ductile fracture situations cannot, currently, be accurately predicted.

High Temperature Processing (HTP)

The evolutions in steel compositions and processing described to date have focused on how the steel suppliers attempted to produce the best possible combinations of properties for pipe plate or strip given the limitations of the conventional metallurgical approaches to achieving the highest strength and toughness required. However, it was becoming increasingly obvious that an alternative approach was desirable and that niobium would feature strongly in the provision of a robust solution to existing problems.

Amazingly, the answer to many of the issues with the presence of vanadium and severe controlled rolling in the A_r3 to A_r1 temperature range has been available, but not widely appreciated for decades. It has taken the increasing demand for even higher pipe strengths, up to X80 and potentially beyond, with further enhanced weldability and with excellent and predictable ductile fracture propagation resistance, to reawaken interest in a metallurgical concept which was first proven over 50 years ago [12] and subsequently demonstrated in a full scale trial, incorporating international evaluation in 1983.

The secret lies in the recognition that the full potential of niobium can never be enjoyed, unless a sufficient quantity of the element can be successfully taken into solution during slab reheating. As already alluded to, and illustrated in Figure 10, this could never be achieved with the carbon levels typical of earlier decades but the demands for improved weldability, and in particular, the need for improved heat affected zone (HAZ) toughness and lower weldment hardness, have inevitably re-opened the door to the wider adoption of the well proven HTP concept.

Weldability is of paramount importance, particularly during girth welding, and whilst the onus is often, erroneously, placed on reducing

CE, it is the significant reduction of carbon itself, ideally to levels well below 0.1%, which guarantees resistance to hydrogen induced cracking [13]. In fact, as implied by Figure 12, there is considerable latitude on CE level once carbon has been effectively reduced. This is important, as it provides the steelmaker with scope to make minor alloying additions of elements such as nickel, chromium, molybdenum and copper, as required, to meet enhanced strength requirements or other specific material demands such as resistance to the presence of sour hydrocarbons.

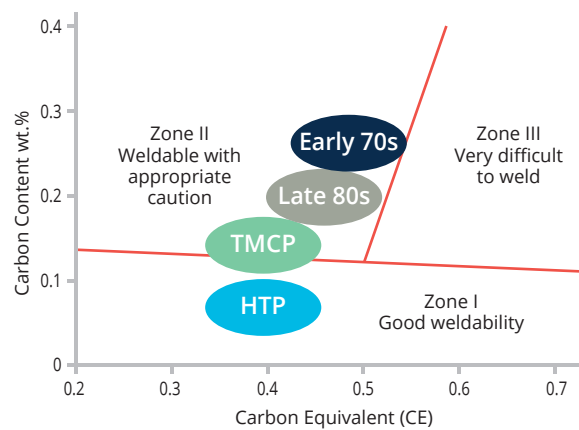


Figure 12. The importance of carbon content to weldability in structural and linepipe steels. (Adapted from an original by Graville) [13].

Figure 13 indicates that if the carbon level can be reduced to the order of 0.05%, then at modest slab reheating temperatures in the range 1150 to 1200 °C, up to 0.12% niobium can be successfully dissolved in austenite.

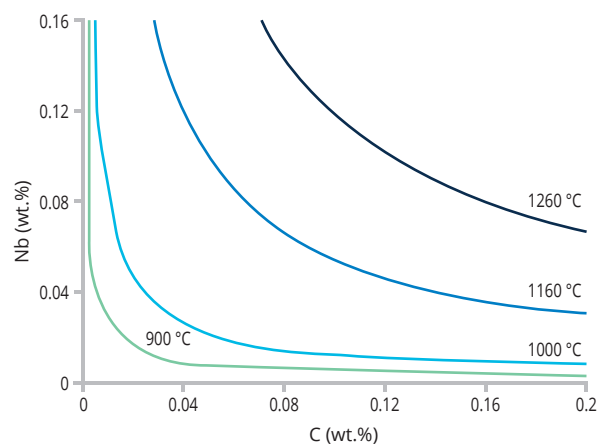


Figure 13. The solubility of niobium in austenite; the roles of carbon and temperature. (Adapted from Pei and Bhadeshia) [6].

This class of steel, colloquially referred to as HTP (High Temperature Processed), has steadily, therefore, become the focus of recent attention. It is the reduced carbon and increasing niobium content which allows higher finishing temperatures and the latter is the key operational parameter underpinning HTP technology. Conventional ferrite-pearlite, niobium-vanadium steels are often *finish rolled* in the 710 to 830 °C temperature range, whereas for the low carbon HTP steels, 840 to 910 °C, or even higher, is more typical.

