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ALLOY DESIGNS FOR HIGH STRENGTH OIL AND GAS TRANSMISSION LINEPIPE STEELS

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Key Words: HTP; acicular ferrite; X80; modeling; microstructure; toughness; pipeline steel; skelp; steckel rolling

Abstract

The economical movement of gas and oil to the marketplace from remote and rugged locations requires transmission pipelines to be designed to operate at higher pressures with improved toughness over a variety of temperature ranges. This is accomplished by increasing either pipe wall thickness or strength, or a combination of both. Increasing wall thickness adds cost to the installation of the pipeline; therefore, specifying higher strength has been the typical pipeline designer's standard practice, with API X70, X80 and beyond being routinely specified over the past 10 years, coupled with increased toughness requirements at various design temperatures. Numerous alloy designs have been used for the production of the higher strength and toughness grades, but these have yielded only two basic types of microstructure: ferrite/pearlite and ferrite/acicular ferrite - each of which behaves fundamentally differently through the pipe-making process. Rolling mill and pipe-making equipment capabilities, in addition steel cost should be used to determine which of the two microstructures is most suitable for meeting the requirements of a particular pipeline project, and computer models have been developed to assist in this.

There are two distinctly different niobium-based alloying approaches to produce the ferrite/acicular ferrite microstructure. One design that has been well documented over the past 15 years uses molybdenum additions. This approach also relies on low temperature controlled rolling which can lead to issues with mill equipment and productivity, depending on the particular plate mill age and design. The other, more recent alloy design utilizes higher niobium (with moderate levels of other strengthening elements). This latter chemistry is unique in that it has the ability to produce the high pipe strength and body impact toughness required for modern transmission pipelines utilizing a higher than normal processing temperature during plate rolling – coined 'High Temperature Processing' or HTP. This, in turn, improves productivity and alleviates certain rolling issues associated with the traditional alloy design. This paper discusses the two different microstructure designs and the alloying/rolling approaches used to generate them, with a focus on the HTP concept. Actual pipeline project results, together with rolling/pipe making equipment and testing issues, and the use of modeling for the prediction of plate and pipe strength are also presented.

Introduction

Proven oil and gas reserves are being found in more and more rugged, remote locations. Typically, these locations are in cold climates, or have circumstances such as unstable surroundings, etc, that can challenge the pipeline material design, Figure 1.

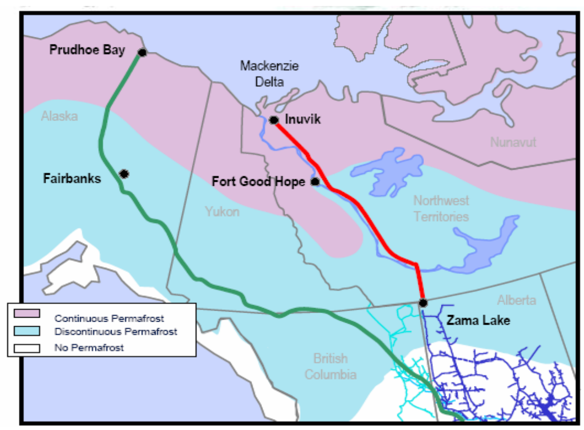


Fig. 1 Example of location route of proposed high strength transmission pipelines. Note regions of permafrost

In addition to the environmental circumstances, pipeline companies have been steadily increasing operating pressures in order to economically move oil and gas to the marketplace, Figure 2.

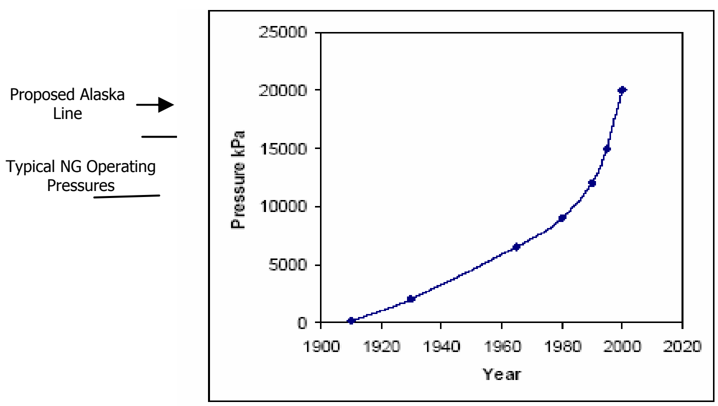


Figure 2. Increase in North American natural gas operating pressures

Past designs for land-based transmission pipeline were mainly stress based, i.e. the pipeline material basically had to only withstand internal pressures and their fluctuations. In contrast, offshore transmission lines used strain-based design principles due to the lateral bending involved with the construction techniques used and the topology of the undersea floor. However, variables of location and climate (e.g. permafrost) associated with the newer reserves have moved the strain-based design from offshore applications to land-based transmission lines. In addition, the shift from sweet to more sour oil and gas reserves, increased public safety and environmental concerns, increasing operating pressures and costs (both material and construction) have resulted in pipeline designs requiring higher strengths, improved crack arrest characteristics (fracture toughness) and resistance to hydrogen induced cracking potential, plus good weldability/formability (low CE/Pcm). These attributes and the implications to the transmission pipeline material are summarized in Table 1.

Table 1. Pipeline design trends and material implications

Pipeline Design Attributes	Pipeline Material Implications
Increased Operating Pressures	Increased pipe strength and/or heavier gauge. Fracture toughness may be compromised and material costs will be higher due to alloy requirements (microalloys and/or other alloys such as Cu, Ni, Cr, Mo), more severe rolling practices. Approaching limit of fracture arrest models.
Colder Environment	High subzero temperature fracture toughness. High energy levels require very clean steels (good steelmaking practices), inclusion shape control, low C, S, P. More severe rolling practices. Additional crack arrest evaluation techniques (CTOD, etc.). Material costs will be affected by required steel processing and chemistry limitations.
Surrounding Earth Stability (e.g. permafrost, etc.)	Strain-based design, higher longitudinal strength requirements, higher uniform elongation requirements not necessarily compatible with microstructure design for higher strengths.
Mechanized welding	Lower carbon equivalent (CE/Pcm) may require different alloy designs and tighter strength ranges, with increased processing costs.
Resistance to Hydrogen Cracking (Sour Service)	Low carbon (requiring additional alloy/microalloy for strength). Very clean steels (good steelmaking practices), inclusion shape control, very low S and P. Good segregation control during casting. Higher costs associated with alloy and steel processing.
Offshore	Strain-based design, higher longitudinal strength requirements, reduced anisotropy - potentially requiring additional alloy and thus increased costs.

Table 2 lists some recent specification requirements to address pipeline design attributes[1, 2]

Approaches to Alloy Design

To meet the changing pipeline design needs, there's been an evolution of alloying approaches over the past 35 or so years driven by cost and available steelmaking and rolling technologies. Frequently, the line pipe arena has driven steel technology development, e.g. sour service →low carbon and S, cleaner steels; high toughness→low carbon, S and P, cleaner steels; high strength→microalloying, solute alloying, low temperature rolling, accelerated cooling (ACC). In addition, the move to higher low-temperature toughness (colder environments) plus mechanized field welding drove lower CE's in the early 1990s which put constraints on alloying, e.g. low carbon (~0.08 max, preferably 0.05). The loss of strengthening due to lower carbon had to be made up by other strengthening mechanisms such as microalloying, solute alloys and post-rolling accelerated water cooling practices (ACC).

Table 2. Examples of pipeline design attributes and corresponding specification requirements

Pipeline Design Attributes	Spec 1	Spec 2 - Offshore	Spec 3 - HIC	Spec 4
Increased Operating Pressures	X80, heavy wall	X70 Heavy Wall	Stress based, Grades up to X70	Stress based, X80, 100% SMYS Hydrotesting, Restrictive Hardness
Colder Environment	Restrictive S, TCVN 190 J to -20 C add -55 C, DWTT 85%, CTOD	NA	NA	NA
Surrounding Earth Stability (i.e. Permafrost, etc.)	Strain based, Longitudinal Tensile, Uniform Elongation, Lower YT, Overmatched Weld strength	NA	NA	NA
Mechanized welding	YS and TS range limits, OD dimensional limits	YS and TS range limits, tight OD dimensional limits	NA	YS and TS range limits, OD dimensional limits
Resistance to Hydrogen Cracking (Sour Service)	NA	NA	Restrictive C, P, S, Mn. YS and TS 15 ksi range, restrictive hardness, cleanliness requirement	NA
Offshore	NA	Strain based, Longitudinal Tensile, Lower YT $\leq$0.88, Compressive YS Testing	Collapse Ring Test	NA

The end result of this alloying evolution is two basic microstructures that are now the basis for all current commercial API transmission linepipe produced in the world. These are ferrite/pearlite (F/P) and ferrite/acicular ferrite (F/AF). For practical purposes, acicular ferrite is defined as a low carbon bainite formed by intragranular nucleation. More recently, the advent of X100 and X120 has resulted in a third microstructural scheme comprising other forms of bainite along with small quantities of martensite in the F/AF base.

