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PRODUCTION OF HIGH STRENGTH LINE PIPE STEEL BY STECKEL MILL ROLLING AND SPIRAL PIPE FORMING

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Abstract

Since 1994, IPSCO has produced over 180,000 tons of X80 linepipe. This steel has been produced using a unique combination of electric arc furnace (EAF) melting, controlled rolling on a Steckel mill and spiral pipe-forming with double submerged arc (DSAW) welding. Each of these technologies presents unique challenges for the production of linepipe requiring high strength, low temperature toughness and weldability. Scrap-based EAF melting technology requires careful control of residual elements. Controlled rolling on a reversing Steckel mill demands relatively long rolling times that counter the achievement of fine-grained microstructures. Spiral pipe-forming requires careful control to ensure dimensional tolerances and weld quality are maintained. Nonetheless, each of these technologies offers their own efficiencies and benefits and with proper control, production of high quality linepipe is achievable in an economic manner. This paper will examine the linkage of these various operations to achieve the efficient production of high quality linepipe.

Introduction

The construction of the Cheyenne Plains pipeline in 2004 represents the largest single application of X80 linepipe in North America. Running 380 miles through Colorado and Kansas, the design utilized 0.464 ins. x 36 ins. diameter X80 material for the mainline with 0.667 ins. x 36 ins. diameter X80 employed in regions requiring a greater safety factor [1]. A major portion of the pipe (~300 miles) for this project was spiral-welded linepipe supplied by IPSCO. The IPSCO production process incorporates a unique combination of process technologies. Steelmaking is a scrap-based processs, which incorporates Electric Arc Furnace (EAF) melting and ladle refining. The steel is continuously cast and then rolled in a reversing Steckel mill and coiled. Finally the skelp is transformed into pipe in a Double Submerged Arc (DSAW) spiral welding operation.

IPSCO has utilized these technologies to advantage to efficiently produce steel and pipe for demanding linepipe applications. This paper will review these processing technologies as they apply to linepipe production and demonstrate how these individual technologies can be combined to achieve tightly-controlled properties.

Two major initiatives were incorporated in the Cheyenne Plains project. The first was the production of heavy gauge (0.667 ins.) product, which required upgrades to IPSCO's pipeforming equipment. Secondly, efforts were directed to reduction of nitrogen levels over the duration of the run. This has provided opportunity to analyze the effects of nitrogen on properties. This paper will provide a summary of both of those initiatives as well as highlighting the overall performance.

Steel Processing

Steelmaking

Steelmaking begins with the alloy specification process. For high strength linepipe, IPSCO employs a low-carbon, Ti-Nb microalloyed chemistry (Table I). Manganese, molybdenum and niobium are the principal elements utilized to control strength. As the EAF process is a scrap-based process, it is important to understand the tolerance of the product for such residual elements as (Cu, Cr, Ni, S, P) which originate from the scrap supply. Also of concern is the nitrogen content of the steel.

Table I. Aim Chemisty (wt %)

Gauge (ins)	C	Mn	Mo	Nb	Ti	$CE_{(CSA)}$	Residuals
0.464	0.035	1.70	0.20	0.09	0.020	0.25	Typical of EAF steelmaking

Residual elements

Elements such as Cu, S, P, originate from the scrap supply. For linepipe, fracture toughness is a critical requirement. It has long been recognized that the presence of sulfur, which forms elongated manganese sulfide stringers is highly detrimental to toughness. Dependent on the toughness requirements for a particular project the sulfur level will be restricted accordingly. For the Cheyenne Plains X80 linepipe requiring an all heat average Charpy energy in excess of 200 J, the sulfur level was restricted to a maximum of 0.003 wt %. Similarly, phosphorus is known to be detrimental to toughness and a maximum value of 0.010 wt% was imposed.

Residual elements such as Cu, Ni and Cr have minimal effects on toughness and may actually be beneficial to alloy properties. Cu, Ni and Cr are all known to enhance general corrosion resistance. Further, Ni is considered to have a mildly beneficial effect on fracture toughness. There is frequently concern regarding copper's contribution to hot shortness. Nonetheless, IPSCO has successfully cast and rolled steels with copper levels as great as 0.8 wt %. However, for linepipe applications copper is restricted to a maximum of 0.4 wt%.

All substitutional elements contribute to the hardenability of the steel. While this is of some concern from the rolling perspective, it is of far greater importance when considering weldability. In designing the steel processing schedule, alloying additions are required to suppress ferrite formation and promote the formation of higher strength transformation products during accelerated cooling following rolling (cooling rate 15 to 20^{o}C/s). From the welding perspective, the presence of excess amounts of alloying elements may cause the formation of hard, low temperature phases in the heat affected zone (HAZ) of the field girth weld where cooling rates may be on the order of 30 to 100^{o}C/s. Generally, project engineers will impose a maximum carbon equivalent. To achieve carbon equivalent targets, IPSCO melting practices specify carbon equivalents limits. As there is some variation in content of residual elements from heat to heat, carbon equivalent is determined at the Ladle Metallurgy Furnace before sending the heat to the caster. If the alloy content, as measured by carbon equivalent, remains low, alloy additions will be made to adjust the chemistry.

Nitrogen

At the onset of this project, nitrogen levels were typically on the order of 105 ppm with approximately 5% of heats exceeding 120 ppm. Over the course of the project, initiatives were taken to lower the average nitrogen level and particularly to tighten practices in order to reduce the number of “high” nitrogen heats.

Nitrogen arises from four main sources: the melting stock providing the source of iron, nitrogen entrapped at the arc plasma, the alloy additions and through exposure to the air during processing of the melt.

Nitrogen contents of scrap vary widely. High nitrogen content in scrap will result in high tap nitrogen levels and monitoring of nitrogen content of input materials is essential. However, carbon content of the melt can be used to flush nitrogen from the bath. If carbon content of the scrap is high, a large volume of carbon monoxide bubbles could be generated deep in the bath and, in the process, significant reduction of nitrogen content of the steel can be achieved.