Mill Type	Plate Mill	Plate Mill
Standard	API-5L-X65	API-5L-X70 (HTP Design)
Plate Thickness	14.3 mm	11.8 mm
Chemical Composition	0.1%C, 0.25%Si, 1.4%Mn 0.04%Nb, 0.06%V	0.04%C, 0.15%Si, 1.60%Mn 0.20%Cr, 0.08%Nb, 0.011%Ti
C+ Mn/6	0.33	0.31
Slab Reheating	1250 °C	1180 °C
Final Roughing	1050-1000 °C	1010 °C
First Finishing	910 °C	950 °C
Final Finishing	720 °C	860 °C

Table 2. Typical Chemical Compositions and Thermal Processing Histories Employed for API-5L-X65 Pipe Plate for Alaska in 1969 Contrasted with a 2007 - HTP Alloy Plate Design for an X70 Major North American Project.

Niobium is the only element that enables rolling at higher than normal temperatures, thus avoiding lower temperature austenite processing regimes, which increase mill loads, reduce productivity and

increase wear on equipment. Additionally, niobium retards recrystallization and recovery, subsequently lowering the austenite to ferrite transformation start temperature.

This metallurgical ‘miracle’ uniquely produces a bainitic-ferrite microstructure, which provides the steel with high strength and toughness. The higher finishing temperatures virtually eliminate the presence of the undesirable heavily textured microstructures associated with lower temperature rolling and this leads to superior mechanical property combinations and improved resistance to ductile fracture propagation.

HTP steels have an extensive and reliable service record in important offshore and onshore project applications [14] and their strength level can be tailored, as required, by the judicious addition of chromium and small amounts of titanium. The technology can comfortably take us beyond the X80 strength level but the ultimate capability has yet to be fully demonstrated.

A timeline of HTP developments, from reference 14, can be found in Appendix 1.

Now, at last, increased awareness of the HTP technology is leading to the ongoing revision of the world’s most influential API and ISO standards for pipe plate or strip and, in the not too distant future, carbon levels in higher strength niobium bearing linepipe will be severely restricted.

The HTP story is compelling and there is an irresistible ‘wind of change’ blowing which, if harnessed, could deliver significant technical and economic advantages, which the linepipe industry would be ill-advised to ignore.

Conclusion

Modern high strength linepipe capable of meeting the most onerous demands of discerning end users could not be produced without the use of the uniquely important element, niobium. The advent of lower carbon steelmaking and the realization of the importance of this to steel properties and weldability, in particular, are now relentlessly driving change.

Steelmakers, pipe manufacturers and their clients are increasingly embracing best practice and are taking advantage of our enhanced understanding of the special role played by niobium during conventional thermomechanical controlled processing (TMCP), and the way in which high temperature processing (HTP)

can be implemented to provide the many benefits highlighted in this short document. This recognition is, in turn, influencing the evolution of major end user and international standards and the future for low carbon linepipe steels with an enhanced contribution from niobium has never been brighter.

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Appendix 1.

1960's

Research provides stimulus for development of low carbon steels with niobium levels up to at least 0.12 percent.

1971

'Pearlite free' low carbon X70 steel with niobium and molybdenum commercially applied in Canada.

1972

First 'Arctic' grade X80 molybdenum free linepipe steel produced based on a low carbon, 0.10 percent niobium concept.

1980

Low carbon, nickel X70/X80 developed in Italy with 0.14 to 0.16 percent niobium with outstanding properties.

1983

Full scale demonstration heat of the chromium-niobium HTP steel produced in Japan, sponsored by CBMM, and evaluated internationally.

1990's

Further refinements of low carbon pearlite free steels now commonly referred to as acicular ferrite or bainitic ferrite steels.

1998

The Pemex Cantarell Project uses the pure HTP concept for a Gulf of Mexico, thick wall X70, sour service (pH=5) pipeline.

2003

HTP concept pipe also used for the Cameron Highway crude oil project in the Gulf of Mexico, the largest offshore pipeline system in the USA.

2004

Cheyenne Plains - First onshore X80 pipeline in the USA and a significant portion of the gas line utilizes HTP low carbon, niobium-chromium steel.

2008

Half of the steel for the Kinder Morgan 1,323 mile gas pipeline uses HTP steel similar to that used for Cheyenne Plains.

