PROCESSING OF NIOBIUM-CONTAINING STEELS BY STECKEL MILL ROLLING

L.E. Collins

IPSCO
P.O. Box 1670,
Armour Rd., Regina, Canada, S4P 3C7

Abstract

The Steckel mill is a reversing rolling mill in which steel strip is coiled after each rolling pass in a heated coilbox positioned on either side of the mill. In addition to the lower capital costs associated with a single stand mill in comparison to multi-stand finishing mills, the Steckel mill offers a high degree of flexibility in the steel rolling process. IPSCO has pioneered the use of the Steckel mill for the production of flat-rolled high-strength steel for linepipe and structural applications. Much of this development has been based on an Nb-microalloying strategy. Niobium plays a key role in development of a fine-grained high strength steel in a number of ways: a) Nb(C,N) precipitation in austenite retards recrystallization effectively refining grain size; b) Solute Nb acts to enhance the hardenability of the steel, promoting formation of an acicular ferrite microstructure; and c) Nb(C,N) precipitation in ferrite subsequent to transformation provides substantial precipitation strengthening. This paper will review the use of niobium in microstructure development during Steckel mill rolling.

Introduction

The Steckel rolling mill provides a high degree of flexibility in steel processing. IPSCO operates three such mills located in Regina, Canada, Montpelier, Iowa and Mobile, Alabama, to produce a wide range of flat-rolled steel products. This paper will examine the use of the Steckel mill and, in particular, will focus on its application for processing of high strength microalloyed steels.

What is a Steckel Mill?

Figure 1 illustrates the basic features of a tandem mill compared to a Steckel mill. After roughing, the conventional tandem mill employs a series of mill stands located in close proximity. The steel passes unidirectionally through these stands. In contrast, the Steckel mill is a reversing mill with coil furnaces located on either side of the mill. As the strip passes through the mill on each consecutive pass, it is fed into a furnace where it is wrapped on the coiler drum. By maintaining furnace temperature slightly in excess of the strip temperature, heat is retained in the strip. In the Regina steel operations, the slab is first broken down at a 2 Hi roughing mill before being transferred to the 4 Hi finishing mill. Alternatively, both roughing and finishing operations may be performed on a single finishing stand, as is the case in IPSCO's Montpelier and Mobile facilities. This paper will focus on the production of high strength coil and linepipe skelp in the Regina mill.

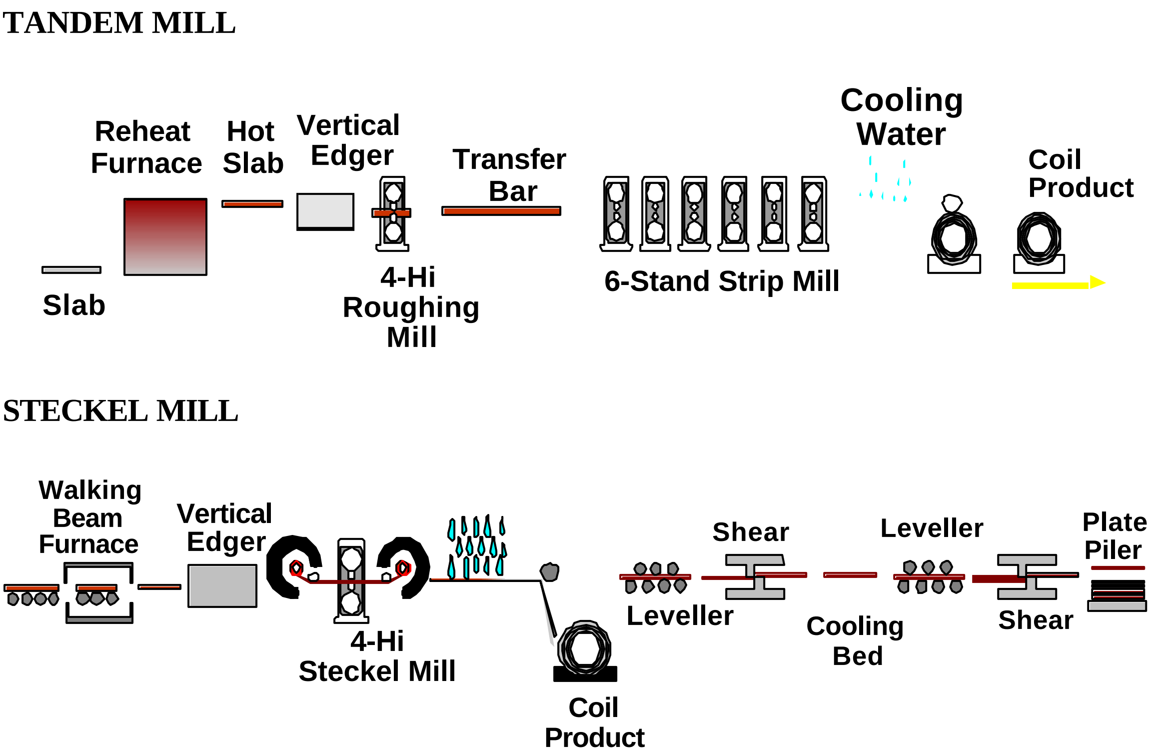


Figure 1: Schematic illustrations of tandem and Steckel mills.

Operating Features

The layout of the Regina plant operations is shown schematically in Figure 2. Scrap is melted in two electric arc furnaces and transferred to a ladle metallurgy furnace for final alloy additions. A 203 mm thick slab is continuously cast and transported to the slab yard. After a period of time, the slab is charged into a walking beam reheat furnace. While a hot charging practice is dictated by metallurgical factors for a small number of high carbon and high alloy products, scheduling of most slabs is dependent on current operational and delivery requirements. Typically 50 to 60 % of slabs are charged at temperatures > 375°C.

After the slab is fully soaked, it is discharged and transported to a 2 Hi roughing mill where it is broken down to a transfer bar between 20 and 38 mm thick. Edging is also performed in conjunction with the roughing operation. Finish rolling is performed at the 4 Hi Steckel mill after which the strip is cooled in a laminar flow cooling system and coiled at the upcoiler. Coil gauges range from 2.25 mm to 19 mm. Also, the upcoiler can be bypassed to allow production of plate in gauges from 9.5 to 76 mm.