The approach to alloy design for API linepipe steels starts with a basic low C-Mn-Si base. This is used for low strength API 5LB and X42. Additions of a single microalloy or a dual microalloy in amounts less than 0.065% each, along with low amounts of various solute alloys (Cu, Ni, Cr), depending on plate thickness and rolling mill power, are used to produce API X52-X70. The main microalloy of choice in API applications is niobium, with vanadium playing a supporting role when additional strength is required. This C-Mn-Si base along with microalloy additions will produce an F/P microstructure regardless of rolling practice. This alloy/microstructure design tends to have the lowest cost to produce.

Alloy designs for higher strength API grades, X70 and above (or for X65 when compensating for lower plate mill power), start with the C-Mn-Si plus microalloy base and then add small quantities of solute alloys such as Cu, Ni, Cr, either singly or in combinations to a maximum combined content of ~0.6%, and Mo to ~0.3%. These additions, particularly Mo, coupled with appropriate rolling/cooling practices will result in an F/AF microstructure. Microalloy additions of up to 0.11% niobium, without molyvbdenum, can also be used to produce the desired F/AF microstructure. This latter route is termed High Temperature Processing (HTP) as the steel can typically be finish-rolled at higher temperatures (see section 3.2.2).

Increased additions of the solute alloys (Mn, Cu, Ni, Cr, and Mo) along with boron are used to produce API X100 and X120. These richer additions produce other forms of bainite along with small quantities of martensite, reducing the steel's weldability and increasing material costs. Table 3 summarizes the general alloy/microstructure design for various API strength levels.

Table 3. Alloying approaches to API linepipe

API Grade	**Steel Alloying Approach**
X120	AF/Bainite/Martensite, C <0.10, Mn<2.0, Si<0.40, Nb<0.06, Cu, Ni, Cr, Mo, V, B, Pcm≤0.25
X100	AF/Bainite, C<0.06, Mn<2.0, Si<0.40,Nb<0.06, Cu, Ni, Cr, Mo, V, Pcm≤0.23
X80	F/AF, C≤0.06, Mn<1.70, Si<0.40, Nb≤0.10, Cu, Ni, Cr, Pcm≤0.18
	F/AF, C≤0.06, Mn<1.70, Si<0.40, Nb≤0.10, Cu, Ni, Mo, Pcm≤0.21
X70	D/t<50: F/AF, C≤0.06, Mn≤1.65, Si<0.40, Nb≤0.10 only, or Nb+Mo, Pcm≤0.18 or 0.21
	D/t>50 F/P, C≤0.10, Mn≤1.65, Si<0.40, Nb≤0.065 only, or Nb+V≤0.15, Pcm≤0.20
X65	F/P, C≤0.10, Mn≤1.65, Si<0.40, Nb≤0.065 only, or Nb+V≤0.15, Pcm≤0.23
X65 Sour Service	F/P, C≤0.05, Mn≤1.35, S≤0.003, Si<0.30, Cu+Ni+Cr ≤0.70, Nb≤0.065 only, or Nb+V≤0.15, Pcm≤0.15
X60	F/P, C≤0.10, Mn≤1.50, Si<0.40, Nb≤0.065 only, or Nb+V≤0.12, Pcm≤0.23
X60 Sour Service	F/P, C≤0.05, Mn≤1.20, S≤0.003, Si<0.30, Cu+Ni+Cr ≤0.70, Nb≤0.065 only, or Nb+V≤0.12, Pcm≤0.15
X52	F/P, C≤0.10, Mn≤1.20, Si<0.40, Nb≤0.050 only, Pcm≤0.17
X52 Sour Service	F/P, C≤0.05, Mn≤1.10, S≤0.003, Si<0.30, Cu+Ni+Cr ≤0.60, Nb≤0.050 only, or Nb+V≤0.10, Pcm≤0.13
X42	F/P, C≤0.10, Mn≤1.00, Si<0.40, Nb≤0.050 only, Pcm≤0.16
5LB	F/P, C≤0.20, Mn≤1.00, Si<0.40, Pcm≤0.16

A balance between the pipeline designs attributes, microstructure, and alloy must be achieved. In general, F/AF is used for increasing strengths, while increasing alloy has a negative effect on many pipeline design attributes. The main pipeline design attributes as they relate to alloy, microstructure and strength are illustrated in Figure 3.

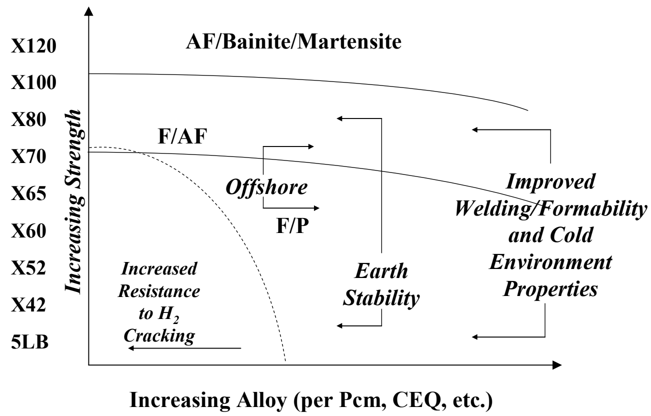


Fig. 3 Illustration of pipeline design attributes, increasing alloy (per Pcm, CEQ, etc) and API strength

API Skelp Production Techniques

Steelmaking

The main goals in steelmaking to produce slabs suitable for API transmission pipeline applications are to:

- Maintain tight chemistry control – promotes consistent microstructure/mechanical properties
- Maintain good internal cleanliness – promotes high toughness, good weldability, HIC resistance, formability
- Minimize centerline conditions – promotes consistent thru-thickness properties/microstructure, HIC resistance, internal lamination issues
- Maintain good surface quality – minimizes pipe surface defects
- Maintain dimensional control – promotes downstream processing efficiencies

Steelmaking facilities for the production of API grade slabs typically consist of a starting metallic process (blast furnace – pig iron, direct reduced iron (DRI), or scrap), melting furnaces (BOF or EAF), ladle metallurgy furnaces (LMF) or stations, vacuum degassing (may or may not be used depending on desired end characteristics), and continuous casters, Figure 4

During the steelmaking process, certain process variables and alloy additions must be properly controlled to meet the goals for slabs suitable for API transmission linepipe, Table 4.

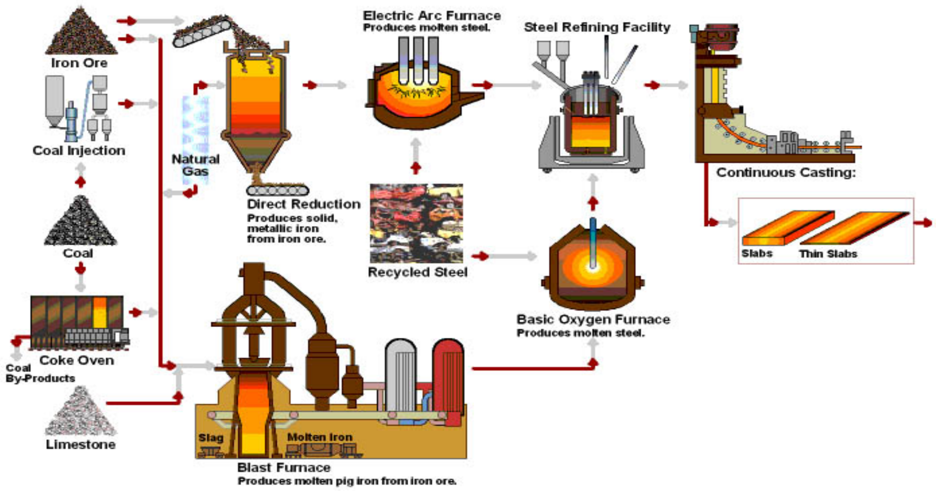


Figure 4. Schematic of the steelmaking process for API transmission linepipe grades

Table 4. Key steelmaking variables and their effect on slab/pipe quality

Process	Key Variable	Effect
LMF	Inclusion shape control	Final impact toughness, HIC resistance
	Argon Final Rinse Time	Cleanliness - impact toughness, internal cleanliness, HIC resistance
	Total LMF Time	Overall cleanliness
Continuous Casting	Argon Shrouding	Overall cleanliness
	Superheat	Centerline chemical segregation/microstructure control, final impact toughness, HIC resistance
	Machine Condition	Centerline chemical segregation/microstructure, centerline looseness (potential centerline laminations)
	Minimum Tundish Weight	1st and last slab cleanliness – impact toughness, internal cleanliness, HIC resistance
	Slag Control	Overall cleanliness – impact toughness, internal cleanliness
	Casting Speed	Surface quality, isolated cleanliness
Slab Cutting	Cutting Temperature	Cold – potential edge and end cracking

Slab thickness for high strength and toughness skelp varies between ~150mm from the newer intermediate thickness casters feeding steckel mills, to 220 - 300mm from conventional casters. There has been some success with lighter gauge skelp (≤12mm) in grades up to X65 using a NbV approach from thin slab cast (50mm) mini mills.