At the EAF, the dissociation of nitrogen molecules into atoms under the high temperature of the electric arc can be a major source of nitrogen. The resulting atoms readily dissolve in the steel through dissociation and chemical reaction at the slag/liquid steel interface. It is thus necessary to minimize air infiltration through various furnace openings during steelmaking. The slag in the EAF also acts as a shielding medium for the arc. To shield the arc from the atmosphere, it is important to have sufficient volume of slag in the furnace. Thus, EAF slag foaming is very important in shielding the arc from the atmosphere.

Surface active elements, primarily oxygen and sulfur, retard dissolution of nitrogen from air into the steel. During tapping, the turbulence from the incoming stream of steel to the ladle results in a large volume of air being entrained in the ladle. This implies that there is a high possibility of the steel picking up nitrogen from the entrained air. However, if the high oxygen potential of the steel is maintained by not adding oxidants like aluminum, silicon and manganese at tap, nitrogen pick-up from entrained air is minimized.

At the ladle metallurgy furnace (LMF), some degree of argon flushing can be achieved through argon stirring. However, care must be taken that intensive stirring does not expose an eye. Furthermore it is necessary that argon stirring remains continuous so that argon bubbles will constantly displace air from contact with the arc and thus ensure minimal nitrogen pick-up. Care must also be taken that sufficient desulphurizing mix is added to provide adequate insulation in the ladle to avoid exposure of the arc to the atmosphere.

The steel delivered to the caster has been completely deoxidized. The steel surface is free of surface reactive elements, especially oxygen. Thus, the propensity for picking up nitrogen from exposure of the steel to the air is high. The use of argon shrouding, minimization of turbulence of the incoming stream of steel from the ladle to the tundish and maintenance of the adequate insulation with tundish cover slag are all-important.

By implementing improved practices over the course of the project, nitrogen levels were reduced from 105 ppm with a standard deviation of 13 ppm in November of 2003 to 88 ppm with a standard deviation of 9 ppm in March of 2004 and remained stable through the duration of production. The overall nitrogen performance is summarized in Figure 1.

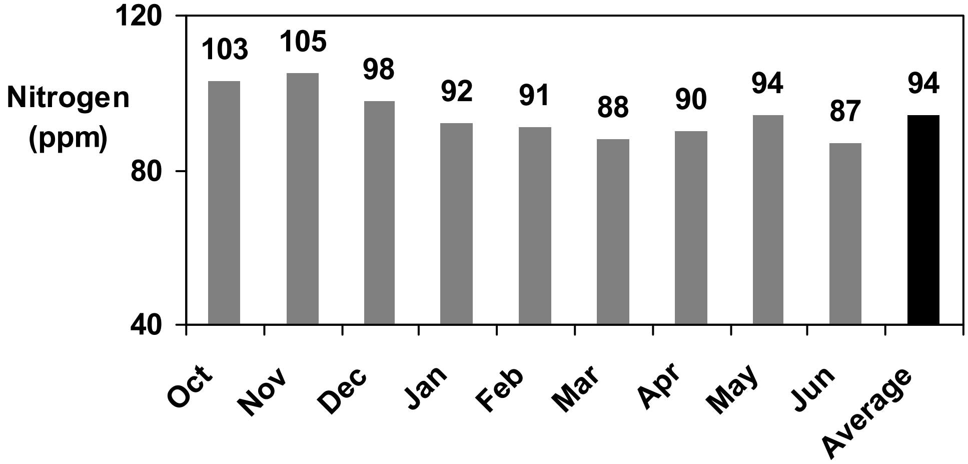


Figure 1a). Reduction in nitrogen level over the course of the Cheyenne Plains project.

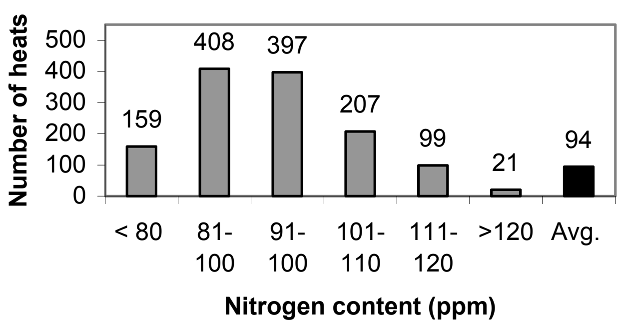


Figure 1b). Overall nitrogen content.

Steckel Mill Rolling

IPSCO's Steckel mill rolling processes have been documented in previous papers [2,3] and are only briefly discussed here. As noted previously, a Ti-Nb microalloying strategy is employed with additions of manganese and molybdenum to promote the formation of an acicular ferrite microstructure. Reheating and rolling practices are designed to control microstructure evolution throughout the process. The ultimate objective is to achieve a fine-grained acicular ferrite microstructure which is precipitation strengthened by Nb(C,N) particles.

The steel is reheated to a temperature sufficient to ensure full dissolution of Nb(C,N), while TiN particles prevent grain growth. Roughing is conducted in a single stand-reversing mill to reduce the slab from the initial 8 ins. slab thickness to a transfer bar that will be sent to finishing mill. This step is intended to refine the austenite grain size. In the finishing mill, the precipitation of Nb(C,N) will inhibit austenite recrystallization resulting in a pancaked austenite microstructure. The transfer bar gauge is selected so that the total reduction in the finishing mill exceeds 50%. Depending on toughness requirements, heavier finishing mill reductions, producing greater austenite pancaking, may be employed. Finishing operations are conducted on a single-stand reversing Steckel mill. For X80 steel, the schedule attempts to achieve isothermal rolling at a low temperature within the austenite regime. Depending upon the final gauge, the transfer bar may be rocked back and forth on the transfer bed while it cools in order to achieve the target finish mill entry temperature. This temperature is specified so as to ensure that the precipitation of Nb(C,N) prevents recrystallization during finish rolling. In the reversing Steckel mill with a

5 pass finishing schedule, total finish rolling times may be on the order of 3 to 5 minutes depending on the final gauge. The precipitation of Nb(C,N) continues as rolling progresses, depleting the supply of solute Nb available for precipitation in the ferrite subsequent to phase transformation. Consequently, every effort is made to minimize rolling time. Immediately after rolling is completed, the strip enters the laminar flow cooling system. Cooling is interrupted at a temperature intended to promote the transformation of the heavily pancaked austenite grain structure to a fine acicular ferrite microstructure. The steel is then coiled and cools slowly (~48 hrs) to ambient conditions. This slow cooling permits the formation of fine Nb(C,N) precipitates in the ferrite which is supersaturated with respect to niobium, carbon and nitrogen. The fine acicular ferrite microstructure achieved at the end of rolling is illustrated in Figure 2.