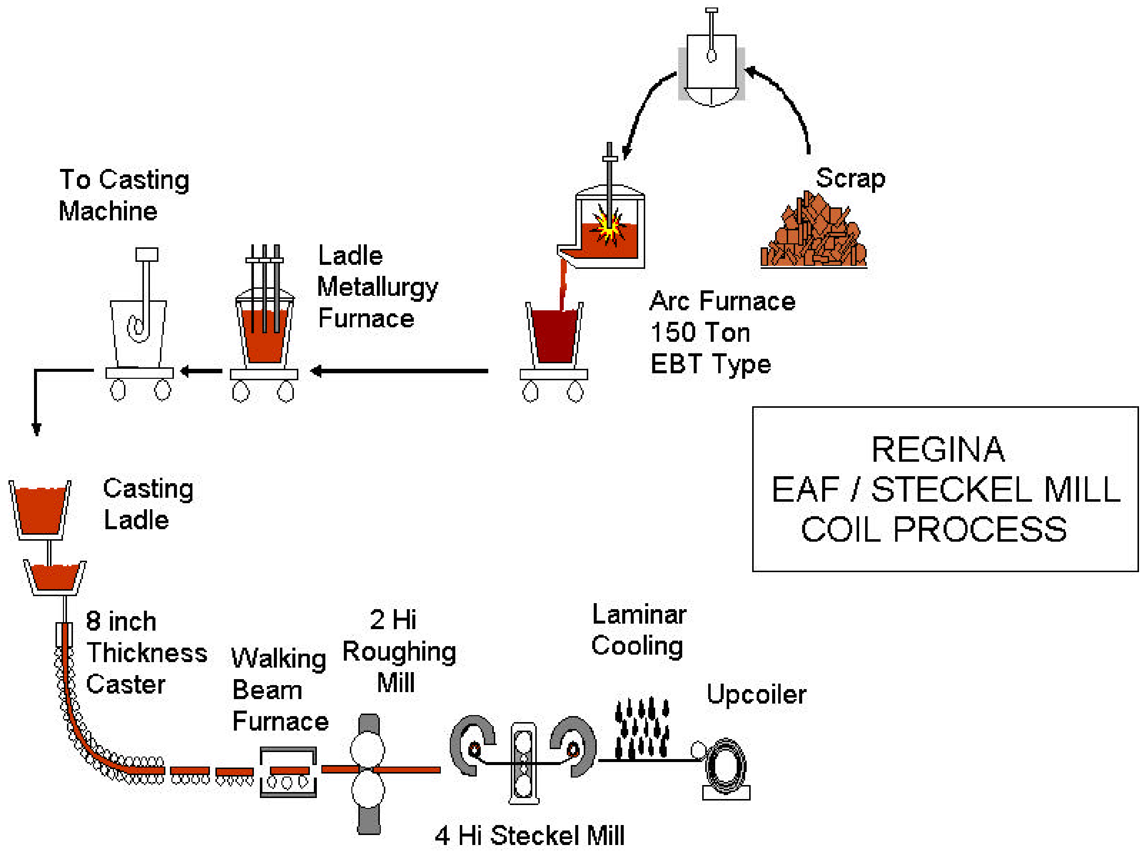


Figure 2: Schematic of EAF / Steckel Mill Production Process.

These operations permit the production of a wide range of alloys including low carbon steels, high strength microalloyed grades, high carbon steels (1085) and high alloy grades (4140, 6150). These products may be shipped directly to customers as coil or plate, or be transferred to IPSCO's cut-to-length coil processing facilities. A significant proportion of Regina production is also transferred to IPSCO's Tubular mills where electric resistance welding (ERW) or spiral double submerged arc welding (DSAW) processes are employed to fabricate products ranging from small diameter (50 mm) water pipe to large diameter (2032 mm) high strength linepipe.

The remainder of this paper will focus specifically on the production of high strength microalloyed coiled product for structural and linepipe applications.

Alloying and Rolling Strategy

Alloying

The production of high strength as-rolled steel requires that a carefully selected alloy design be combined with closely controlled rolling practices.

A Ti-Nb microalloying strategy has been adopted as the basis for the development of high strength steels. As outlined in Table I, carbon is generally kept < 0.06 wt% to enhance toughness and weldability. Manganese and molybdenum are the principal alloying agents. Both provide solid solution strengthening and act to suppress the austenite to ferrite phase transformation, thereby promoting the development of a fine acicular ferrite microstructure during the transformation from austenite to ferrite. Titanium nitrides, formed early in the solidification and cooling process are utilized to suppress austenite grain growth during reheating and during recrystallization rolling.

Table I Alloying strategy for high strength steels

Element	Purpose
C< 0.06 wt%	High impact toughness, good weld ability
Mn	Transformation control, solid solution strengthening
Mo	Transformation control, solid solution strengthening
Ti	Grain growth control during recrystallization rolling
Nb	Inhibit recrystallization, transformation control, precipitation strengthening
S<0.004 wt%	Impact toughness

Niobium plays a key role as it performs 3 functions:

a) By precipitating as Nb(C,N) in the austenite during finish rolling, niobium acts to pin grain boundaries and prevent recrystallization;
b) Niobium retained in solid solution at the completion of finish rolling will aid manganese and molybdenum in the suppression of the austenite to ferrite phase transformation; and
c) Upon completion of transformation, the ferrite is supersaturated with niobium, carbon and nitrogen. Further precipitation of fine Nb(C, N) particles after coiling provides an additional component of precipitation strengthening to the steel.

For applications requiring impact toughness, sulfur is kept low (<0.004 wt%) to minimize formation of MnS inclusions, which are detrimental to fracture toughness. As an electric arc furnace is employed to melt scrap feedstock, residual levels of Cu, Ni and Cr will also be present. Melting practices employ an aim carbon equivalent and adjustments are made to manganese content to minimize any variation in hardenability, which might arise from variations in residual levels.

Rolling

For high strength products, a controlled rolling strategy is followed (Fig.3). Continuously cast slabs are reheated in a walking beam furnace with Level II control system to ensure slabs are uniformly soaked. Upon completion of reheating, the slab is discharged and transferred to the 2 Hi roughing mill where it is rolled to a gauge of between 20 and 38 mm in 12 to 14 passes.

The bar is then transferred to the finishing mill for final rolling. Depending on the gauge and the entry temperatures specified for the product, the transfer bar may be rocked back and forth on the roll table to dissipate heat prior to entering the Steckel mill. For controlled rolled products, the entry temperature will be specified to be less than the recrystallization stop temperature (T_{nr}), which generally may be taken to be 925°C [1].

