APPLICATION OF LINEPIPE METALLURGY FOR NON-LINEPIPE STRUCTURAL APPLICATIONS – CASE STUDIES

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Abstract

Linepipe steels are now produced with excellent low temperature toughness even at high strength levels. Due to lean alloy chemistry, these steels offer excellent weldability with minimal pre- or post-weld heat treatment requirements. There has been increased interest among construction, mining and machinery fabricators for non-heat treated as-rolled high strength plates for application as structural members. Linepipe steels offer significant cost benefits apart from dimensional and metallurgical advantages. Any of the linepipe steel grades can be suitably adapted for structural applications with intelligent modifications to chemistry and process design, but simply adhering to the fundamentals of linepipe process protocol. At ArcelorMittal Burns Harbor, some linepipe grades have been successfully applied as structural products satisfying both chemistry and applications' requirements. Some case studies are presented in this paper.

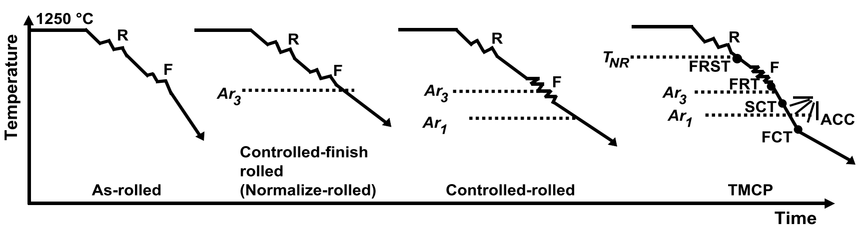
Introduction

Metallurgy of linepipe steels has advanced significantly in the last four decades, both in chemistry and process design, taking advantage of technological innovations in steelmaking, casting and finishing processing practices. Newer and cleaner microstructures are engineered through thermomechanical processing with leaner, microalloyed compositions achieving stronger and tougher steels. Thermomechanical controlled processing (TMCP) imparts strengthening by grain refinement and low temperature precipitation through a combined process of controlled rolling and accelerated cooling. The essence of the chemistry design is a lean, very low C composition with Nb-microalloying to facilitate retardation of austenite recrystallization in the hot working range so that austenite grain boundary area is maximized and is available for later transformation [1-3]. Linepipe steels with yield strengths as high as 100 ksi (690 MPa) have been developed with excellent weldability and toughness [2,3]. From an end user's perspective, these steels offer reduced fabrication costs due to significant weight savings (high strength-to-weight ratio), minimum or no post welding treatments and, more importantly, enhanced bendability which is an added attraction for fabricators requiring high strength steels for machinery and automotive structural components [4].

In contrast, a similar magnitude of development has not been witnessed for structural steels for construction, mining or machinery except for the development of some microalloy-strengthened HSLA steel grades. The advantage of both microalloying and thermomechanical controlled processing (TMCP) could not be fully realized in structural grades due to limitations in thicknesses up to which TMCP can be successfully imparted, without heavily burdening the finishing mills.

Higher strength structural steels are usually quenched and tempered grades with high alloy costs, carbon equivalent and fabrication costs associated with pre- and post-welding heat treatments. From an economic standpoint, many steel fabricators are looking for lower cost alternatives to heat treated grades for many structural and construction applications, albeit not at the expense of strength and toughness. This has led to exploration of opportunities for linepipe metallurgy to be applied in the development or enhancement of steel properties to meet structural steel requirements.

Interestingly, a quick survey of many structural grade chemistry specifications reveals that many grades can be easily accommodated within the scope of some linepipe steel specifications. Therefore, merely by adjusting the alloying contents of structural or linepipe grades permissible within the specification and/or applying thermomechanical processing, a better quality steel product can be produced with lower or equivalent costs. Such manufacturing options have been advocated earlier for offshore structural steels [5]. The only limitation to such practices is the maximum practical thickness to which the advantage of TMCP processing can be realized depending on individual mill capabilities.



Process Control: **R: Roughing, F: Finishing, ACC: Accelerated Cooling,**
FRST: Finish Rolling Start Temperature, FRT: Finish Rolling Temperature,
SCT: Start Cooling Temperature, FCT: Finish Cooling Temperature,
T_{NR} : Temperature of no recrystalization

Figure 1. Schematic representation of various hot rolling practices imparted for specific structure property combinations in steel plates.