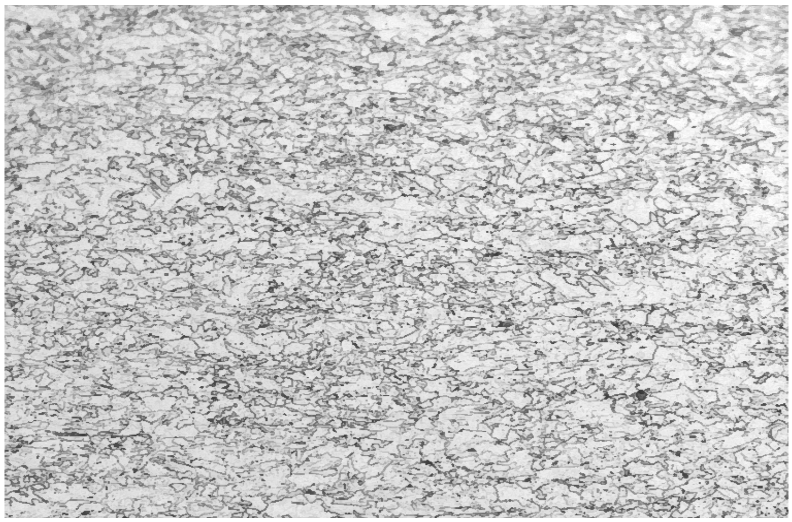


Figure 2. Microstructure of as-rolled skelp.

Spiral Pipe-Making

The spiral pipemaking process has received relatively little attention in the literature. Unlike UOE processes, which employ individual plates to make each pipe, the spiral process employs coils as feedstock offering the opportunity to make several pipe from the same coil.

IPSCO operates three large diameter spiral forming mills, feeding two parallel finishing lines. The processing stages in each mill are similar (Figure 3). The coil is unwound at the uncoiling station and the skelp is passed through a three-roll flattener to flatten the lead end of the coil. The tail end of the previous coil and the head end of the new coil are both cropped at the hydraulic shear. They are then butt-welded together with a single pass at submerged arc welding (SAW) station. By joining the new coil to the previous coil, it is easily threaded through the pipe forming section of the mill. The length of pipe containing this splice weld will later be cut out and discarded.

Figure 3. Spiral Mill Operations Flow Chart.

After the butt weld is completed the strip passes through a seven-roll leveller to fully flatten the strip. At the milling station, approximately 3/8 ins. of material is removed from each side of the strip. This process serves several purposes: the mill edge is removed providing clean mating surfaces for the spiral welding process; any variation in the width of the skelp is eliminated; and an appropriate bevel may be imparted on the edge of the skelp to ensure a satisfactory weld is achieved.

The strip then passes through the drive rolls, which propel the skelp through the forming process. Edge crimping stands are positioned beyond the drive rolls. If the flattened skelp is subject to the forming process, the edges of the strip will tend to flare out and result in a peak at the weld. To counter this behaviour, the edge of the strip is deliberately bent upwards i.e. towards the inner diameter of the pipe so that after the pipe is formed, the mating surfaces come together squarely. The amount of the crimp must be adjusted depending upon the grade and gauge of the skelp.

The skelp is next fed through the forming process. Two parallel sets of bed rolls support the skelp on either side of a set of forming rolls located on the boom and centered between the two sets of bed rolls (Figure 4). A hydraulic cylinder exerts downward force on the boom pressing it down against the strip applying the bending force necessary to form the pipe. The diameter of the pipe is controlled by the pressure applied through the hydraulic cylinder to the boom and the spacing between the parallel sets of bed rolls.

Prior to the Cheyenne Plains project, IPSCO had produced limited amounts of pipe in gauges greater than 0.600 ins. The Alliance Pipeline project had required 400,000 tons of 36 ins. x 0.561 ins. X70 (D/t =64.2) and 1250 tons of 0.625 ins. x 36 ins. X60 (D/t = 57.6) had been produced for another order. Prior to starting the production of the Cheyenne Plains project, a trial was undertaken to assess the mill's capability of forming the heavy gauge (0.667 ins.) material. The trial confirmed that the mill possessed sufficient capability for unwinding, flattening and milling operations. However, problems were encountered in the forming stands. Specifically, the crimp stand lacked sufficient capability to crimp the edges of the strip; internal bearing surfaces on forming rolls on both the boom and forming bed quickly failed due to overloading, and the boom itself showed significant deflection as the pipe was being formed. It was recognized that forming 0.667 ins. X80 (D/t = 45.0) would significantly tax the existing forming equipment. Consequently, an upgrade project was undertaken on mill 3 with the objective of increasing pipe forming capability to permit forming 30 ins. x 0.750 ins. X80 (D/t = 40).

The project incorporated three key components:

a) replacement of the crimp stand;
b) replacement of the forming rolls; and
c) enhancement of the boom rigidity.

The three-roll crimp stand was replaced with a two-roll stand in which contoured rolls are employed to crimp the edge of the strip. The contour of the rolls is such that the curvature at the edge may be adjusted by moving the rolls laterally relative to the edge of the skelp. At the forming station, the forming rolls were replaced with rolls of larger diameter and greater width to reduce the bearing load experienced by each roll. Finally, the boom was replaced with a design, which employed heavier wall thickness and utilized stiffeners along the length. The internal calibrating head was also replaced with a sturdier design incorporating the same wider forming rolls as the beds.