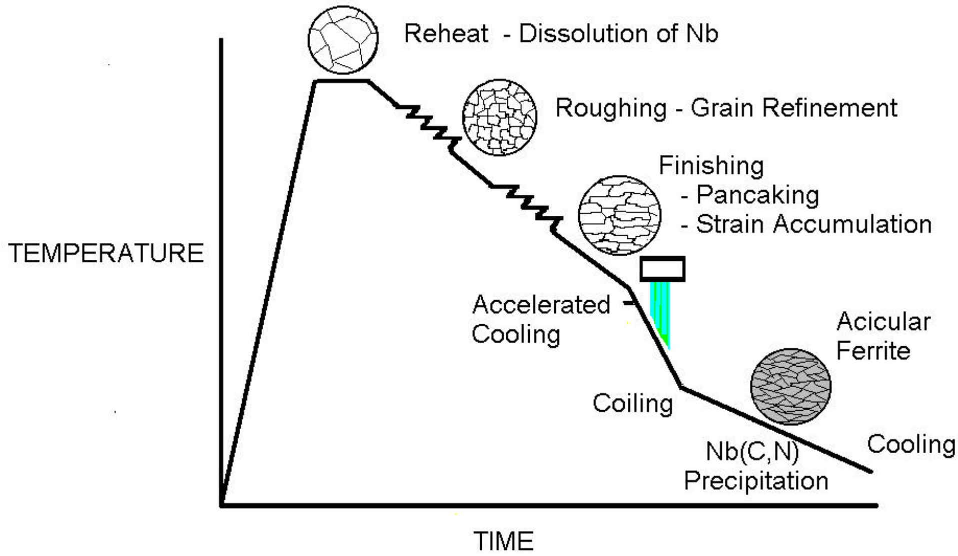


Figure 3: Stages of controlled rolling.

The strip will be rolled to the final gauge using a 5 or 7 pass schedule. The strip exits the mill at a temperature slightly greater than the transformation start temperature and immediately enters the laminar flow cooling system. Coiling temperature is specified to ensure transformation to a fine-grained ferrite and/or bainite microstructure.

Figure 4 illustrates the benefit of accelerated cooling after rolling. The objective of accelerated cooling is to rapidly reduce the austenite temperature. It has long been appreciated that greater undercooling below the Ac_1 temperature enhances the driving force for the austenite to ferrite transformation thereby increasing nucleation rate. Ferrite growth rates, which are dictated by diffusion processes, slow as temperature is reduced. Ideally, transformation would occur isothermally at a temperature, which produces a high ferrite nucleation rate and low ferrite growth rate. It must be remembered that if cooling is excessive, the diffusional processes required for ferrite nucleation become rate determining and will eventually inhibit ferrite nucleation and result in formation of bainite or martensite. Depending upon alloy content, accelerated cooling is normally interrupted in the temperature range of 525 to 625°C.

In selecting the coiling temperature, the subsequent precipitation of Nb(C, N) in ferrite as the coil slowly cools to ambient conditions is also considered. It is well known that a dispersion of fine precipitates in the steel provides a valuable strengthening mechanism. It has been found that the Nb(C, N) particles, which precipitate in austenite during rolling, are too coarse to provide significant precipitation strengthening. Rather, formation of a fine dispersion of Nb(C, N) in the ferrite must be encouraged. This can be accomplished by the natural slow cooling of the finished coil after accelerated cooling. Evidence of such precipitation behaviour was provided by laboratory studies in which the steel was controlled rolled on a pilot-scale mill, cooled at 15°C/s to 550°C and then air cooled (1°C/s) to ambient conditions. Air-cooling provides insufficient time for the Nb(C, N) precipitation in the ferrite to reach completion. When the steel was then reheated to 550°C for a period of time and then retested after cooling, the yield strength was observed to gradually increase as precipitation proceeded. Various studies have shown that optimum strengthening is achieved between 500 and 600°C [2,3].