Skelp Rolling

Rolling Mill Types

Slabs for API transmission pipelines are processed into coiled or plate skelp using various mill configurations shown schematically in Figure 5. Coiled skelp is produced on a tandem hot strip mill or a Steckel mill, whereas plate skelp is produced on either a reversing plate mill, Steckel mill, or from hot rolled coils flat sheeted through a cut-to-length facility (for thicknesses <9.5 mm).

Plate mills are typically single or two-stand 4-high reversing mills. Two stands are used when a separate mill is used for rough rolling slabs from their as-cast thickness to an intermediate transfer gauge – typically for increased mill productivity reasons. Due to temperature decay along the plate length, rolled product lengths from conventional plate mills are usually limited to ~50m depending on final thickness.

Tandem hot strip mills consist of one or two 4-high reversing mills used for roughing followed by a series of four to seven 4-high single direction mill stands for finish-rolling. Runout lengths can be in excess of 0.8km depending on final thickness.
Steckel Mills are basically a 4-high reversing plate mill with the addition of heated coiling furnaces on entry and exit sides of the mill. This enables the production of long product runouts as seen in strip mills due to the mitigation of temperature loss. Coils up to 22mm thick by over 3m wide are now being produced in weights up to 35-40 tonnes by this process.

All of these mill configurations may be followed by various types of accelerated water cooling schemes, ranging from several banks of laminar cooling headers with total system capacities from as low as 1000 m^3/h up to 20 000 m^3/h, to even more intense systems capable of imparting 15-20°C/s cooling in ≥50mm plate.

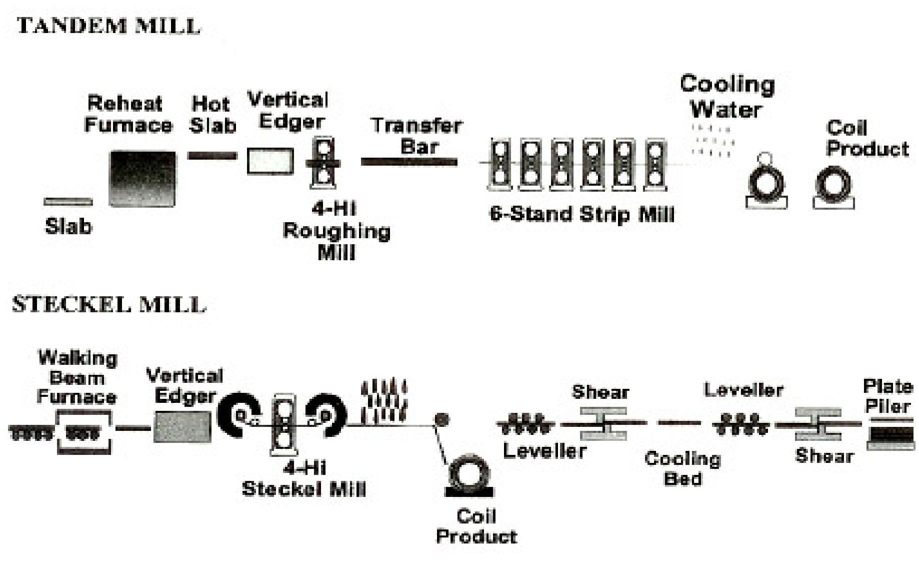


Fig. 5 Typical tandem (strip) and Steckel mill layouts

Rolling Strategies for API Grades

Utilizing the various mill configurations described above, the main goals in rolling skelp suitable for API linepipe are straightforward, but not necessarily easy to achieve and maintain:

- Maintain temperature control during reheating and rolling to meet prescribed temperature setpoints → microstructure, mechanical properties
- Maintain drafting schedule → microstructure, mechanical properties, shape, productivity

The key variables that need to be closely controlled and their effect on linepipe properties are summarized in Table 5.

Table 5. Key variables in rolling and their effect on coil/plate/pipe quality

Process		Key Variable	Effect
Reheating		Reheating time-temperature trajectory for alloy design	Cost effective use of alloy design, consistent microstructure/mechanical properties. Good toughness control.
Rolling	Roughing	Drafting practice for plan view and turn-up control, and recrystallization control-rolling. Attain prescribed intermediate thickness and temperature for mill and alloy design	Productivity, toughness (impact/DWTT), shape
	Finishing	Correct drafting schedule for alloy design	Strength, toughness, microstructure, shape
		Correct finish temperature for alloy design	Strength, toughness, microstructure, shape
ACC		Correct cooling rate	Microstructure, strength
		Correct finish temperature	Microstructure, strength

The slab processing routes consist of first reheating the slab to a prescribed temperature sufficient to allow for the dissolution of microalloys in the steel, followed by one of two basic types of hot rolling: 'conventional' and 'thermo mechanical controlled processing (TMCP)'. Each of these two rolling schemes has several sub-categories generally defined by the degree of deformation below the steel's recrystallization-stop temperature and the final reduction pass temperature relative to the steel's transformation temperature. Each rolling scheme may or may not be followed by some form of accelerated water cooling, Figure 6.

Conventional Hot Rolling:

- Hot Rolled (HR) – the product finishes at its prescribed final thickness with no regard to the final reduction temperature, i.e. it finishes naturally based on the mill's capability - number of passes, draft/pass, etc, to make the final thickness.
- Control Rolled (CR) – this involves setting a desired finish temperature and/or invoking a mild (2xfinal thickness, or 2T) intermediate hold temperature along with a desired finish temperature.

Thermo-mechanical rolling:

- Thermo Mechanical Control Processing (TMCP) – generally involves a more substantial form of control rolling, i.e. a 3T-5T intermediate hold at 832-900 °C, along with a finish rolling temperature close to the steel's Ar3. Rolling through the Ar3 by up to 50°C (so-called 2-phase rolling) may be used for further (dislocation) strengthening. Lower than normal reheating temperatures may also be used for improved toughness (shear values).
- High Temperature Processing TMCP (HTP) again involves a substantial (3T-5T) intermediate hold but at 925-1020 C due to the higher niobium content, along with higher finish temperatures typically +80 °C above Ar_3.[3]

These rolling process routes are can be used for both coil and plate products used in the production of API linepipe[4].