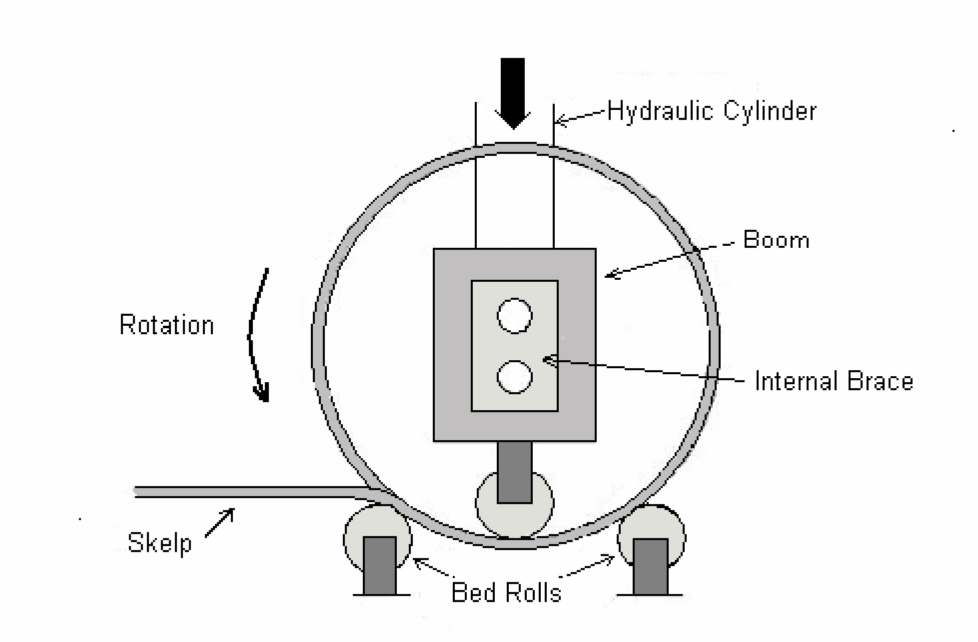


Figure 4. Schematic of the boom and bed rolls.

Inner diameter (ID) welding is initiated at the point at which the two edges of the strip meet. The submerged arc welding process employs a two-wire welder. The ID weld employed Lincoln L61 wire with Bavaria BF 6.5 flux. As the seam of the rotating pipe approaches the apex, the OD weld is applied using Bavaria S2Mo wire and Bavaria BF 6.5 flux. A laser tracking system is employed is ensure that the weld is located directly over the gap between the strip.

In the forming process, the pipe is made very slightly undersize. After welding the pipe passes over a calibrating head located at the end of the boom. This head slightly expands the pipe, thereby imparting a compressive residual stress into the pipe. This is evidenced by cutting a ring off the end of the pipe, and then making a cut through the ring in the longitudinal direction of the pipe. The pipe will be observed to collapse inwards. This is an important benefit when the application of the pipe is considered, as this compressive residual stress imparts an extra level of conservatism into the pipe strength.

An ultrasonic inspection unit is located immediately beyond the welding station. Although a detailed inspection cannot be performed at this point because the pipe is continuously advancing, any indications are immediately identified and quickly hand probed. In this way, operators receive immediate feedback on the quality of the weld and problems may be addressed promptly. Finally, a mobile plasma unit, which moves in parallel with the pipe is utilized to cut the pipe to the final length. This is usually 80 feet. However, the cut-off length is readily adjusted to shorter lengths to meet specific customer requirements. Due to limitations on coil length, not all pipe will be 80 feet long. As well, weld or steel defects detected during the subsequent inspection processes may necessarily be cut out of the steel generating short pipe. Clearly provision of full-length pipe to the customer is essential as the number of field welds is reduced. IPSCO employs a double-jointing (DJ) process to join shorter lengths of pipe together to produce full lengths. At the DJ station, the ends of the pipe to be joined are machined to produce an appropriate bevel. The two pups are then advanced to an OD welding station where the adjoining ends are brought together and clamped using an ID clamping device. The pipe is then rotated as a submerged arc weld is applied at the 12 o'clock position. After completion of the circumferential weld, the pipe is advanced to the next station at which an ID welding device is inserted into the pipe. A camera mounted on the ID weld head allows the operator to properly align the head. The pipe is then rotated as the submerged arc ID weld is applied at the 6 o'clock position.

Pipe are next advanced to the hydrostation where they may be subjected to test pressures up to 100% SMYS. Although most projects normally specify testing at 95% SMYS, requirements for the Cheyenne Plains project required testing at 100% SMYS. Although this requirement initially caused some concern about the potential for pipe growth and distortion during hydrotesting, few problems were encountered. Following hydrotesting, the ends of the pipe are subjected to a sizing operation in which an expander measuring about 6 inches in length is inserted into the end of the pipe. Hydraulic pressure is applied to the wedges of the expander forcing the pipe to grow very slightly (strain < 0.3%). This ensures that all pipe ends are the same diameter. This is very advantageous in aligning pipe for field welding, and virtually eliminates high-low problems.

Pipe Performance

Over the course of the Cheyenne Plains project, over 1200 heats of steel, totaling over 139,000 tons were processed into pipe. The pipe properties are summarized in Table II below.

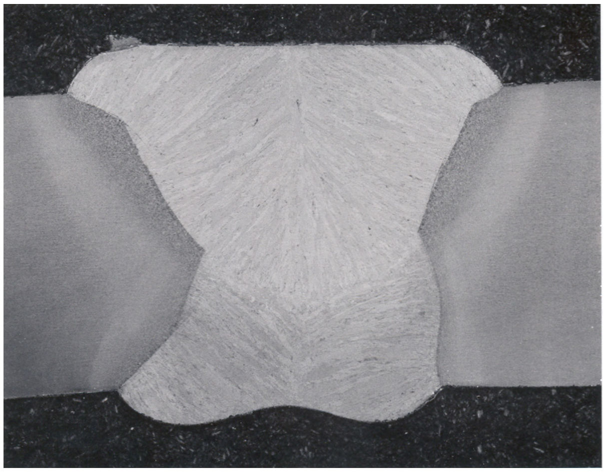
Table II. Average Mechanical Properties

Gauge (ins)	YS		UTS		Elong. (%)	Y/T	Charpy Energy @ - 7^{o}C	
	Avg. (MPa)	Std. Dev. (MPa)	Avg. (MPa)	Std Dev. (MPa)			Avg (J)	Std. Dev. (J)
0.464	582	17.6	707	17.0	33.7	0.82	240	37.7
0.667	581	32.9	691	32.0	40.2	0.84	229	42.6

Weld Properties

Gauge (ins.)	Transverse Weld Axis				HAZ Charpy Energy @ -7^{o}C		
	Avg. YS (MPa)	YS Std.Dev. (MPa)	Avg. UTS (MPa)	UTS Std.. Dev. (MPa)	Avg. Charpy Energy @-7C (J)	Std. Dev. (J)	Shear (%)
0.464	620	20.0	711	14.7	192	30	97.8
0.667	619	32.7	717	21.1	179	34	94.8

A typical spiral weld and hardness profile is shown in Figure 5. It is seen that similar hardness values are achieved 1 mm from both the ID and OD welds with the weld metal hardness closely matching that of the parent metal. Some degree of softening is observed in the heat-affected zone (HAZ). At the centerline, the hardness of the weld is reduced relative to the OD and ID locations.