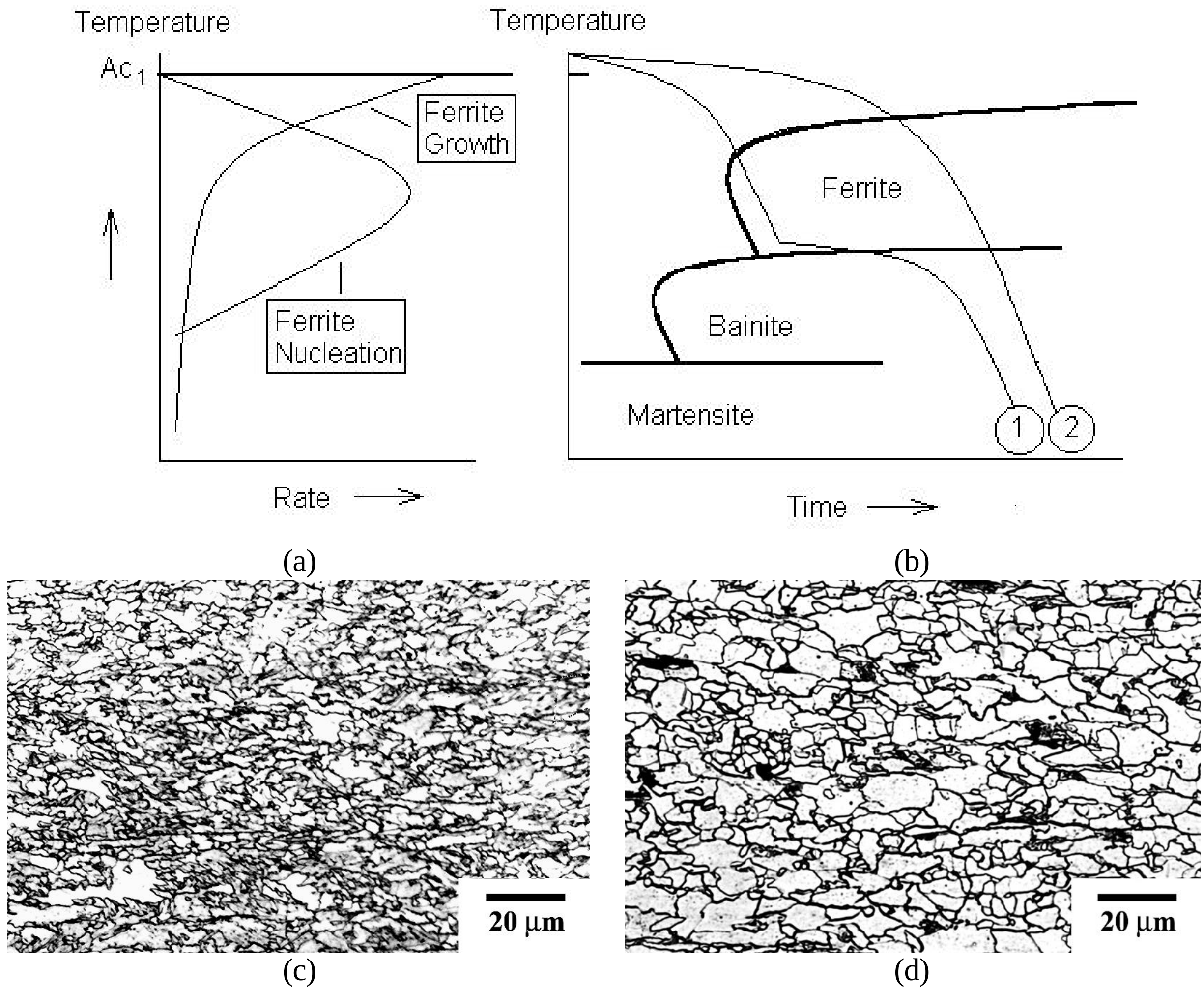


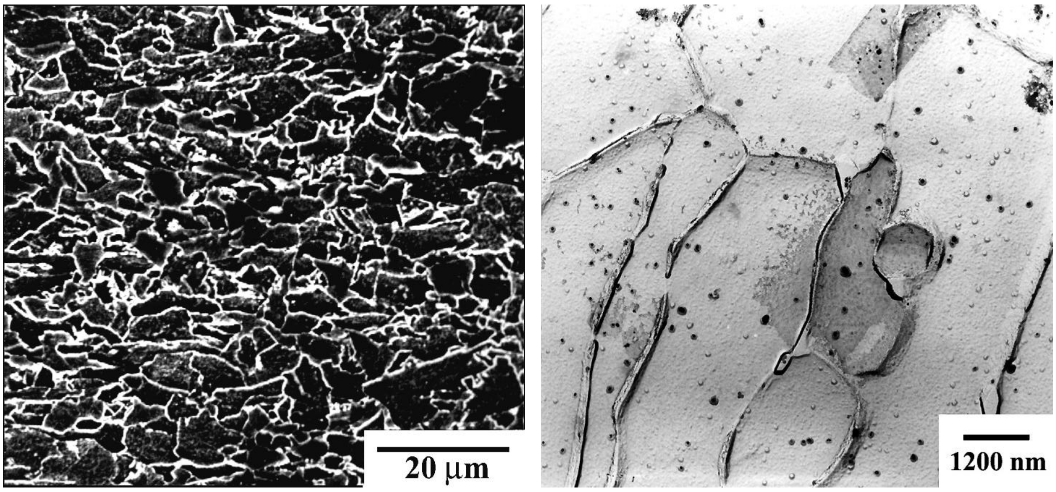
Figure 4: Effect of cooling conditions on microstructure. a) Variation of ferrite nucleation and growth rates with temperature; b) Corresponding CCT diagram illustrating accelerated cooling (1) and air cooling schedules (2); c) Fine-grained ferrite microstructure from accelerated cooling followed by slower cooling after coiling and d) Coarse grained microstructure resulting from slow cooling.

Secondary Processing

The final properties of the steel will also depend upon any secondary processing. Within IPSCO, two types of operations may result in further modification of the properties. These are: a) Pipemaking, and b) temper leveling.

The forming processes involved in pipemaking may result in either an increase or decrease in pipe strength depending on gauge and pipe diameter due to Baushinger effects associated with pipeforming and subsequent testing. Temper leveling operations produce an increase in strength through dislocation strengthening mechanisms.

By following the alloying and rolling strategies outlined above, a fine acicular ferrite microstructure strengthened by Nb(C,N) precipitates is obtained (Figure 5).



(a) (b)

Figure 5: Microstructure of Grade 80 Steel. a) SEM micrograph showing fine acicular microstructure. b) TEM micrograph showing dispersion of coarse and fine Nb(C,N) precipitates.

Processing Features of the Steckel Mill

Although the general alloying and processing strategy employed in a Steckel mill is similar to that utilized in tandem mills, there are some important processing differences, which affect the final properties.

<u>Time</u>

There is a very significant difference between a tandem mill and a Steckel mill in the timing of passes. This is illustrated schematically in Figure 6.

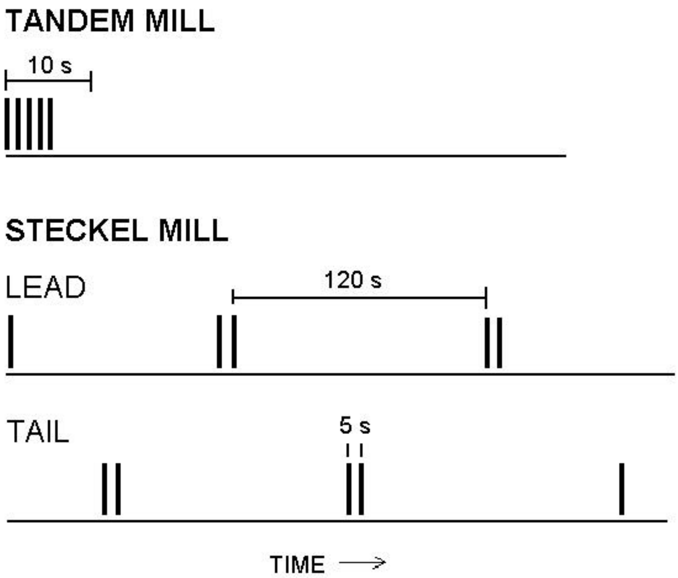


Figure 6: Timing of passes in tandem and Steckel mill operations.

In the tandem mill, interpass times are relatively short, (on the order of seconds) as the strip is fed from one stand to the next. Furthermore, the interpass times decrease as the strip advances through the mill in proportion to the amount that the strip accelerates as it passes from one stand to the next. It should be noted that every portion along the length of the bar experiences approximately the same interpass time between stands.

In contrast, the Steckel mill is a reversing mill. Obviously, the full length of the bar must complete each pass before the subsequent pass can be initiated. Thus, total rolling times are very much longer than those of a tandem mill, typically ranging from 250 to 400 s depending on the final gauge of the product. As well, different portions of the strip experience significantly different thermomechanical cycles. After the lead end of the strip feeds through the mill for the first pass, it will remain on the Steckel drum for almost 100 seconds before the second pass, as the bar is fully wrapped on the drum, the mill is reversed and the second pass is completed. At the tail end of the strip, the interpass time between the first and second passes is on the order of 5 s as the strip drops out of the mill after first pass, the rolls are repositioned and the strip is threaded back into the mill for the second pass. The ends of the bar continue to experience this pattern of alternating long and short holds on the Steckel furnace drums until rolling is complete. At the mid-length of the bar, interpass times are more consistent, but gradually increase as the length of the strip increases from pass to pass.