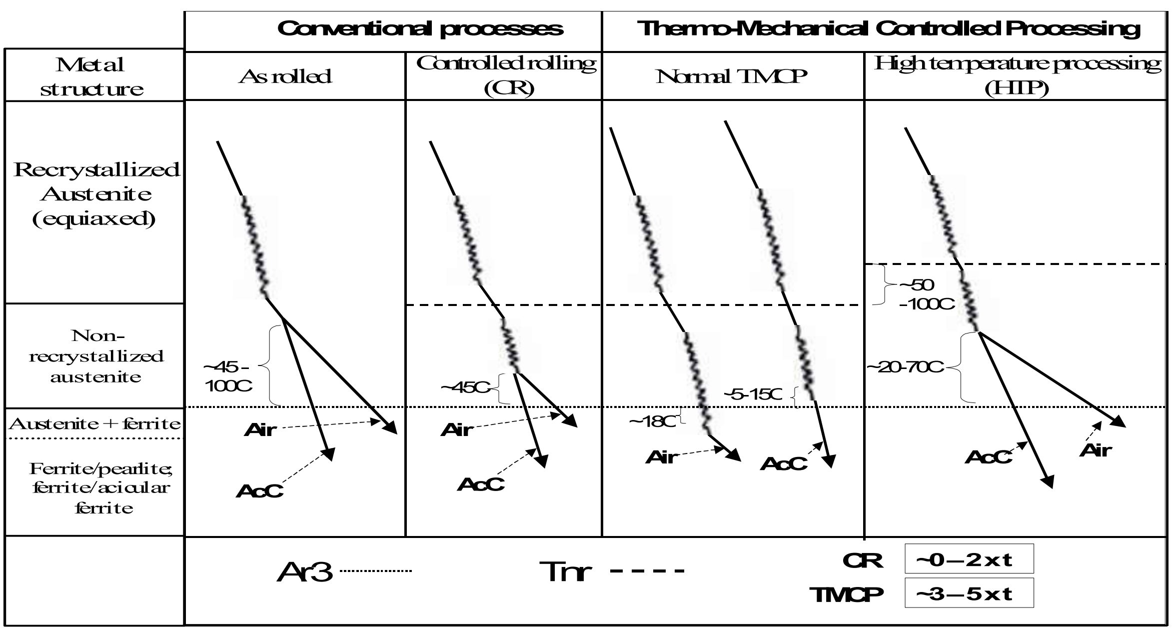
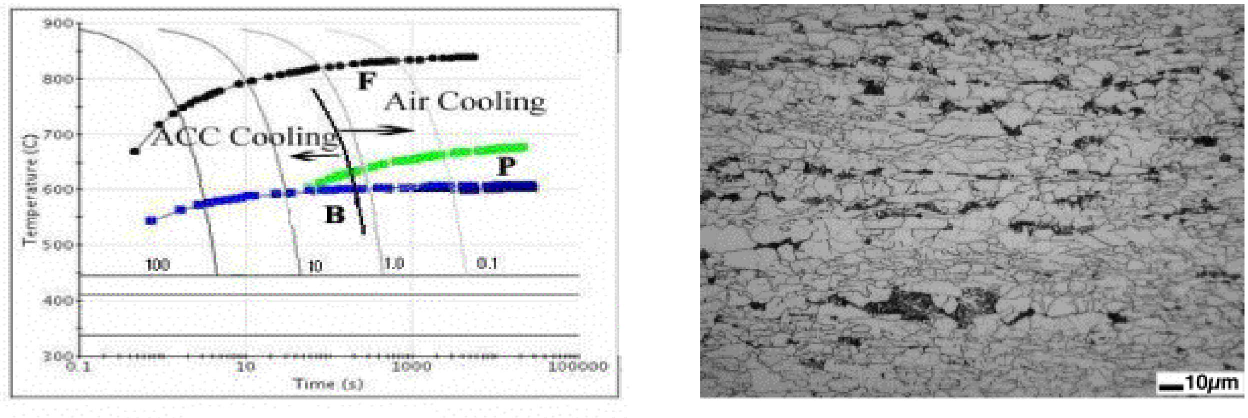
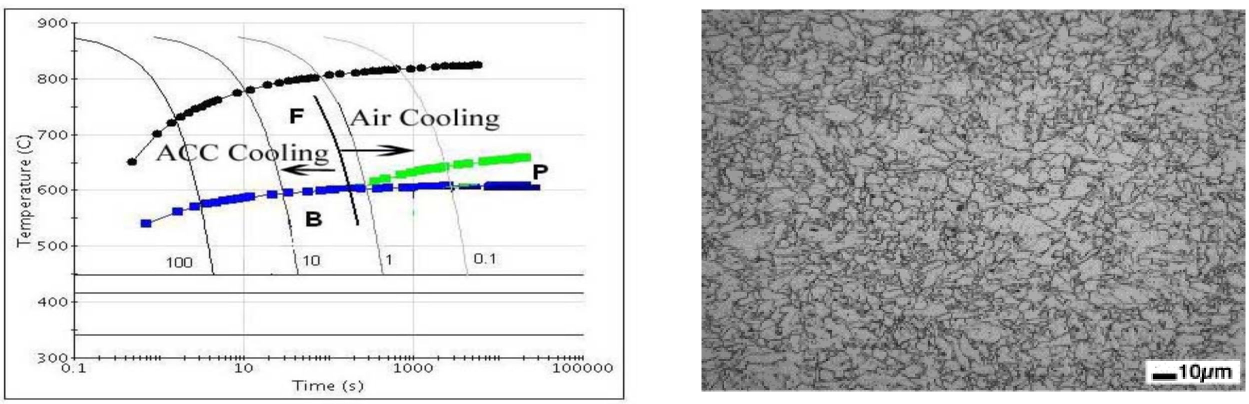


Figure 6. Schematics of rolling process thermo-mechanical paths for the production of API linepipe coil and plate

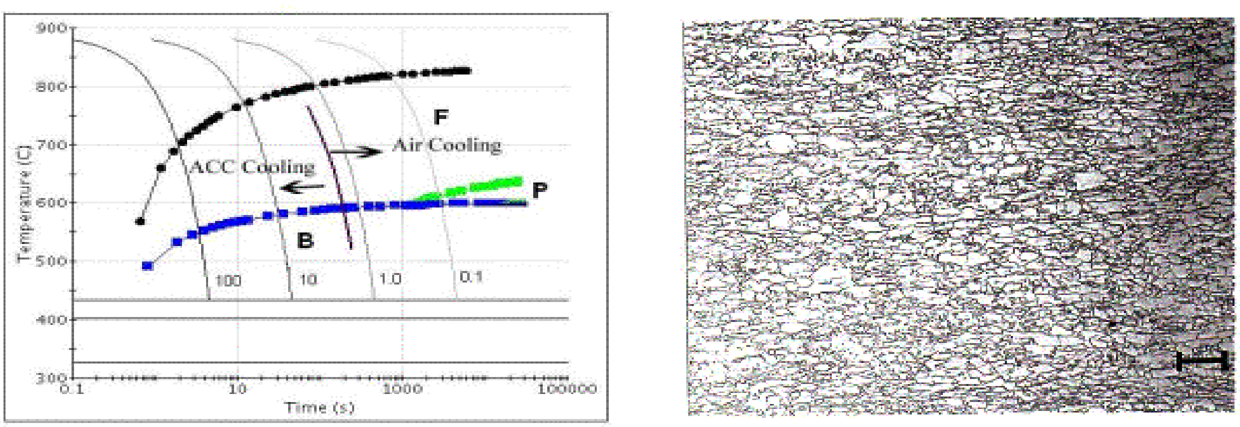
After hot rolling, the steel is air or water cooled to achieve the desired microstructure, hence strength. Continuous cooling transformation (CCT) diagrams can be used to determine the requisite post-rolling cooling rate to achieve this. Example CCT diagrams of actual API designs of an F/P, and two different alloy approaches to F/AF (high niobium HTP and MoNb) are shown in Figure 7.



a) X70 F/P Diagram, C-Mn-Si-V-Nb, Pcm-0.17



b) X80 HTP F/AF CCT Diagram, C-Mn-Si-Nb, Pcm-0.16



c) X80 F/AF CCT Diagram, C-Mn-Si-Nb-Mo, Pcm-0.17[5]

Fig. 7 Example CCT diagrams and resulting microstructures (500x) for F/P and F/AF steels

The carbon equivalent as measured by Pcm is similar with all three steels even though the alloy design is quite different; note the shift of the pearlite transformation curve from Figure 7a to 7b and finally to Figure 7c. The addition of high niobium (Figure 7b) and Mo (Figure 7c) drive the suppression of the pearlite transformation such that acicular or bainitic microstructures can be produced at relatively low post-rolling cooling rates (5-7°C/s), obviating the need for intense accelerated cooling. In fact, F/AF microstructures can be formed from air cooling Mo-based and HTP steels in thicknesses up to ~12-16mm.

A summary of alloy design, processing route and resulting microstructures for various API strength levels is given in Table 6.

Table 6. Approaches to strength

Strength	C-Mn-Si	Micro Alloy	Solute Alloy	HR	CR	TMCP	HTP	Microstructure
5LB	X			X				F/P
X42	X			X	X			F/P
X52	X	X			X			F/P
X52 Sour	X[1]	X	X[2]		X			F/P
X60	X	X				X		F/P
X60 Sour	X[1]	X	X[2]			X		F/P
X65	X	X				X		F/P
X65 Sour	X[1]	X	X[2]			X	X	F/P
X70	X	X	X[3]			X	X	F/P or F/AF
X80	X	X	X			X	X	F/AF
X100	X	X	X			X		F/AF/Bainite
X120	X	X	X			X		AF/Bainite/Martensite

1 – Restrictive C, Mn, and Si for sour service.
2 – Needed due to the restrictive C, Mn, and Si requirement for sour service.
3 – Solute alloy additions are not required in F/P microstructure design.

In summary, API grades up to X70 using a basic low C-Mn-Si-NbV microalloy design produce an F/P microstructure, regardless of hot rolling practice. As strength level and/or wall thickness increases, an F/AF microstructure produced through additional alloying and more stringent rolling and cooling processing routes must be used.

Pipe Production

Production of pipe from discrete plate or coiled skelp is typically accomplished through Electric Resistance Welding (ERW) or double submerged arc welding (DSAW). Forming of DSAW pipe is through helical (spiral), UOE/JCOE (U/JC forming, O pressing, E – expansion), or pyramid forming. Illustrations of the various techniques are shown in Figure 8.

ERW mills (Figure 8a) use a series of increasingly contoured rolls in successive mill stands, or a 'cage' of rolls, to form a pipe from a flat product, and then use electrical resistance to heat the strip edge along with a mechanical upset to form a metallurgical weld. ERW pipe is typically produced in strengths up to APIX65, and in diameters and wall thicknesses less than 610 mm (24") and 9.5 mm (0.375") respectively, although some production product has been produced in grades up to X80. ERW pipe is used extensively in lower pressure feeder or distribution lines.