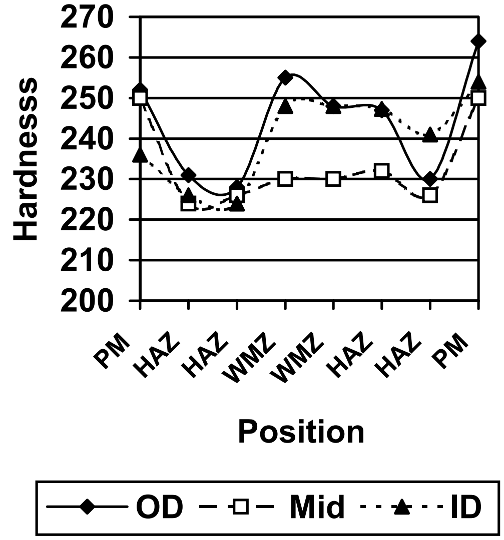


Figure 5. Cross section of Spiral weld and corresponding hardness profile.

Heavy Gauge Production

The production of the 0.667 ins. material presented three technical challenges: a) coiling of the material; b) forming the pipe; and c) achieving the specified toughness.

Limitations on the upcoiler in the rolling mill proved to be the greatest problem. After five months of X80 production, a number of maintenance issues became apparent. Ultimately, it was necessary to reduce skelp width from the value of 74 ins. used for the 0.464 ins. material to 60 ins. in order to reduce the forces required to coil the skelp.

The pipe-forming issues were successfully addressed by the equipment upgrades described previously.

Initially, there was some inconsistency in the achieving the DWTT requirements (85% shear @-7^{o}C). Recognizing the need to produce a fine uniform microstructure, the reduction per pass in the roughing mill was increased in an effort to promote development of a finer recrystallized grain structure. This was in part facilitated by the reduction in skelp width from 74 to 60 ins. The transfer bar gauge was also increased in order to produce greater pancaking of the austenite microstructure during finish rolling. As the steel gauge after the first pass at the finish mill now exceeded the Steckel furnace coiler capacity, the strip was flat passed on the first pass at the finishing stand. Finally, nickel content of the alloy was increased to 0.4 wt % as Ni was thought to promote toughness.

Although no one of these adjustments can be demonstrated to be a critical parameter, in total, they proved sufficient to improve DWTT and Charpy performance. The properties of the 0.667 ins. material are compared to those of the 0.464 ins. material in Table II and a typical Charpy transition curve is shown if Figure 6.

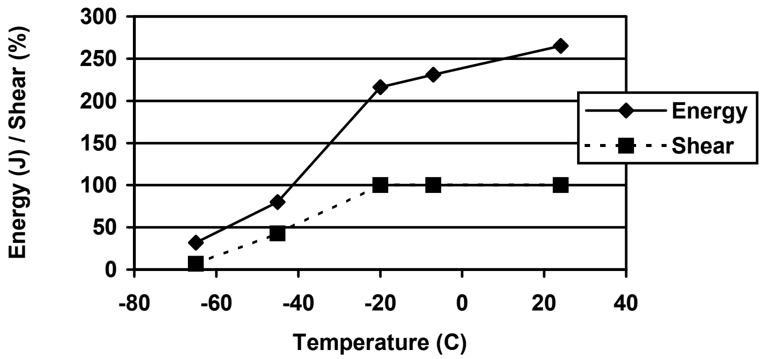


Figure 6. Typical Charpy transition curve and spiral weld hardness for the 0.667" material.

Spiral weld properties were not significantly different than those achieved in the lighter gauge material as seen in Figure 7.

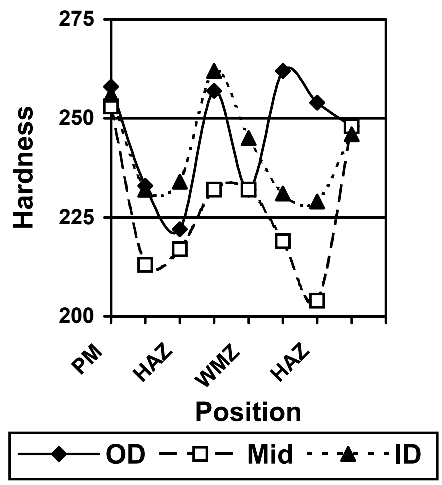


Figure 7. Hardness profile of spiral weld on 0.667 ins. pipe.

The mill performance during the production run is summarized in Table III. Prime yield fell below target, due to the initial difficulties in meeting toughness criteria. However after optimizing the rolling schedule and chemistry, yield improved dramatically. A significant allowance was made for commissioning of the upgraded components. However, the commissioning of the mill proceeded with few problems resulting in mill availability exceeding 100% of the target. Overall performance is an internal measure, which accounts for prime yield, availability and welding speed. The performance of 124 % despite the impact of steel properties on yield reflects the success of the heavy gauge upgrade from the pipemaking perspective.

Table III. Mill Performance During Production of 0.667 ins. X80.

	Performance vs Target
Prime Yield	92.3%
Availability	135.5%
Overall Performance	124.3%

Since completion of the Cheyenne Plains project, other trial work has demonstrated the capability of forming 36 ins. x 0.700 ins. X80 (D/t = 52.5) and 30 ins. x 0.638 ins. X80 (D/t = 47).