Temperature

The second area of consideration is temperature performance. In a tandem mill, the very short interpass intervals allow little time for temperature to drop and, consequently, tandem rolling can be considered to be an isothermal process. In the Steckel mill, the coiler furnaces are intended to maintain the temperature of the strip. Nonetheless, there is some temperature loss between passes. This results from interpass descaling, and deliberate cooling. As well, the shaft of the coiler drum is water-cooled and thus there is some temperature loss to the drum itself, particularly on the end of the strip in direct contact with the drum. Further cooling occurs on the on the last portion of the bar to pass through the mill on each pass. This tail end is not taken into the coiler furnace after it drops out of the mill, but is left sitting on the table rolls for the short interval (~5 s) between passes. For these reasons, the ends are chilled more than the body of the coil during rolling. With lighter gauge coils, both the rolling time and cooling rates increase and the colder ends of the strip are accentuated.

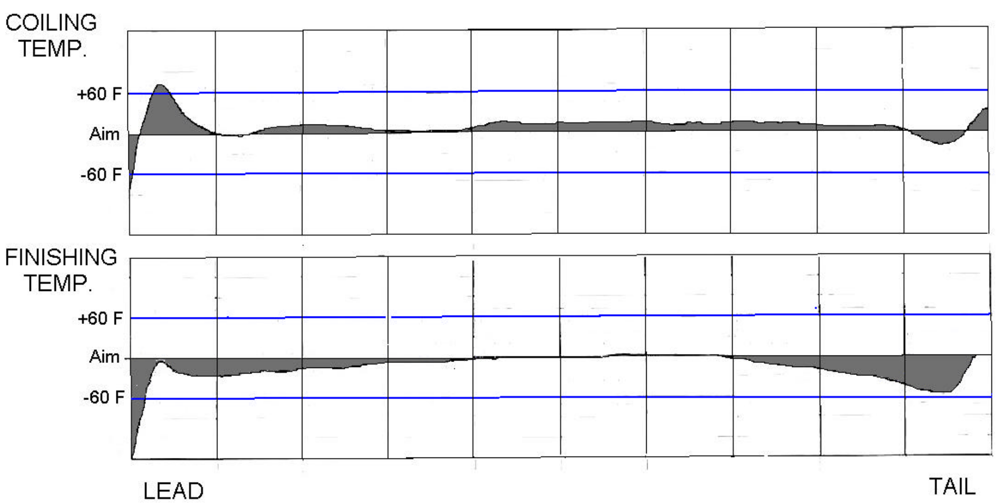


Figure 7: Mill exit and coiling temperature profiles of a light gauge strip.

The culmination of all these factors on the strip as it exits the mill on the last pass is a temperature profile illustrated in Figure 7. Both ends of the strip have a lower temperature than the body of the strip. To maintain a constant coiling temperature, the relatively cold lead and tail can be accommodated to some extent by reducing the amount of water utilized by the laminar flow system on the ends of the strip. In fact, by judicious use of the laminar flow cooling, a hot head end can be produced in which the first 25 feet of the strip is deliberately maintained at a slightly higher coiling temperature than the body of the strip. This is particularly desirable for heavy gauge, high strength coils to improve pickup at the upcoiler.

Metallurgical Effects

Variations in both temperature and time from the ideal controlled rolled schedule impact the metallurgical characteristics of the strip. It is well documented that recrystallization and grain growth are dependent on both interpass time and temperature. In carbon steels, recrystallization will be complete during the relatively long interpass times associated with Steckel mill rolling. This limits the ability to refine grain size. The minimum austenite grain size that can be achieved in recrystallization rolling is 25 to 30 µm. It is for this reason that niobium plays a critical role in IPSCO's processing of high strength steels. By inhibiting austenite recrystallization during finish rolling, a pancaked austenite grain size can be achieved with a grain boundary separation of ~ 5 µm. One disadvantage of the long rolling times in Steckel mill rolling is that Nb(C, N) continues to precipitate in the austenite as rolling proceeds. This reduces the amount of Nb retained in solution upon completion of rolling and, in turn, the ferrite precipitation strengthening potential is reduced. This effect is exacerbated by the relatively high levels of nitrogen (typically 90 to 120 ppm) present in steel produced by electric arc furnace processes. The nitrogen will continue to combine with the Nb until the solubility limit is reached. Thus, much of the niobium added to the steel is effectively wasted, forming a distribution of coarse carbonitrides in the austenite, which exceeds that required to prevent recrystallization during finish rolling.

The colder ends of the bar also have metallurgical implications. In general, it is observed that strength increases with lower rolling temperature as is illustrated in Figure 8. This is due to enhanced grain refinement.

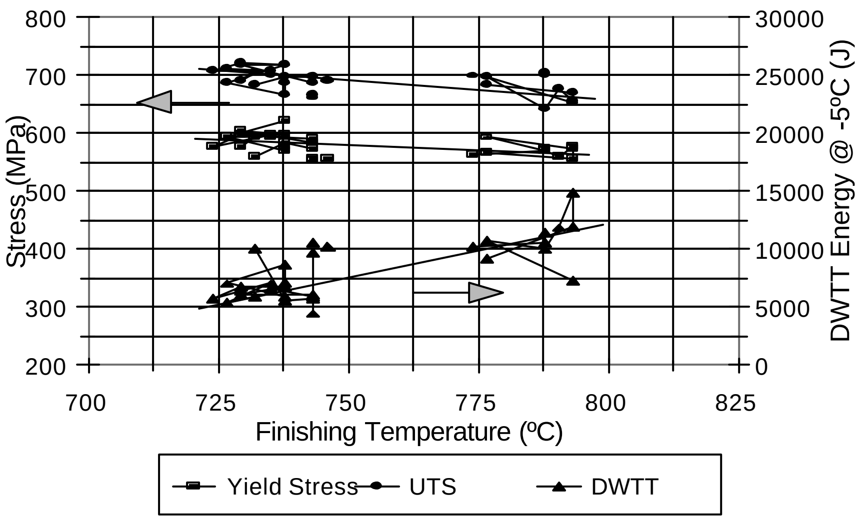


Figure 8: Effect of finishing temperature on strength.