ArcelorMittal Burns Harbor (AMBH) USA is actively engaged in the production of a wide range of structural, construction and linepipe grade plates at its Plate Mills. Over the years, the processing fundamentals of linepipe metallurgy have been intelligently applied in many linepipe, offshore and structural grades microalloyed with Nb and/or V [6,7]. A schematic representation of various hot rolling practices with process controls is shown in Figure 1. Recently some of the linepipe compositions have been successfully applied as high strength structural steel grades requiring enhanced weldability, formability and impact toughness. This paper discusses some of the case studies on grade interchangeability.

Case Studies

Structural Plates Requiring Yield Strength of 65 ksi (450 MPa) vs API 5L X65

ASTM A945-06 Gr 65 addresses high-strength low-alloy structural steel plate intended for use in welded construction and allows processing in the as-rolled, control-rolled, thermomechanical control processed (TMCP) or quenched and tempered condition up to a thickness of 2.5" or 65 mm. However, plates over 1.25" (32 mm) thickness are to be supplied only in the quenched and tempered condition. Tables I and II list the chemical composition and mechanical property requirements, as per the ASTM A945-06 specification [8]. The low C, S and residual contents have been specified for improved weldability and formability considerations. Table I also lists the chemical composition requirements of API 5L X65 (L450) grade plates up to a thickness of 25 mm [9]. It is easy to comprehend from the two specifications that a single chemistry can be worked out which can satisfy both ASTM A945 and API 5L X65 (L450) chemistry requirements. The chemistry specification for production of API 5L X65 plates in AMBH is indicated in Table I. This chemistry was chosen for production of A945-06 structural plates up to a thickness of 1.25" (32 mm).

Table I. Chemical Compositions of Selected Steel Grades, wt.%

Grade	C max	Mn	P max	S max	Si	Cu max	Ni max	Cr max	Mo max	V max	Nb max	Ti	Al max
ASTM A945-06 Gr 65	0.10	1.10-1.65	0.025	0.010	0.10-0.50	0.35	0.40	0.20	0.08	0.10	0.05	0.007-0.020	0.08
API 5L X65 (L450)	0.12	1.60 max	0.025	0.015	0.45 max	0.5	1.0	0.5	0.5	Nb+V+Ti≤0.15			0.060
AMBH-API 5L X65	0.10	1.60 max	0.015	0.005	0.40 max	0.10	0.10	0.10	0.005	0.10	0.05	0.01-0.02	0.02-0.045

Table II. Mechanical Property Requirements of ASTM A945-06 Gr 65 Plates

Grade	YS ksi (MPa)	TS ksi (MPa)	CVN at -40 ºC J (ft lb)
65	65 (450)	78-100 (540-690)	95 (70)

Processing Design. AMBH practices a controlled rolling approach for the production of API 5L X65 grade plates with the chemistry listed in Table I. Nb in amounts up to 0.05 wt.% allows austenite conditioning at higher temperatures and V adds to strengthening through low temperature precipitation and is considered necessary for thicker plates up to 32 mm. Table III lists typical controlled rolling schedules followed for processing plates up to 32 mm. Plates were finish rolled just at or below the Ar_3 temperature to produce a fine grained final microstructure with microalloy carbide (VC) precipitation and possibly substructure strengthening. The extent of substructure will depend however, on the finishing temperature, as shown in Figure 2, and the thickness of plate [10].

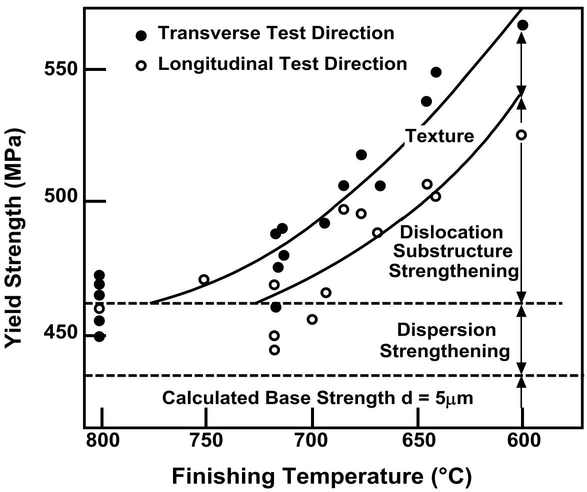


Figure 2. Substructure strengthening in ferrite as a function of finish rolling temperature [10].