2010

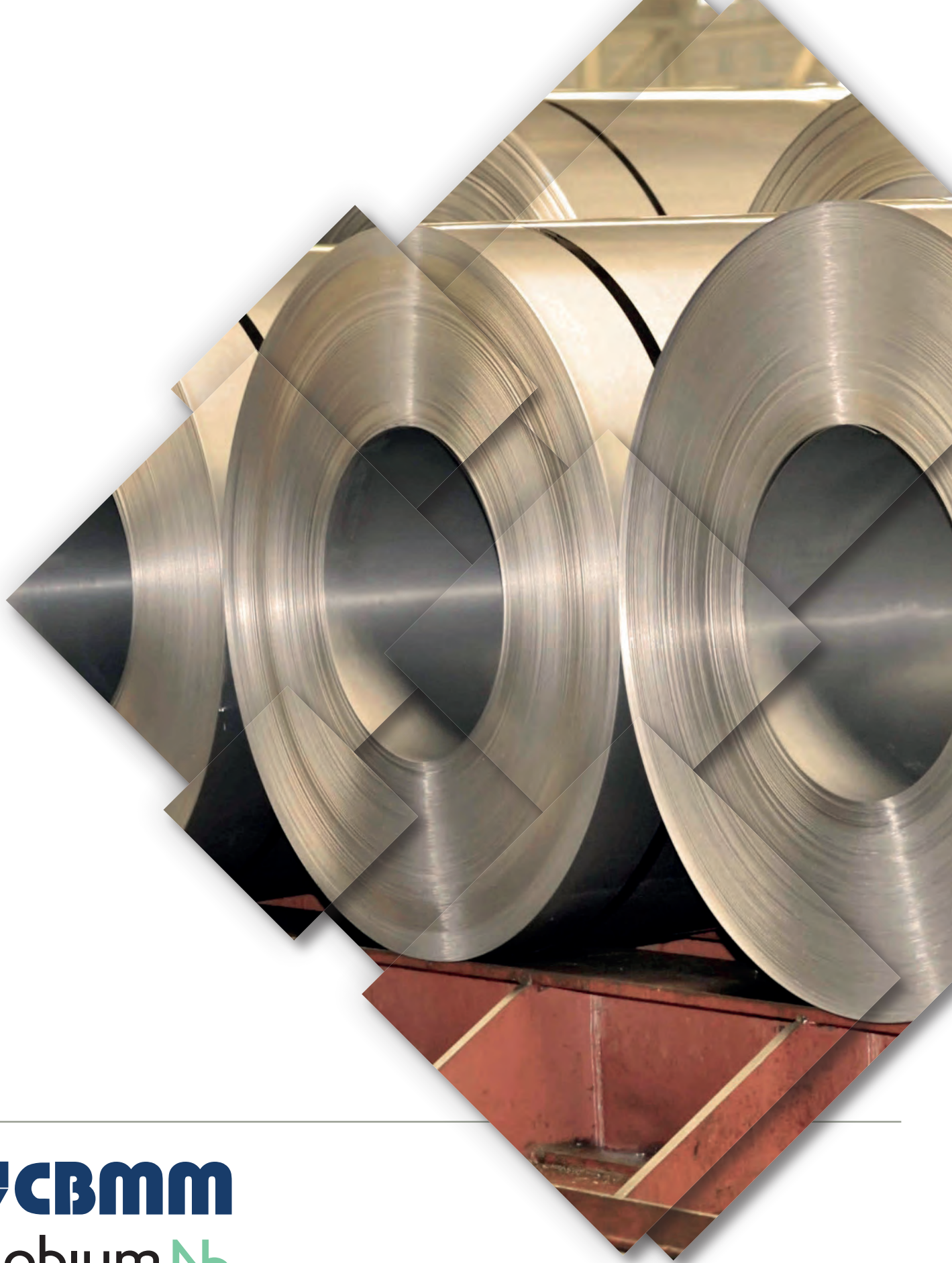
China adopts HTP technology and applies it successfully in their 5,500 mile X80, 2nd West East high pressure gas pipeline.

2015/16

310,000 tonnes of X70 low carbon, niobium HTP steel supplied for a key section of the TANAP gas pipeline project, and a further 75,000 tonnes to the TAP project.

2017+

Low manganese, 'sour service' variants of HTP steels and optimized 'OHTP' steels with carefully tailored chemical compositions will become available.



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