Effects of Nitrogen

Considerable effort was made over the course of the Cheyenne Plains project to reduce nitrogen levels in the steel. This was accomplished without significant modification to the alloy chemistry or rolling schedule. It is thus instructive to examine the effects of reduced nitrogen on the final properties of the pipe. To do so, the qualification test results have been used. These qualifying tests are taken at the trail end of the first pipe from one coil from each heat. For the 0.464 ins. material, this provided a database of over 1200 heats.

The effect of nitrogen on strength is shown in Figure 8. In Figure 8a, it is seen that as the nitrogen level is reduced, both yield stress and ultimate tensile strength increase. Nitrogen will react strongly with Ti to form TiN particles, which are expected to contribute little to the strength of the steel. However, the interaction will reduce the solute N content and it is thus appropriate to examine the effects of "free" nitrogen on mechanical properties. Free nitrogen was defined as the nitrogen in excess of the amount, which will react stoichiometrically with Ti. ie. $N_{free} = N - 3.42Ti$, where the amounts are specified in wt%. As shown in Figure 8b, a slightly stronger relationship is seen between free nitrogen and strength. YS decreases by 2.5 MPa for each 10 ppm N and UTS decreases by 3.7 MPa.

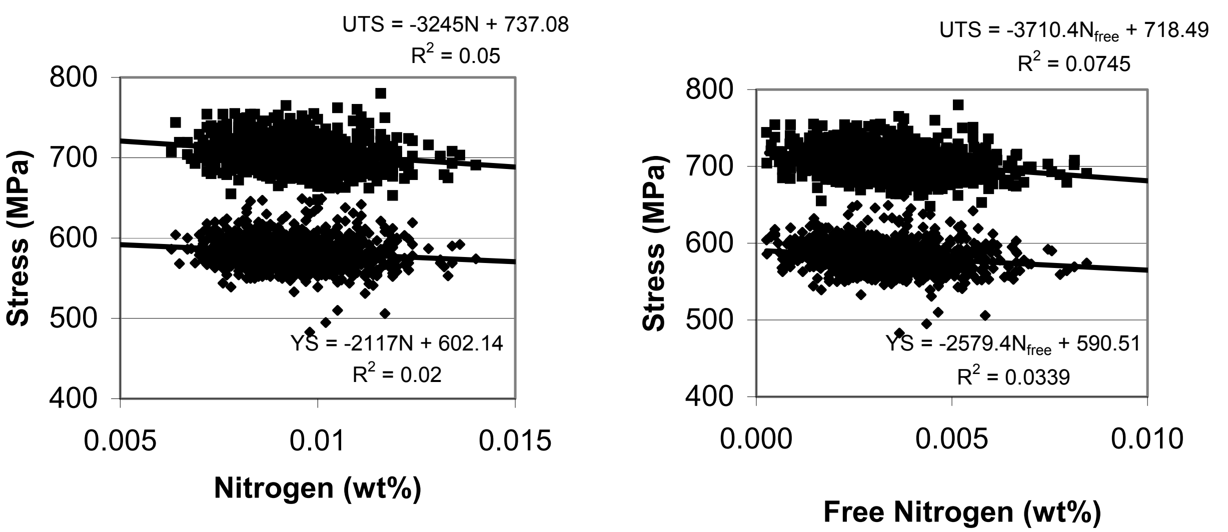


Figure 8. Effect of nitrogen and "free" nitrogen on tensile properties.

The effect of nitrogen content on Charpy toughness was also examined. In Figure 9, it is seen that Charpy energies at –7°C show a slight positive correlation with nitrogen content. When free nitrogen was considered, a stronger relationship between toughness and nitrogen was observed. Nitrogen had no effect on the Charpy performance of the weld Spiral weld HAZ.

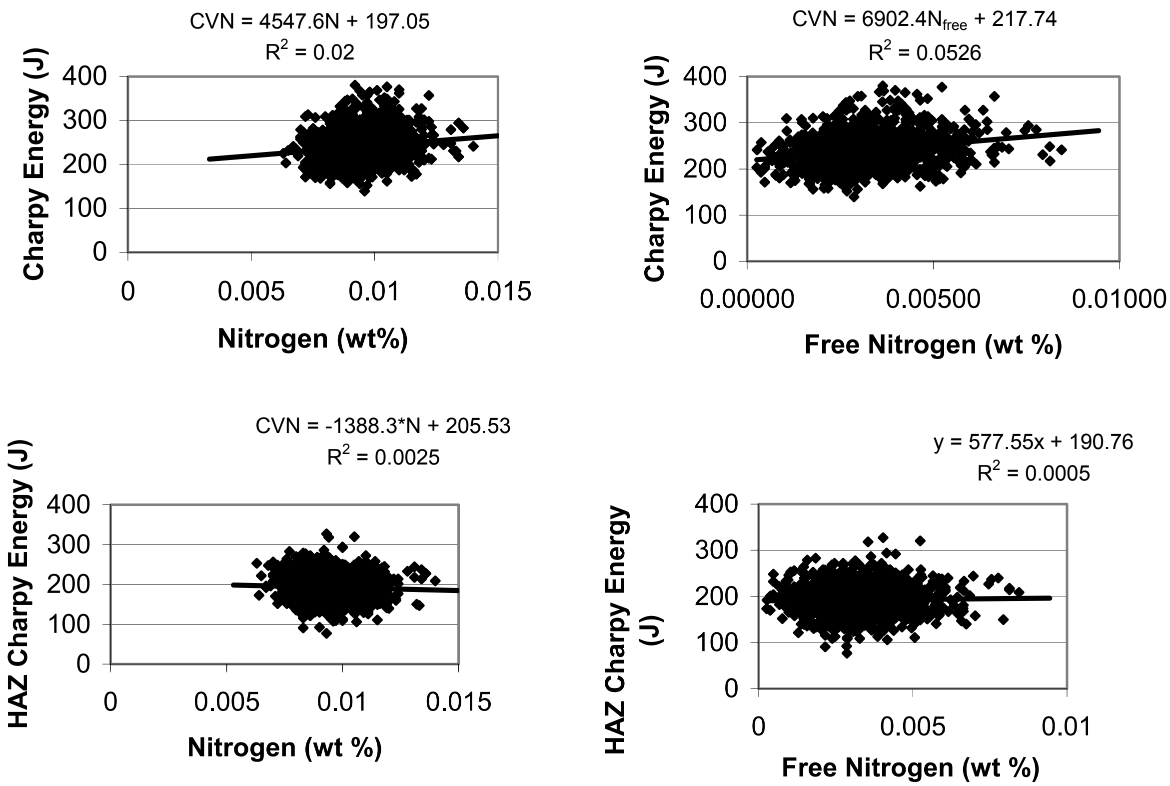


Figure 9. Effect of nitrogen on Charpy energy at –7°C.