Table III. Typical Controlled Rolling Schedule Followed for Structural Plates

Alloy	Reheat Temperature (°C)	Start Finish Rolling Temperature (°C)	Finish Rolling Temperature (°C)	Total finish deformation (%)
AMBH-API 5L X65 for ASTM A945-06 Gr 65	1225-1250	960-1020	690-775	60-80

Results. Table IV lists the mechanical properties achieved in controlled rolled API 5L X65 plates in thickness of 1.25" (32 mm). The data indicate successful qualification as per First Article Inspection for AMBH Plate Mill. Excellent toughness was achieved using a lean, lower cost composition which guarantees not only excellent weldability but also bendability. AMBH currently routinely applies API 5L X65 grade slabs for the production of A945-06 Gr 65 structural plates up to 32 mm.

Table IV. Mechanical Properties of 32 mm (1.25") Thick ASTM A945-06 Plates Produced at AMBH.

Location in Plate	Test Direction	Yield Strength ksi (MPa)	Tensile Strength ksi (MPa)	El (2") %	Average CVN at -40 °C, J (ft-lb)
Front end	**L**	67.2 (463)	78.5 (541)	31	240 (177)
	T	70.8 (488)	81.5 (562)	31	198 (146)
Center North	**L**	66.0 (455)	80.2 (553)	29	233 (172)
	T	68.5 (472)	81.7 (563)	29	218 (161)
Center South	**L**	67.7 (466)	81.4 (561)	28	242 (179)
	T	67.2 (463)	81.9 (565)	30	187 (138)
Tail end	**L**	65.2 (449)	78.9 (544)	30	256 (189)
	T	69.3 (477)	82.9 (571)	28	198 (146)
ASTM A945-06 Gr 65 specification		**65 (450)**	**78 (540)-100 (690)**	**18**	**95 (70)**

L - Longitudinal, T - Transverse

Offshore Structural Plates API 2Y Gr 50 for ASTM A945-06 Gr 65 Structural Plates

After successfully applying API 5L X65 grade slabs for the production of A945-06 Gr 65 structural plates up to a thickness of 32 mm, AMBH explored production of the same using API 2Y Gr 50 grade slabs. API 2Y Gr 50 specifies quenched and tempered steel plates for offshore structures and the chemical specification is given in Table V along with ASTM A945-06 specification. The table also lists the chemical specification adopted for API 2Y Gr 50 plate production at AMBH.

It is clear from Table V that the chemical composition for API 2Y Gr 50 is much leaner than specified by ASTM A945-06 Gr 65. Since the specified Nb content (0.03 wt.%) was lower than in API 5L X65 or ASTM A945-06 grade a tighter controlled rolling practice was thought necessary to compensate for loss in strengthening due to reduced austenite conditioning for thicker plates [7]. Controlled rolling parameters were set the same as indicated in Table III but with a finish rolling temperature just below the Ar_3 temperature. Figure 3 indicates mechanical properties of API 2Y Gr 50 plates processed in a controlled rolling condition to achieve properties meeting A945-06 Gr 65 plate up to 32 mm thickness. All the plates processed to date meet ASTM A945-06 Gr 65 mechanical property requirements.