Larger diameter and heavier wall thickness pipe for transmission service is produced either through helical (spiral), UOE/JCOE, or pyramid forming using double submerged arc welding (DSAW). Cold expansion of the formed pipe up to 1.5% on diameter is frequently used for improved pipe dimensional control. Typically, all strengths levels of API in diameters up to NPS72 and in thicknesses up to 50mm can be produced by one or more of the pipe making processes.

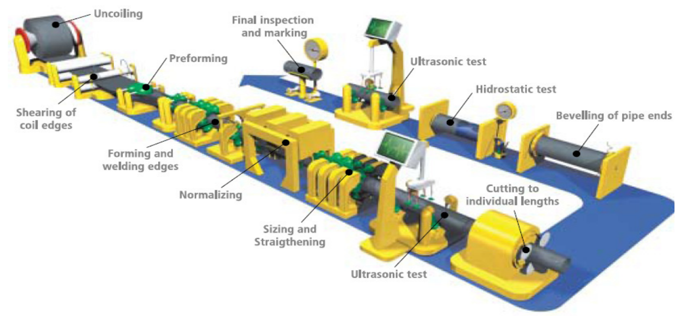
Skelp-to-Pipe Mechanical Property Response

General Relationships:

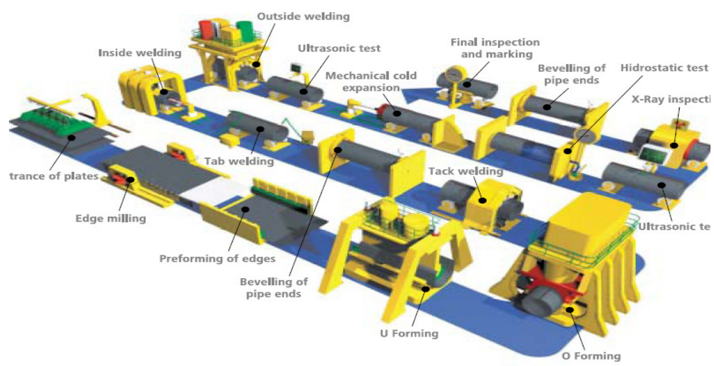
Nowadays, because the pipe producer is frequently not the same company, or not even on the same continent as the skelp producer (or the steel producer), it is important to understand the relationship between pipe properties and skelp (coil/plate) properties. Skelp properties are irrelevant if final pipe properties are not met.

Generally, the relationship between skelp strength and pipe strength is linear, but is statistically weak when actual production data is used, as compared to controlled laboratory or pilot plant data. The notch toughness relationship is similarly weak. Measured pipe strength can be higher or lower than the skelp strength depending on the steel's microstructure and other variables such as pipe production processing, thickness, diameter, etc. The difference between the two is not consistent.

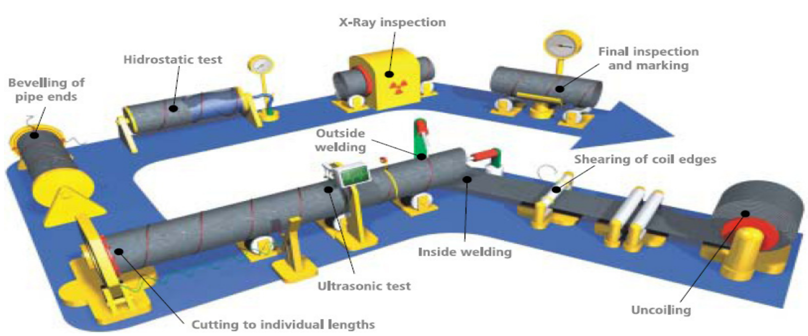
It is well known that a ferrite-pearlite microstructure generally leads to a drop in yield strength between skelp and pipe, sometimes up to 70 MPa, while an acicular structure can lead to an apparent yield strength increase. There's generally less scatter in the relationship between pipe tensile strength and skelp tensile strength, with the shift in tensile strength during pipemaking being always neutral or positive. As such, the shifts between skelp and pipe yield and tensile strengths can each be in different directions. These points are illustrated in Figures 9a and b.



a) ERW

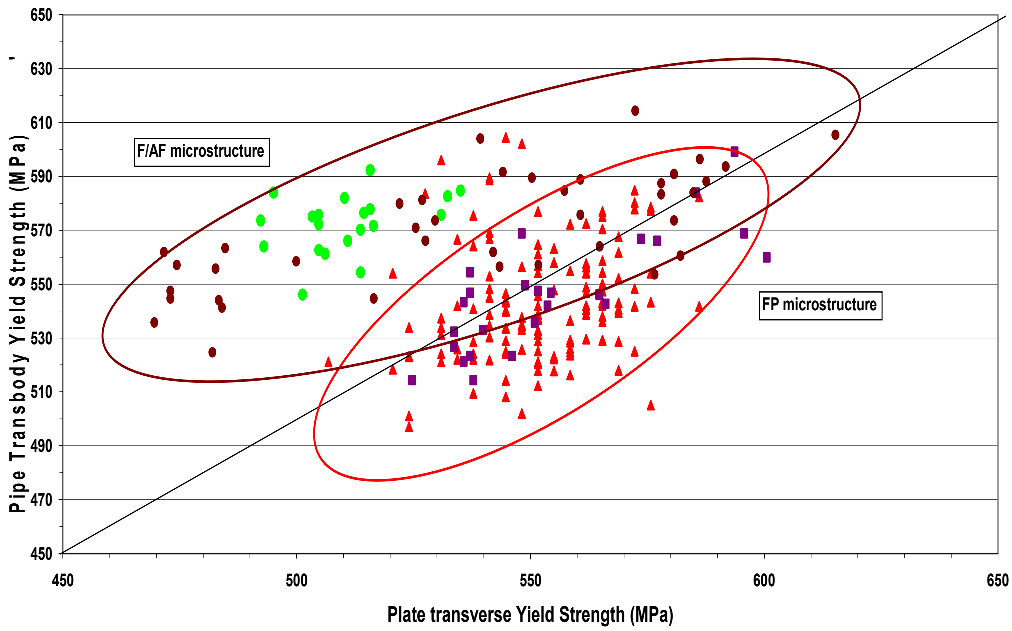


b) UOE

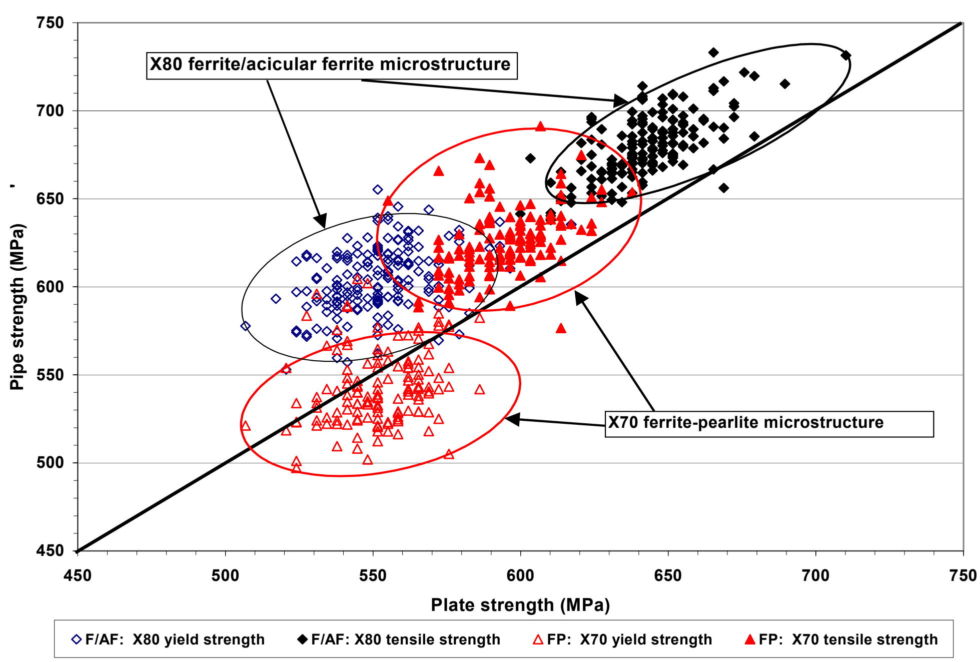


c) Helical (spiral) forming

Figure 8. Schematics of Pipemaking Techniques



a) X70 UOE – various recent North American projects



b)

b) Recent X70 and X80 – illustrating the generally neutral or positive shift in tensile strength compared to yield strength

Figure 9. Pipe and Skelp Strengths – Recent X70 and X80 Trials

Figure 9a is X70 data from several North American pipeline projects since 2000 using data from different plate and pipe mills. It clearly illustrates the different yield strength response of F/P and F/AF Figure 9b is both X70 and X80 data from two fairly recent North American projects. The pipe YS and TS changes with the F/AF X80 microstructure are compared to the same thing from an F/P X70 microstructure. In the F/AF case, both YS and TS have increased during pipemaking, while in the F/P X70 case, YS has decreased while TS has increased.