The strengthening effect of the lower rolling temperatures tends to be offset by the more rapid cooling of the coil ends after the strip has been coiled. The contribution of precipitation strengthening after coiling was noted earlier. As the inner and outer wraps tend to cool more quickly than the body of the coil, precipitation strengthening in these areas is inhibited. Air-cooling compared to coil cooling of X70 skelp can result in a loss of 40 MPa in yield strength.

It is fortuitous that rolling patterns at the ends of the bar and center portions have offsetting effects on metallurgical behaviour. The mid-length of the bar has higher rolling temperatures but experiences slower cooling in the coil, whereas the ends experience lower rolling temperatures, but cool more quickly after coiling. Reduced ferrite precipitation strengthening on the outer wraps of coils is offset by the strengthening effects of the colder rolling temperatures at the ends of the bar. The result is a product with relatively uniform properties throughout the length.

<u>Summary of Role of Niobium in Steckel Mill Rolling</u>

Niobium has been a critical component of IPSCO's alloying strategy for Steckel mill rolling. It offers three key metallurgical benefits:

1) Nb(C, N) precipitation in austenite strongly suppresses austenite recrystallization during finish rolling. This beneficial effect is seen despite the long and varying interpass times experienced in Steckel mill rolling.
2) Niobium in solution acts to inhibit transformation promoting formation of a fine acicular microstructure in low carbon steels; and
3) Nb(C, N) provides precipitation strengthening in the final ferrite microstructure.

It should be noted that several factors mitigate the most effective use of niobium in the electric arc furnace / Steckel mill rolling processing route:

1) The prolonged rolling times promote excessive Nb(C, N) precipitation during rolling, thus demanding that large amounts of Nb be added to the steel to achieve the desired precipitation strengthening effects of ferrite subsequent to transformation.
2) Excess nitrogen associated with electric arc steelmaking further promotes the wasteful precipitation of Nb in the austenite regime and every effort is required to minimize nitrogen content of the steel.

Recent Developments in Processing High Strength Steels

IPSCO's development of X80 linepipe (minimum YS = 550 MPa, 80 ksi) began in the early 1990's with the first commercial production in 1994 [4]. The production of Grade 550 structural steel soon followed. These products are now routinely produced in gauges ranging from 4.75 to 16 mm. Looking to the future, there is increasing demand for hot rolled steel with even greater strength for both structural and linepipe applications. As well, greater wall thickness is now being sought for linepipe applications. Recent development activities in both these areas will be highlighted below.

<u>Grade 690 Structural Steel</u>

Driven primarily by demands from the transportation industry for steels with high strength to weight ratio, IPSCO undertook the development of a Grade 690 coiled plate product. Target properties included: YS > 690 MPa; UTS > 760 MPa; Elongation > 15% and Bend radius < 2.5 t.

The alloy design was based on IPSCO's linepipe formulation. However, Canadian Standards Association (CSA) specifications limit the addition of Mn in structural steels and thus the primary alloying agent that has been employed to increase yield strength beyond 550 MPa has been the addition of titanium. As illustrated in Figure 9, a linear relationship is seen between yield strength and titanium content with additions from 0.02 to 0.07 wt %. Trial work resulted in the successful development of steel with yield strength in excess of 620 MPa, but failed to produce a product which consistently achieved the 690 MPa target yield stress (See Table II).

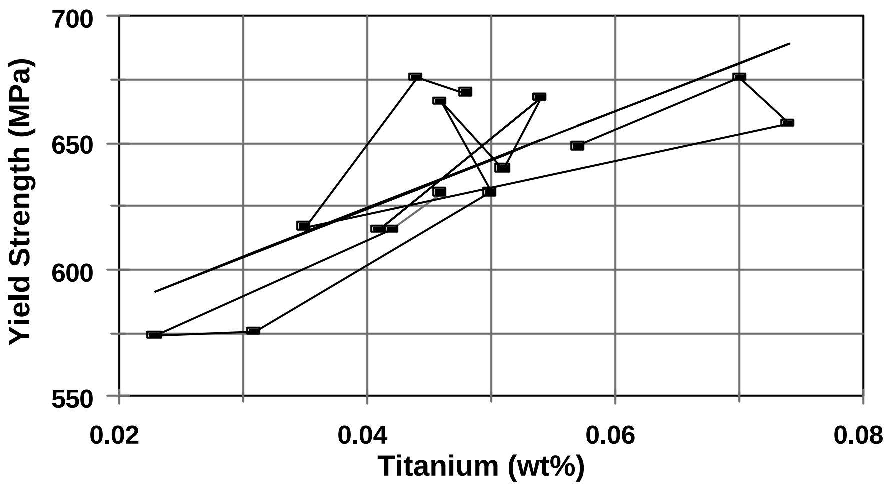


Figure 9: Effect of Titanium on Yield Stress

Table II Grade 620 Properties. Base chemistry: 0.06 C, 1.55 Mn, 0.090 Nb; Gauge = 6.35 mm.

Alloy	Ti (wt%)	YS (MPa)	UTS (MPa)	Elongation (%)	Charpy* @ -20 C (J)	Bend Radius
Gr. 550	0.025	584	687	27	98	<2.5t
Trial	0.055	668	788	17	77	2.5t

* ½ size charpy sample.

To achieve a yield stress of 690 MPa, it was recognized that IPSCO's temper leveling operations could be applied to strengthen the steel by cold work. These facilities utilize a 4 Hi cold mill in front of a conventional leveling stand to cold roll steel strip. Typical cold reductions of 1 to 3 % are applied. In addition to the strengthening effect, temper leveling has the following benefits:

a) Improvement of surface finish;
b) Reduction of strip crown; and
c) Elimination of discontinuous yielding in carbon steels.

As demonstrated in Table III, cold reduction of the steel can be used to increase the strength by as much as 100 MPa, dependent upon the reduction applied. A small reduction in elongation is observed roughly equal to the percent reduction in the cold mill. Charpy impact properties are not greatly affected.

Table III Effect of Temper Levelling. Base Chemistry (wt%) - 0.060 C, 1.55 Mn, 0.050 Ti, 0.090 Nb; Gauge = 7.93 mm.

Condition	YS (MPa)	UTS (MPa)	Elongation (%)
Untempered	660	809	23.0
Tempered	791	908	21.3

A Grade 690 product has now been sold commercially and is finding application in crane booms and truck frame rails.