Table V. Slab Interchangeability Options for ASTM A945-06 Gr 65 and API 2Y Gr 50, wt.%

Grade	C max	Mn	P max	S max	Si	Cu max	Ni max	Cr max	Mo max	V max	Nb max	Ti	Al
ASTM A945 Gr 65	0.10	1.10-1.65	0.025	0.010	0.10-0.50	0.35	0.40	0.20	0.08	0.10	0.05	0.007-0.020	0.08 max
AMBH-API 2Y Gr 50	0.10	1.60 max	0.020	0.005	0.40 Max	0.30	0.40				0.03	0.007-0.018	0.020-0.045
API 2Y Gr 50	0.12	1.15-1.60	0.030	0.010	0.05-0.50	0.35	1.0	0.25	0.15	0.10	0.03	0.003-0.02	0.015-0.055

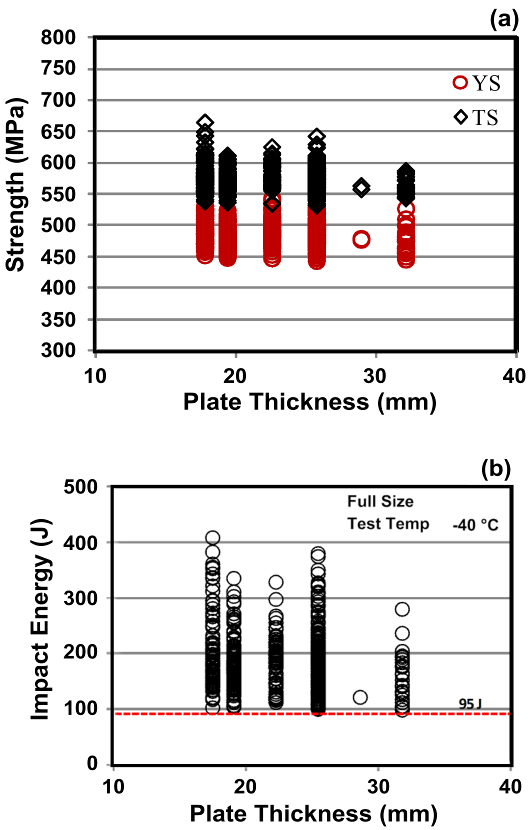


Figure 3. Transverse; (a) Tensile properties and (b) Charpy impact toughness properties of ASTM A945-06 Gr 65 plates processed with API 2Y Gr 50 slabs.

Structural Plates Requiring Yield Strength of 70 ksi (460 MPa) or More

ASTM A656 specification covers four different strength grades of high strength, low alloy, hot rolled structural steel plates with improved formability for use in truck frames, crane booms, rail cars, tank wheels, etc. The highest strength grade is ASTM A656 Gr 80, requiring a minimum yield strength of 80 ksi (550 MPa) in plates up to a thickness of 0.75" (19 mm). Chemical composition requirements are given in Table VI for three different types of alloying choices depending on the intended applications [11]. Mechanical property requirements are as follows:

- Yield Strength: 80 ksi (550 MPa) min;
- Tensile Strength: 90 ksi (620 MPa) min;
- Elongation (2"): 12% min.

Table VI. Chemical Compositions of Steels Chosen for the Current Study, wt.%

<table>
<tr><th>Grade</th><th>Type</th><th>C max</th><th>Mn max</th><th>P max</th><th>S max</th><th>Si max</th><th>V max</th><th>Nb</th><th>Comments</th></tr>
<tr><td rowspan="3">ASTM A656 Gr 80</td><td>3</td><td rowspan="3">0.18</td><td rowspan="3">1.65</td><td rowspan="3">0.025</td><td rowspan="3">0.035</td><td rowspan="3">0.60</td><td>0.08</td><td>0.008-0.10</td><td></td></tr>
<tr><td>7</td><td>0.15</td><td>0.10 max</td><td rowspan="2">Nb+V+Ti ≤0.20</td></tr>
<tr><td>8</td><td>0.15</td><td>0.10 max</td></tr>
<tr><td>AMBH API 5L X70</td><td></td><td>0.09</td><td>1.65</td><td>0.015</td><td>0.003</td><td>0.35</td><td>-</td><td>0.10 max</td><td>Others: Mo, Ni, Cu</td></tr>
</table>

AMBH produces API 5L X70 grade plates up to a thickness of 26 mm using TMCP. Depending on thickness and strength requirements the plates are either controlled rolled with or without accelerated cooling. The chemical composition is given in Table VI. The composition can be easily accommodated against ASTM A656 Gr 80 structural grade, provided mechanical properties are satisfied in plates. During an experimental trial it was found that for API 5L X70 linepipe slabs, when processed using controlled rolling, mechanical properties meeting ASTM A656 Gr 80 can be achieved up to a thickness of 19 mm with excellent flatness and uniformity of tensile properties along the length and across the width of plates [6,7]. Significant volumes of commercial production were subsequently made for production of ASTM A656 Gr 80 plates using API 5L X70 grade slabs through controlled rolling with a finish rolling temperature just below the Ar_3 temperature.