Another key feature that can be seen in the figure is that the change in strength from plate to pipe is not consistent even for one microstructural type. For example, as skelp YS increases with F/AF steel, the difference between skelp and pipe YS decreases – Figure 9a. For F/P, the skelp YS relative to the maximum achievable YS for a give alloy design will determine the degree of increase or decrease during pipemaking. A higher skelp YS in an F/P steel can lead to a substantial decrease in pipemaking (e.g. up to ~70MPa,) whereas a lower YS (lower Y/T ratio) may actually see a YS increase.
The data in the figures, above, has been combined with other data from various linepipe projects to illustrate, in a more general way, the dependence of the strength shift on alloy design, Figure 10.

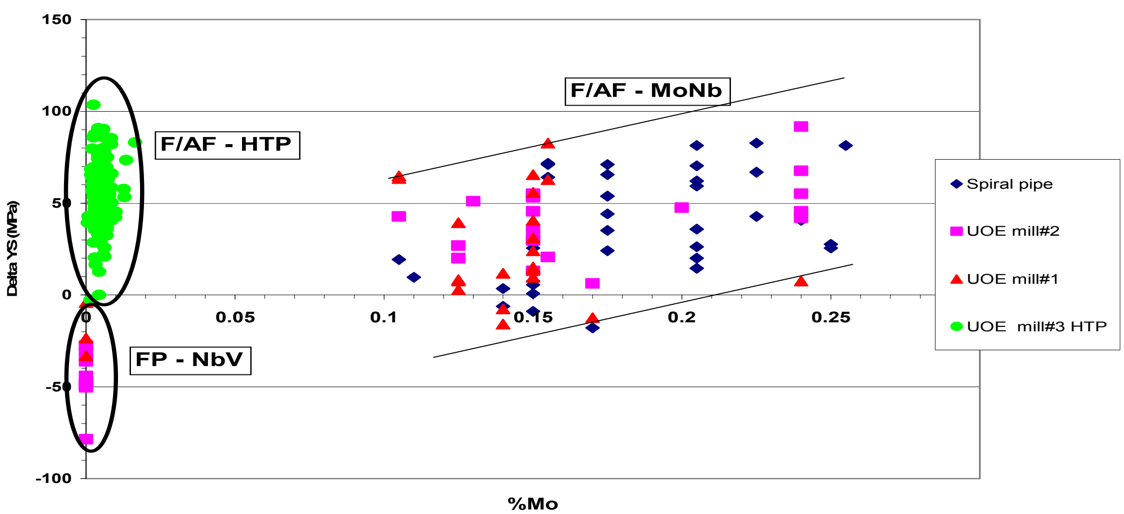


Figure 10. Dependence of plate-to-pipe YS change on Mo content – X65 – X80

Figure 10 shows the increasing pipe strength pickup with increasing molybdenum content. For large diameter X80, the HTP (~0.095%Nb+Cr) and Mo-based (~0.08%Nb) F/AF microstructures behave in an equivalent manner during pipe making at ~0.25% molybdenum.

The strength change phenomenon has been well documented in the technical literature for over 30 years; however, it is still a source of frustration for the skelp producer who needs practical methods to set a skelp strength target based on a pipe specification, and without necessarily having good knowledge or understanding of the subsequent pipemaking operation. This has led to searches for simple, practical pipe strength estimation methods, discussed later.

Toughness also changes during pipemaking, behaving somewhat similarly to strength, Figure 11. Although the toughness change is not as well understood, it is equally as important for the skelp producer to have a practical way of estimating subsequent pipe toughness from skelp testing. Usually, a lower-than-specified test temperature is used (skelp testing ~15°C or more below pipe requirements), and this has proven generally adequate. However, at the very high toughness levels now being obtained with low sulfur, very clean steels, some manufacturers are seeing a divergence between the skelp and pipe results, indicating an apparent shift in notch toughness during pipeforming, Figure 11[5].

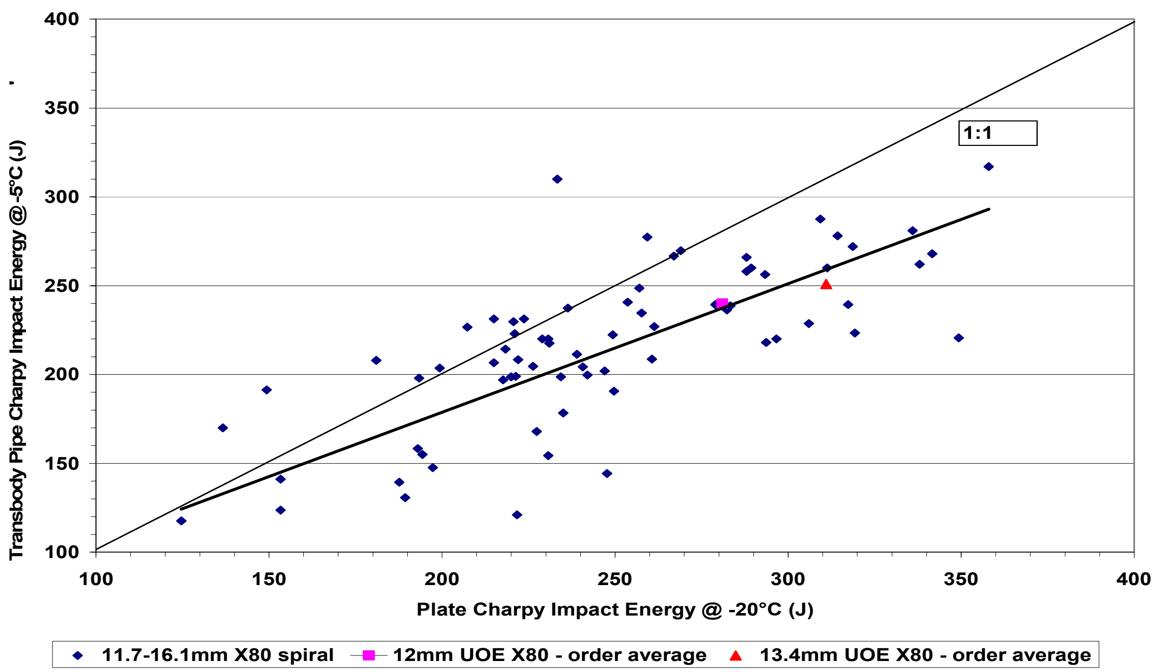


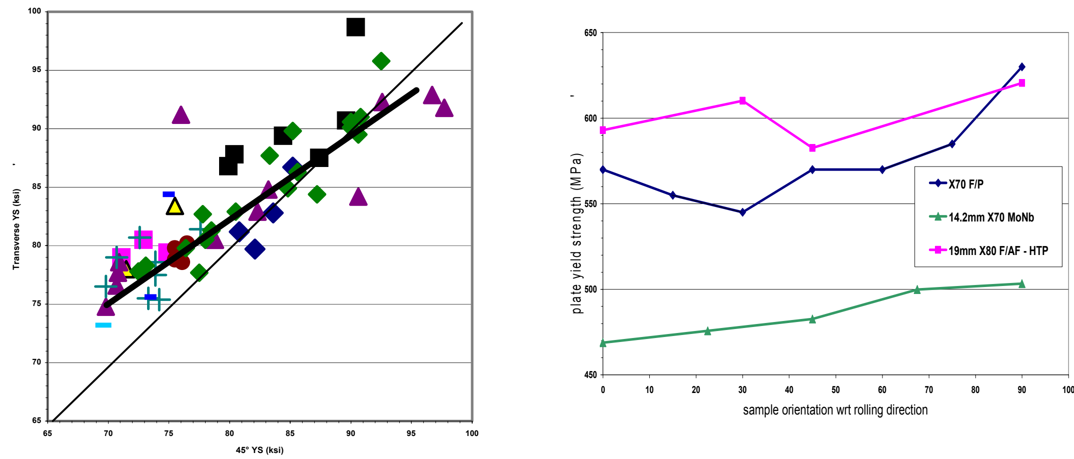
Figure 11. Skelp-to-pipe CVN toughness change

The anisotropy of skelp mechanical properties must also be considered in understanding the relationship between skelp and pipe properties for two main reasons:

- In helical, or spiral pipe forming, the standard trans-body pipe test direction does not correspond to the transverse skelp direction (i.e. 90° to the rolling direction) as it does with the long-seam pipemaking processes (e.g. U&O and ERW), and
- In strain-based pipeline designs, both longitudinal and transverse strength is important and specifications exist on their acceptable ratio.

The degree of property anisotropy is influenced largely by crystallographic structure. Normally, strength at 90° to the rolling direction is highest for controlled-rolled steels,

Figure 12. At the 45°orientation, strength may or may not be lower than at either 0° or 90° depending on rolling practice. Generally 2-phase rolling 'sharpens' (increases) the differences.



a) 45° vs. 90°

b) Testing at various angles to the rolling direction

Figure 12. Ilustration of skelp strength anisotropy – X80

Toughness also has directionality as illustrated in Figure 13. Interestingly, the figure shows a toughness trough at 45° to the rolling direction – the same orientation as lower strength.