Challenges of Heavy Gauge Linepipe

At the current time, consideration is being given to construction of a "Northern Pipeline" to transport natural gas from the Arctic (Prudhoe Bay and/or the Mackenzie Delta) to the southern 48 states, a distance greater than 3000 km. Economic considerations in constructing such a pipeline are forcing examination of pipelines which would operate at pressures as great as 17,240 kPa (2,500 psi). Such lines would in turn, require high strength, heavy wall pipes. In 2000, Alliance Pipeline completed construction of a 914 mm diameter pipeline from Fort St. John to Chicago, which operates at 12,000 kPa (1,750 psi) [5]. At the time, that line was considered a significant leap forward and generated a major debate over the appropriate fracture toughness criteria. To aid Alliance Pipeline in satisfying regulators, IPSCO agreed to supply pipe with a minimum all heat average charpy energy of 280 J at –5°C. Burst tests performed by Alliance on this design demonstrated that the crack arrested in pipe with Charpy energy of 220 J [6].

Typical pipe properties of the pipe produced for Alliance are listed below:

Tensile Properties

YS = 540 MPa   UTS = 634 MPa   Elong. = 42%

Fracture Toughness

Charpy Energy = 347 J @ -5°C;   Shear = 99.7%

DWTT = 7099 J @ -5°C,   Shear = 95.7%

Preliminary proposals for the Northern Pipeline call for a minimum yield strength of 550 MPa, and wall thickness ranging from 17 to over 25.4 mm thick (Table IV).

IPSCO has a wide range of experience in pipe production and can claim to be one of the world's most experienced producers of X80 linepipe having produced over 32,000 tons of spiral X80 pipe in gauges ranging 9.8 to 16 mm [4,7]. Nonetheless, the proposed requirements for the Northern Pipeline present major challenges to all steel producers. These are best understood by examining the ideal processing conditions for production of heavy gauge linepipe.

In the Regina mill, operators have sought to achieve the following conditions for production of strong, tough skelp:

80% rolling reduction at the roughing mill;
60% reduction below T_{nr};
Cooling rate after rolling greater than 15°C/s; and
Slow cooling of the final coil.

Table IV Proposed designs for a Northern pipeline

Grade	Diameter (mm)	Gauge (mm)	Pressure (kPa)	(psi)
X80	1067 or 1219	17.0 – 26.5	12,485 - 17,240	2050 - 2500
X80	1067	18.0 – 32.4	14,900 – 17,240	2160 - 2500
X80	1321	28.6		

Attaining each of these requirements each presents its own challenges. Achieving the 80% reduction during roughing followed by 60% reduction below T_{nr} requires an initial slab thickness of 238 mm for a 19 mm thick final product and a slab thickness of 317.5 mm for a 25.4 mm thick final product. Clearly, a compromise is required if the initial slab thickness is limited to 203 mm. There is some scope to reduce the requirement for 80% reduction during roughing while still attaining a fine recrystallized austenite grain size at the end of roughing. As well, IPSCO's new mills in Montpelier and Mobile are capable of greater reductions in each pass than has been possible in Regina. It has been found that employing heavier reductions during individual passes offsets to some extent the requirement for large total rolling reductions in order to achieve fine grain sizes.

A further problem with rolling a thick final product is achieving penetration of the deformation into the center portion of the slab. As illustrated in Figure 10, the deformation and consequent grain refinement will tend to concentrate near the surface while the interior will undergo less deformation, resulting in a coarse grain size that is detrimental to both strength and toughness. One means by which this might be addressed is by cooling the transfer bar temperature to deliberately create a temperature gradient through the thickness. During finish rolling, the cooler outer surface of the bar would be more resistant to deformation and the strain would effectively be transferred to the core of the bar.

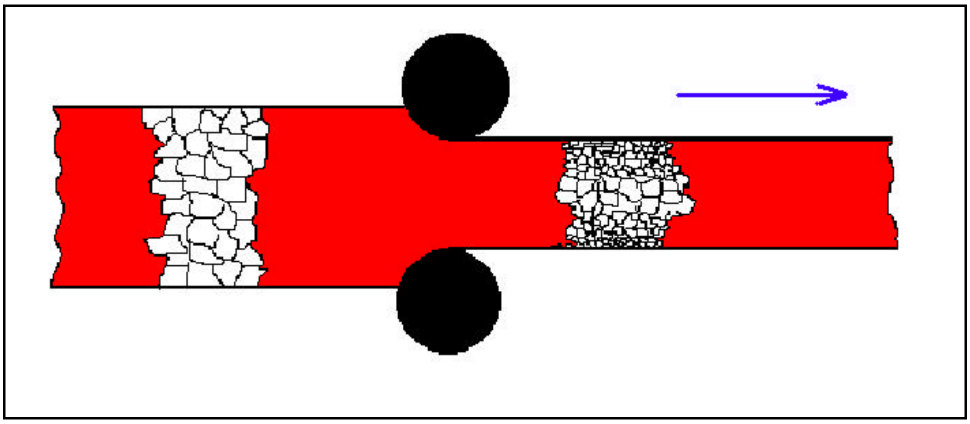


Figure 10: Schematic illustrating grain refinement during rolling of heavy gauge material.

Finally, cooling rate after rolling is important. As discussed previously, grain refinement and increased strength are closely linked to increased cooling rate on the run out table. As skelp thickness increases, it becomes increasingly difficult to maintain a high cooling rate in the interior of the bar. This in turn promotes a gradient in microstructure and properties through the thickness of the skelp with a greater grain size and lower strength obtained towards the mid-thickness of the skelp (Figure 11).

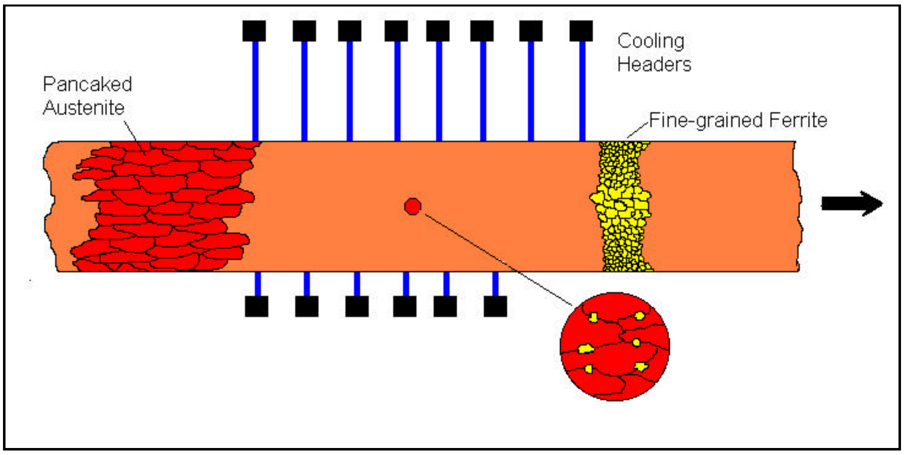


Figure 11: Effect of rolling penetration on *g*rain *r*efinement

The variation in properties through the thickness of the steel is demonstrated in Table V. Three mm thick transverse tensile samples were cut from various positions through the thickness of a 13.3 mm thick X80 strip. The top and bottom surface samples have greater strength than do the interior samples. A full thickness sample produces a result, which is intermediate between the surface samples and the interior samples. Similarly, Charpy impact toughness values have been found to be greater at the surface than in the interior. These enhanced properties near the surface correspond to the finer microstructure, which is obtained in the vicinity of the surface.