Results. Figure 4 shows yield and tensile strengths of API 5L X70 plates processed up to a thickness of 19 mm. All plates exhibited yield and tensile strengths greater than the requirements of ASTM A656 Gr 80.

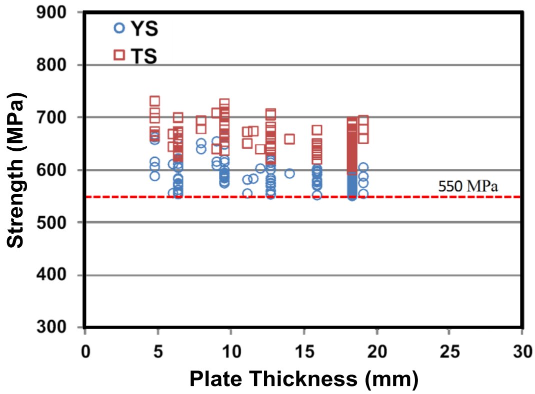


Figure 4. Tensile properties of API 5L X70 plates controlled rolled to produce 80 ksi (550 MPa) minimum yield strength in plates up to 19 mm thickness.

Impact toughness energy values are not stipulated for ASTM A656 Gr 80 but Table VII indicates some impact toughness data from controlled rolled plates processed as per a customer order. It is seen that excellent low temperature impact toughness values were obtained in plates up to 0.75" (19 mm) thickness.

Table VII. Impact Toughness Values in ASTM A656 Gr 80 Plates Rolled at AMBH

Grade	Plate Thickness (mm)	Specimen Thickness	Impact Test Temperature °C (°F)	CVN Values J (ft lb)
AMBH ASTM A656 Gr 80	0.72 (18)	5 mm	-18 (0)	230 (170)
	0.75 (19)	5 mm	-34 (-30)	156 (115)

Figure 5 shows a typical microstructure of a controlled rolled 12 mm thick API 5L X70 plate with fine elongated ferrite and bainite plus retained austenite, carbide and occasionally M-A constituents. Bainite packets are very fine and not present as bands which explains the excellent impact energy values at low temperatures. The influence of this microstructural feature was also manifested in excellent bendability performance of this steel.

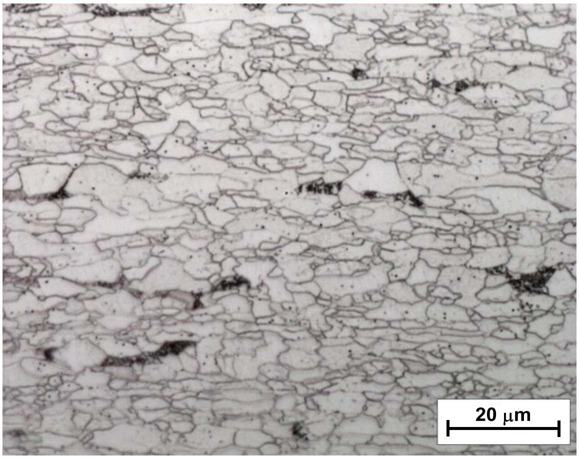
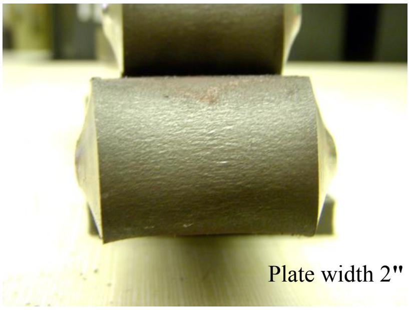


Figure 5. Typical microstructure of a controlled rolled 12 mm thick API 5L X70 plate processed as ASTM A656 Gr 80 plate showing very fine elongated ferrite and bainite grains. 2% nital etch.