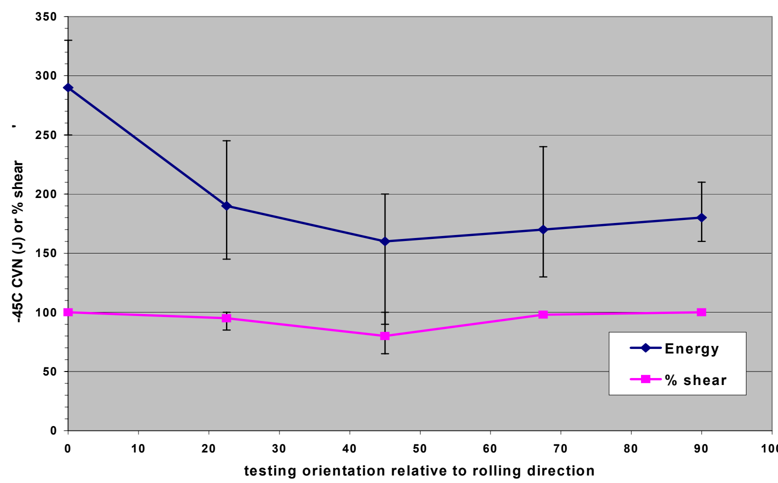
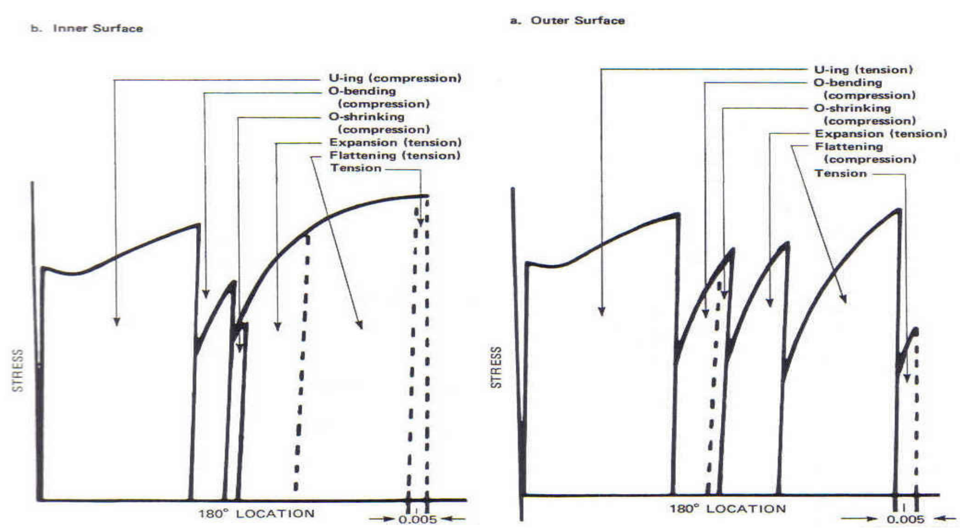


Figure 13. CVN energy as a function of testing direction 14.2mm-X70 MoNb[6]

This directional dependence of properties as a function of alloying and rolling practice needs to be understood by the skelp producer in order to supply to the various pipemaking processes.

Steel Yielding Behavior

Pipe strength is mainly dependent on skelp yield strength modified by the steel's yielding behavior through the strain path during pipe-forming and subsequent cold expansion (if applicable), and then tensile testing. This strain path typically involves several tensile and compressive strains and reversals for each surface depending on the pipeforming and testing methods employed. An example strain path for UOE pipe forming is shown in Figure 14.



Inner surface **Outer surface**

Figure 14. Inner and outer surface strain path in UOE pipe forming and testing

The diagram shows that the inner surface of the skelp goes through several compression cycles followed by tension cycles during cold expansion, tensile specimen flattening then the tensile test itself. In contrast, the outer surface goes through a tension cycle during initial pipe forming, followed by some compression, then tension during cold expansion, compression through tensile specimen flattening, and finally tension in the tensile test. Each element of the skelp through-thickness will go through various parts of these cycles. As such, the final pipe strength is built up from a composite of many reverse strain and compression cycles.

The steel's yielding behavior can be characterized in practical terms by its stress-strain curve and, during the pipemaking process, by the Bauschinger effect which is basically the reduction in yield strength of the material in compression following pre-strain, or vice versa. The key characteristics of the stress-strain curve are the basic yield strength value, yield point or Luder's elongation (YPE), work hardening rate and then tensile strength. These values are driven by the atomic or crystallographic nature of the material, i.e. its microstructure, alloying, microalloying, etc. A ferrite-pearlite microstructure behaves differently from an acicular structure, Figure 15.

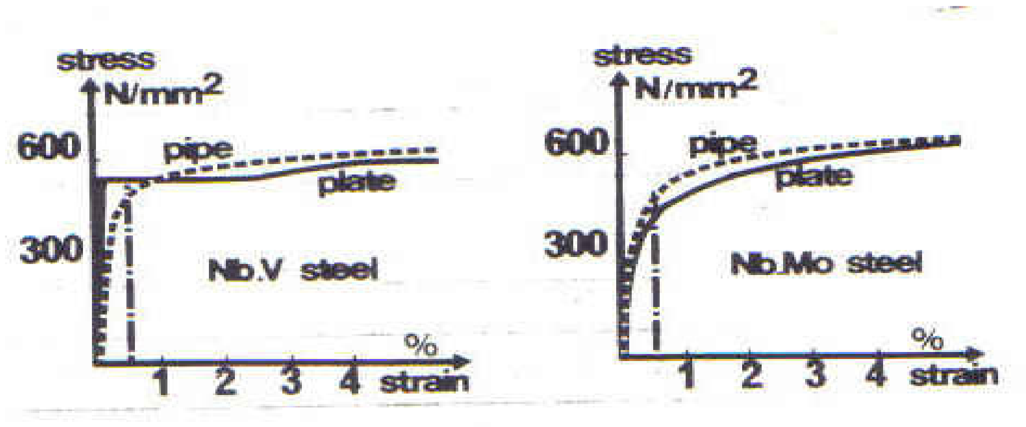


Figure 15. Typical stress-strain curves for linepipe steels

Figure 15 shows the existence of a distinct yield point and yield point elongation for the F/P steel as compared to the more continuously yielding behavior of the F/AF steel. This fundamental yielding behavior of the steel can be used on a practical basis to estimate the change in yield strength from skelp to pipe. This is illustrated in Figure 16, derived from actual X70[7] and X80 production data, which shows the significant change in strength between skelp and pipe as a function of skelp yield point, or Luder's elongation.

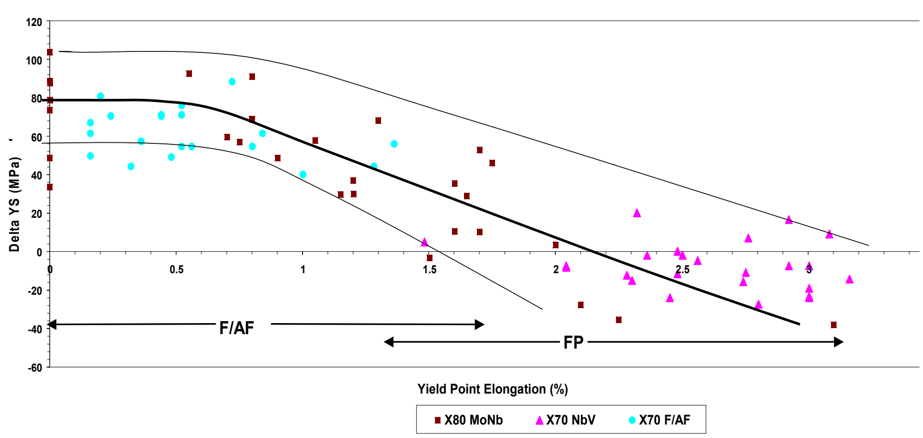


Fig. 16 Dependence of plate-to-pipe strength change on Luder's elongation X70 and X80, t/D~0.9-1.2%

As illustrated in Figure 16, the steel's YPE is fundamentally different between F/P and F/AF steels – ranging from 0 to ~2% for F/AF and between ~1.5 – 3.5% for F/P. The YPE, in turn, is based largely on the various constituents of the steel's microstructural composition with more highly-hardenable microstructures leading to more continuously yielding stress-strain curves.

Pipe forming

The effects of the actual strain path during pipemaking on pipe strength can be reasonably well characterized by the:

- pipe forming ratio – t/D
- cold expansion, and
- pipe strength testing method, e.g. flattened strap vs. ring vs. round tensile bar

First, higher forming ratios lead to higher strength pickups, Figure 17[7]. Generally, a plate-to-pipe strength increase of ~13Mpa per 0.2% forming ratio increase in the typical forming range of large diameter pipe.