Table V Variation of properties through the thickness of 13.3 mm X80

Location	YS (MPa)	UTS (MPa)
Top Surface	619	722
Upper middle 1/4	605	716
Lower middle 1/4	598	710
Bottom surface	617	726
Full Thickness	612	719

The effects of the increasingly inhomogeneous microstructure through the thickness as gauge increases are particularly deleterious to impact toughness. This is illustrated in the variation of Drop Weight Tear Test (DWTT) properties with gauge (Figure 12). Although it has been possible to achieve X80 tensile properties in gauges up to 16.1 mm, a steady deterioration is Charpy toughness and drop weight fracture appearance has been observed.

The achievement of X80 tensile properties in gauges up to 19 or 25.4 mm can likely be achieved through further alloy addition, coiling at lower temperatures and/or cold working. The achievement of suitable fracture toughness is the major challenge owing to the difficulty of refining the interior grain size in heavy gauge material. These challenges are not specific to Steckel mill operations, but must be overcome by all steel producers. If a heavy wall Northern Pipeline is to proceed, it may not be possible to rely on the inherent properties of the steel for fracture toughness and other means of crack arrest will need to be employed.

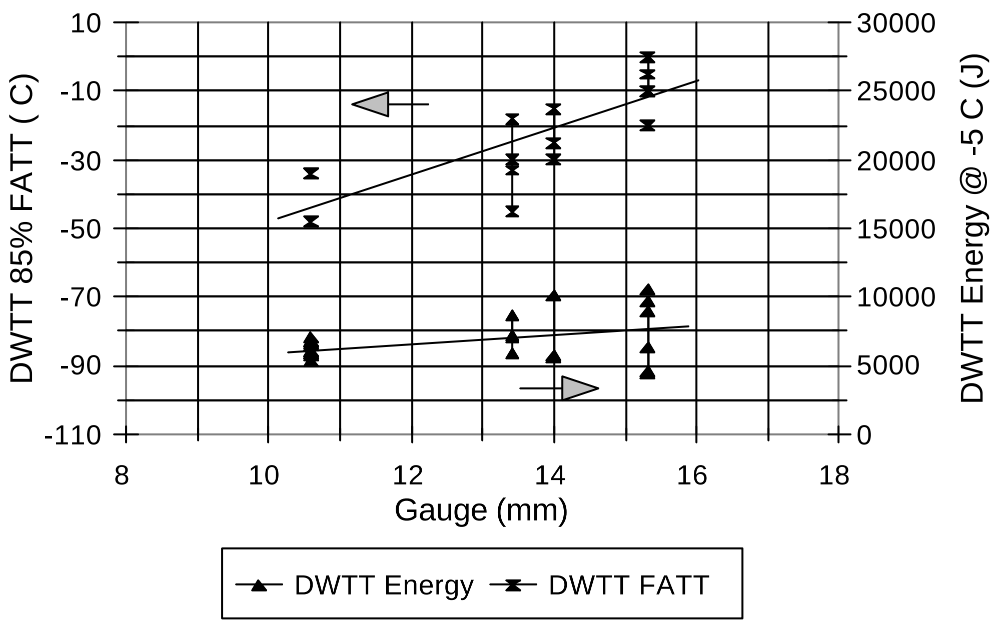


Figure 12: Variation of Drop Weight Tear Test (DWTT) impact properties with gauge for X80 linepipe.

Conclusions

1) Niobium has proven a crucial alloying element in IPSCO's development of high strength steel produced by Steckel Mill rolling. Through its multiple roles as a grain refiner, solid solution strengthener and precipitation hardener, niobium provides uniform properties in controlled rolled steels despite variations in rolling time and temperature throughout the coil.

2) The application of the Ti-Nb microalloying approach appears to saturate at 550-620 MPa owing to the prolonged processing time, which permits excess precipitation in the austenite phase. It appears that new approaches will be required to achieve higher strength particularly in applications requiring fracture toughness.

Acknowledgements

The author wishes to thank IPSCO for the permitting publication of this article. The results presented here are based on contributions of many people. Of particular note is the on-going collaboration with Milos Kostic and Rob Mackenzie at IPSCO and Don Baragar and John Bowker at CANMET.

References

(1) L. E. Collins, "Influence of Thermomechanical Processing on Nb(C,N) Precipitation Behaviour and Mechanical Properties of X70 Linepipe" 34th Mechanical Working and Steel Processing Conference, Iron and Steel Society, Warrendale , PA, (1992).

(2) M. Militzer, E. B. Hawbolt and T. R. Meadowcroft, Metall. Mater. Trans. A vol. 31A, 2000 pp1247-59.

(3) M. Militzer, D. Q. jin and I. V. Samarasekera, in Advances in Industrail Materials, Ed. D. S. Wilkinson, W. J. Poole and A. Alpas, The Metallurgical Society, of CIM, 1998.

(4) M. M. Kostic et al. "Development and Production of X80 (550 MPa) Gas Transmission Linepipe", Pipeline Technology, Proceedings of the 2nd International Pipeline Technology Conference, Ostend, Belgium, September 11-14, 1995, Volume II, pp.399-409.

(5) B. Eiber, B. Leis and L. Carleson, "Fracture Control for the Alliance Pipeline", 2000 International Pipeline Conference – Volume I, ASME 2000, pp 267 – 277.

(6) D. M. Johnson, N. Horner, L. Carleson and R. Eiber, "Full Scale Validation of the Fracture Control of a Pipeline Designed to Transport Rich Natural Gas", Pipeline Technology, Volume 1, Ed. R. Denys (Editor), 2000 Elsevier Science B.V., pp 331-342.

(7) M. M. Kostic, L. E. Collins, A. Kapoor, and R. D. O'Hara, "Development of Heavy Gauge X80 Linepipe, Proc. Of the International Pipeline Conference, (IPC'96), Calgary, June 7 – 11, 1998, ASME, New York, NY (1998) pp. 665-688.