Bendability evaluation of 11.5 mm thick ASTM A656 Gr 80 structural plates processed at AMBH from API 5L X70 slabs are presented in Figure 6. The plates were bent over a ½" radius at ambient temperature with the bend axis transverse to the rolling direction and indicated no surface cracking inside or outside [7].



Front view

Side view

Figure 6. Crack-free front and side surface appearances of 11.5 mm thick steel plates produced as per ASTM A656 Gr 80 specification using API 5L X70 linepipe slabs. The bend axis is transverse to the rolling direction [6].

Application of Linepipe Chemistry for Offshore Construction

API Specification 2MT1 (Spec 2MT1) [12] was developed in the 1990s at the suggestion of Dr. Malcolm Gray with the explicit aim of making available steel plates with improved toughness suitable for "cold forming and welding as per API Spec 2B." The primary use of 2MT1 plates is for Class B application in construction of offshore structures and the aim was to replace generic ASTM A572 Gr 50 for such use. Table VIII lists the major specification requirements of API 2MT1 and ASTM A572 Gr 50.

Table VIII. Comparison of 2MT1 and A572 Gr 50 Specifications

Specification	C wt.% max	CE_{IIW} max	Pcm max	YS ksi (MPa)	TS ksi (MPa)
2MT1 to 2"	0.12	0.43	0.24	50 min (345)	65 to 90 (448-620)
2MT1 >2" to 2.5"	0.12	0.45	0.25		
A572 - 50	0.23	None	None	50 min (345)	65 min (448)

API Spec 2MT1 permits a wide choice of plate processing methods – as-rolled, controlled rolled, TMCP, normalized or quenched and tempered. The restricted C content along with Carbon Equivalent (CE and Pcm) guide the plate producers toward the use of a linepipe type chemistry (similar to X60) along with a thermomechanical controlled processing (TMCP) production method. Chemistry interchangeability of typical API 5L X60 type linepipe grade and 2MT1 practiced at AMBH is shown in Table IX along with ASTM A572 Gr 50.

Table IX. Suggested Chemistry Between API 2MT1 and ASTM 572 Gr 50

Specification	Chemical Composition (wt.%)					CE_{IIW}	Pcm
	C	Mn	Nb	V	Ti		
2MT1	0.07-0.12	1.15-1.60	0.040 max		0.020 max	0.34-0.38	0.16-0.20
API 5L X60			Nb+V+Ti≤0.15				0.25 max
A572 Gr 50	0.16-0.23	1.60 max	0.005-0.05	0.01-0.15		0.40-0.48	0.24-0.28

API 5L X60 linepipe chemistry and rolling protocol can be successfully applied to the offshore structural grade 2MT1 with considerable advantages as compared to standard ASTM A572-Gr 50. In most cases, and with the proper choice of production method, A572 Gr 50 is capable of meeting the minimum strength and toughness specified for 2MT1 but cold forming and welding characteristics will fall far short of expectations set out in guiding specifications for the construction of offshore structures. Therefore, the introduction of API Specification 2MT1 and its further improved 2nd Edition in 2001 filled an important void by making available a new class of steel "amenable to fabrication and welding under shipyard and offshore conditions."

Summary and Conclusions

The results of steel grade cross-applicability for structural and linepipe grade steels as discussed in this paper present an important frontier in the advancement of high strength high toughness steel plate development for different applications. The advent of newer steelmaking and casting technologies has enabled production of much cleaner steels with regard to S, P and unwanted residuals thereby eliminating the need to add costlier alloying elements needed to guarantee low temperature toughness. Thermomechanical controlled processing can be designed to achieve the desired microstructure and properties with reduced C content thereby significantly improving low temperature toughness, weldability and bendability.

API 5L X52-X70 slabs can be suitably used to produce structural steel plates with 50-80 ksi yield strength along with excellent low temperature toughness. From the few case studies presented in the paper it has been demonstrated that offshore structural and linepipe slabs could be successfully used to produce structural plates requiring yield strengths up to 80 ksi (550 MPa) with excellent strength-toughness combinations. The study also showed that leaner and hence lower cost linepipe grade slabs can be used to produce high strength high toughness structural plates with excellent weldability and bendability.

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