The apparent effects of nitrogen on both strength and toughness are somewhat surprising, as nitrogen is an interstitial element, which would be expected to provide strengthening while reducing toughness. In fact, opposite effects are observed. To fully understand the effects of nitrogen and provide perspective on the magnitude of the nitrogen effects, it is instructive to examine the effects of other elements on both strength and toughness. Although carbon equivalent (CE_{CSA}) was maintained in a range of 0.235 to 0.265, a relatively strong effect on UTS is observed (Figure 10). This is believed to be due to the effects of increased CE_{CSA} in promoting the formation of harder phases (M/A) in the microstructure.

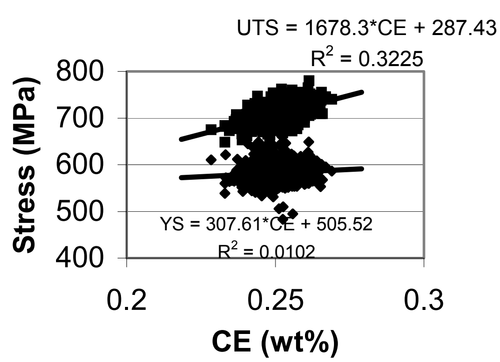


Figure 10. Effect of carbon equivalent (CE) on YS and UTS.

Over the very limited range of niobium employed (0.07 to 0.09 wt%), niobium had little effect on yield stress, and UTS (Figure 11). However, if the interaction of nitrogen with niobium is considered, a greater effect is observed. Precipitation of fine Nb(C,N) particles in ferrite subsequent to transformation contributes significantly to strength, whereas coarser Nb(C,N) precipitates formed during rolling are considered to contribute little to the final strength of the alloy. Thus, an attempt was made to estimate the amount of Nb retained in austenite after rolling. It was first assumed that nitrogen reacted completely with Ti. The remaining free nitrogen is available to react with Nb in the austenite. The greater the solubility product $[Nb]*[N_{free}]$, the greater is the driving force for Nb precipation in austenite thereby depleting the amount of Nb available for precipitation strengthening of the ferrite. As seen in Figure 11b, both YS and UTS increase as the solubility product $Nb*N_{free}$ decreases indicating reduced precipitation potential in austenite. Since the free nitrogen is, in turn, dependent upon the Ti content, a complex relationship between strength and the Ti, N and Nb content of the alloy emerges.

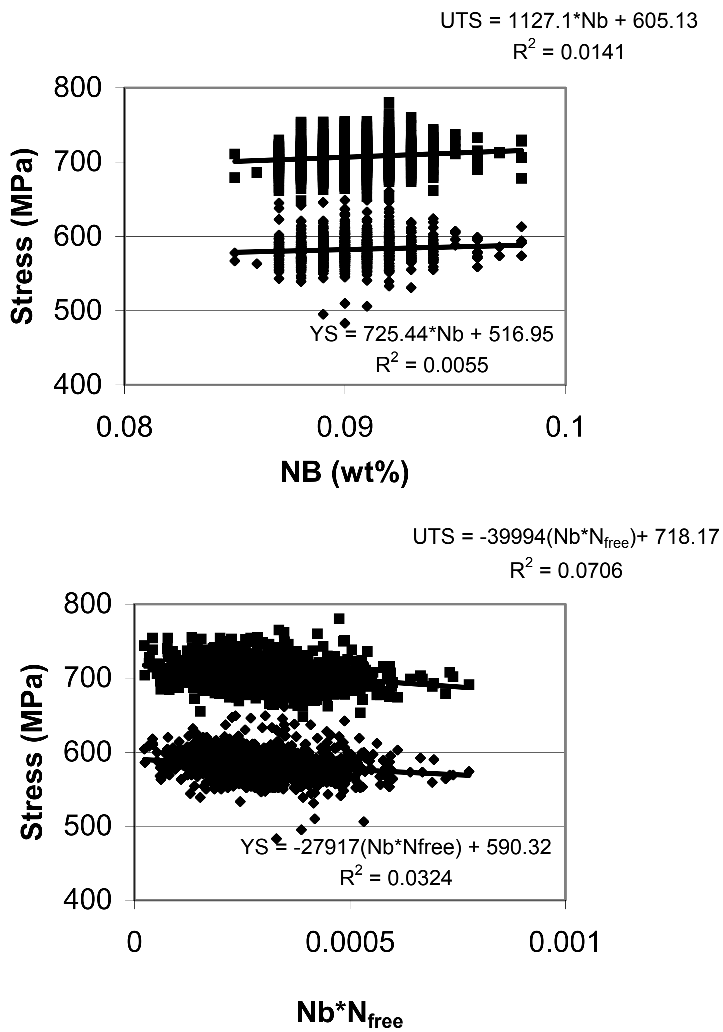
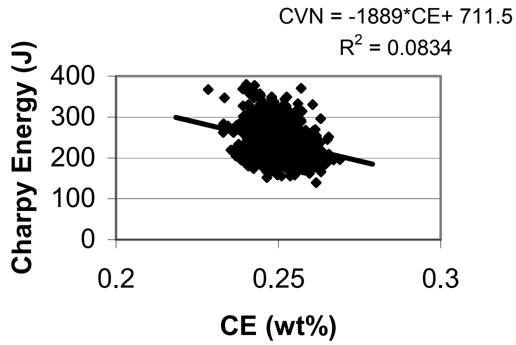


Figure 11. Effect of a) Nb and b) $Nb*N_{free}$ solubility product on YS and UTS.

With regard to Charpy energies, both carbon equivalent and Ti content were observed to significantly influence Charpy Energy at -7^oC (Figure 12).



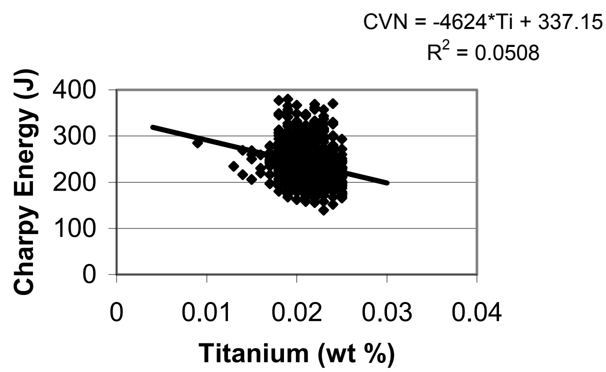
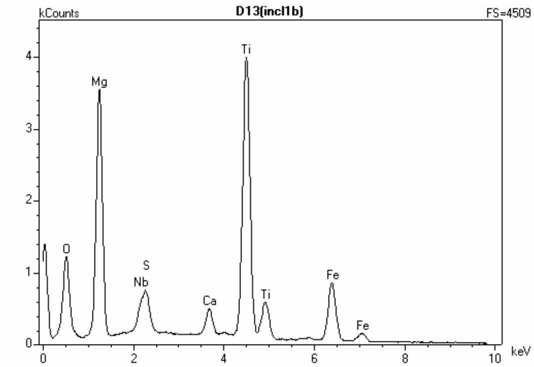


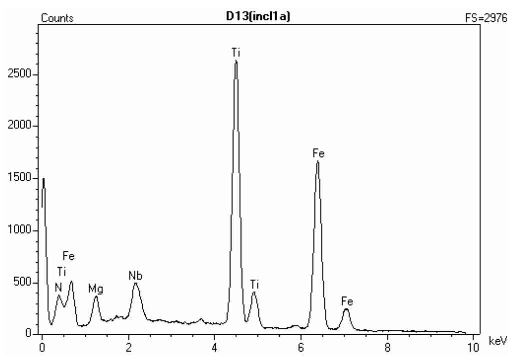
Figure 12. Effect of carbon equivalent (CE_{CSA}) and Ti on Charpy energy at $-7^{o}C$.

Again the increased presence of harder phases in alloys with increased carbon equivalent will be detrimental to toughness as illustrated in Figure 12a. There is also a strong negative relationship between Charpy fracture energy and Ti content as shown in Figure 12b. No clear correlation between Nb and fracture energy could be found.

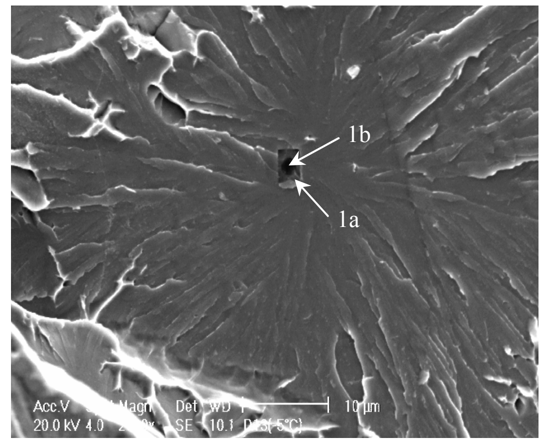
Titanium was observed to have a relatively strong effect on Charpy energy (Figure12). It is apparent that the precipitation of coarse TiN particles in austenite contributes to a reduction in fracture energy. This has been supported by micro-structural observations (Figure 13) in which coarse TiN particles (1 – 10 µm in size) are frequently observed on fracture surfaces and appear to act as initiation sites. A reduction in the both the frequency and size of these particles has been observed as Ti and N levels are reduced.



(a)



(b)



(c)

Figure 13. TiN particle observed on surface of broken Charpy bar.

There is an inverse relationship between the amount of free nitrogen and titanium content as shown in Figure 14. Thus a low value of free nitrogen is indicative of a greater amount of TiN precipitation. As the presence of TiN precipitates has a dominant effect on Charpy energy, the data creates the misperception the reducing free nitrogen is detrimental to fracture toughness.

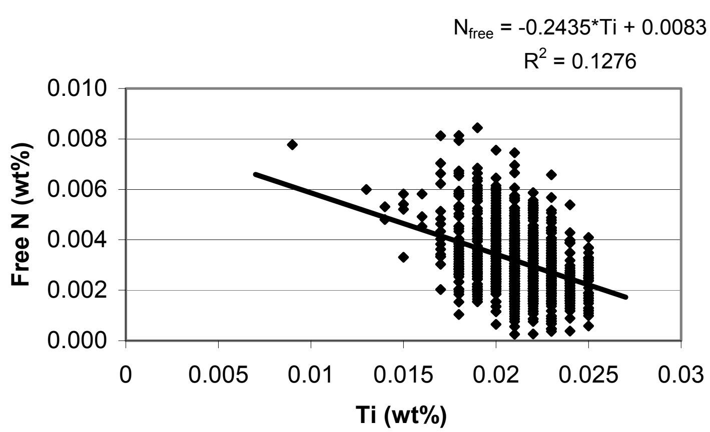


Figure 14. Relation between free nitrogen and titanium.

Conclusions

The Cheyenne Plains X80 project is the largest X80 project undertaken in North America to date. Over the course of the project, IPSCO was able to deliver 1.5 million feet of pipe, totaling 139,579 tons, of pipe on time to meet construction schedules.

Of particular note was the successful production of 30,940 feet of 0.667 in gauge X80. Production of this heavy gauge linepipe represented a significant extension of IPSCO's pipemaking capabilities.

Over the course of the project, significant improvement in nitrogen control was achieved resulting in average nitrogen contents declining from 108 ppm at the onset to <90 ppm at the conclusion of the project. Although there was clearly a beneficial effect of reduce N content on steel strength, there was no evidence of improved Charpy impact performance at – 7^{o}C.

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