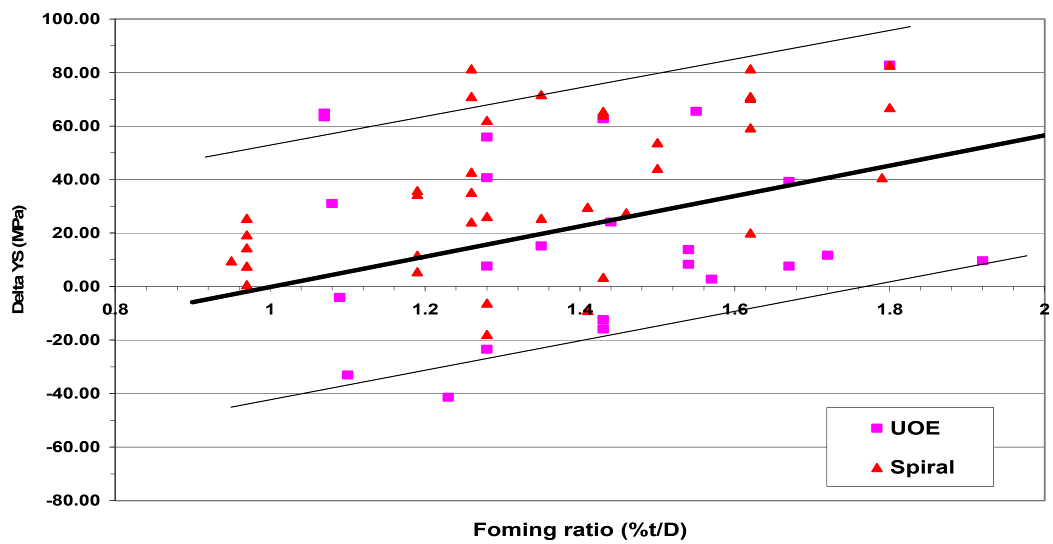


Figure 17. Strength change on pipe forming ratio

Following pipe forming, cold expansion up to ~1.5% is typically used to improve API pipe's diametral dimensional conformance. This process also increases pipe strength as shown in Figure 18 where the responses of an F/P and F/AF are compared.

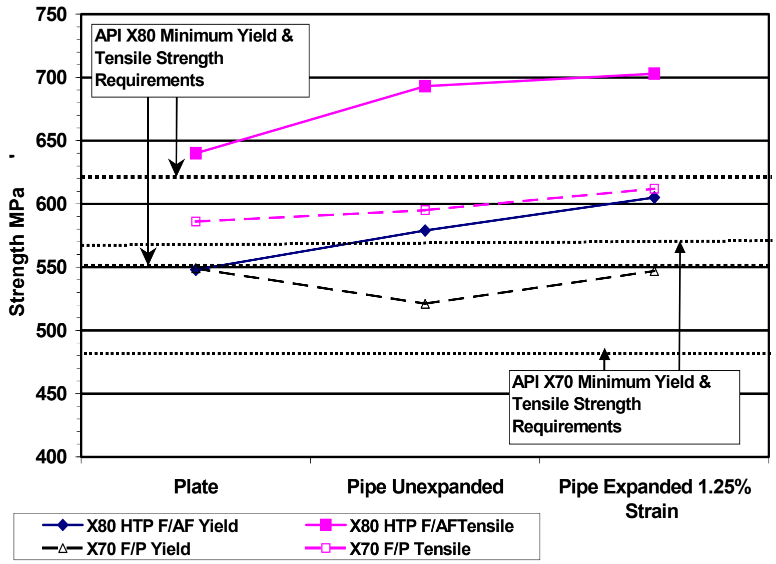


Figure 18. Strength change during pipeforming and cold expansion.

In summary, it is important for both skelp and pipe producers to understand the strength change from skelp to pipe and the reasons for it. F/AF steel behaves fundamentally differently from F/P steel due to yielding behavior which is largely driven by microstructural composition. Simple statistical and empirical relationships, all the way up to computer models can be used to predict this – see next section.

Guidelines to Choosing the Alloying/Microstructural Design

Mathematical Models

Skelp Strength

Mathematical models of various degrees of complexity have been used since the 1960s to predict skelp and pipe mechanical properties as a function of the key alloying and subsequent processing variables. Initially, in the plate and hot rolled strip area, multiple linear regression models that combined alloy additions and some representation of rolling practice were used to predict plate or strip strength and toughness, e.g.

<mechanical property> = $\Sigma\, a_i$(chem components) + $\Sigma\, b_i$(rolling variables) ……….. (1)

where 'rolling variables' could simply include final thickness and finishing and/or coiling temperature. The rolling variables, such as thickness, may be intertwined with the chemistry terms.

The range of applicability of this approach is constrained by the ranges of the independent variables in the equations, and so is generally limited to a specific rolling (plate or strip) mill. However, results can be very acceptable, Figure 19, and the approach is still in use, enjoying a good degree of success on a working basis[8]. It has been used successfully to support skelp alloy designs and cost analyses.

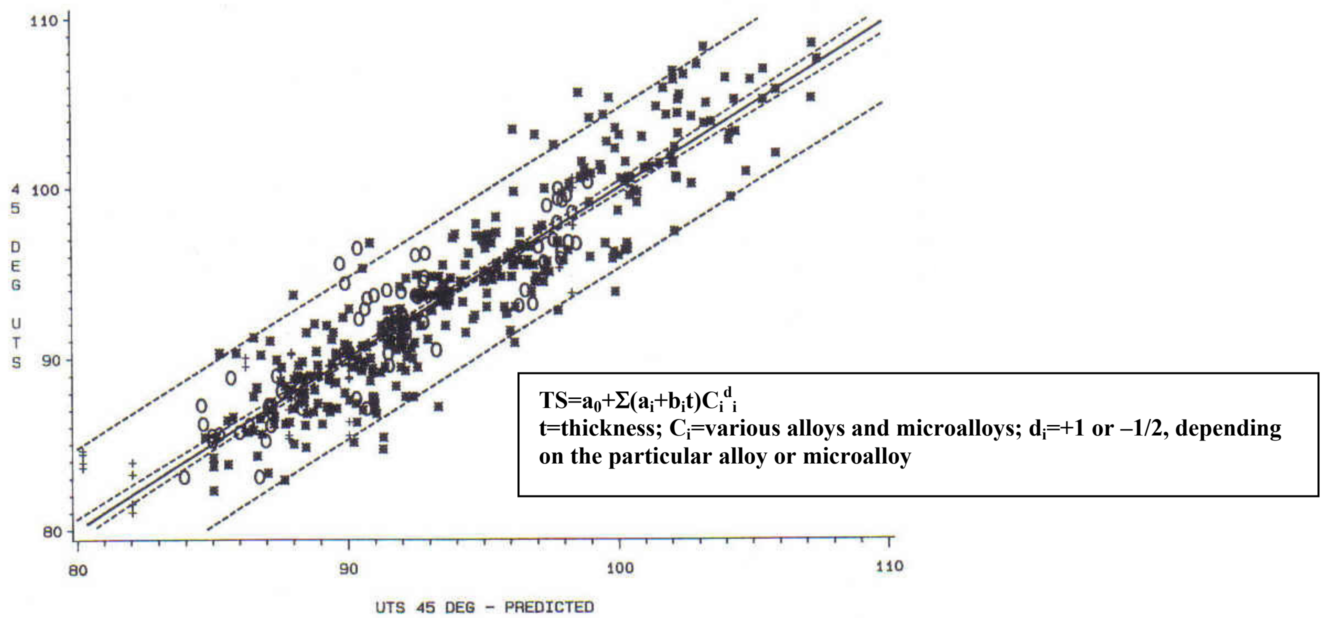


Figure 19. Tensile strength prediction model

The statistical approach does not explain the basic phenomena behind mechanical properties. Initial models in this area were based on an expanded Hall-Petch relationship where yield strength and toughness were basically additive components of the various strengthening mechanisms, e.g.

$$YS \text{ (or FATT)} = \sigma + kd^{-1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(2)$$

d = grain size, and $\sigma = \Sigma a_i \sigma_i$
where σ_i = various components of strength, e.g. solid solution, precipitation, dislocation, texture, etc.

This approach has proven useful in describing the relative roles of the various strengthening mechanisms on a more metallurgical basis and so has been suited to explaining or justifying alloying approaches, but it has not proven well-suited to actual property prediction.

Over the past two decades, these approaches have been gradually replaced by more theoretically based models that better describe the basic physical metallurgy involved in the hot deformation of low carbon, complex steel alloys - predicting mechanical properties from final grain structure, alloying and precipitate fractions, etc. Building on the pioneering work of Sellars et al and others in the late 1970s[9], where practical equations describing the basic constitutive and recrystallization behavior of steels were presented, these models are now well beyond the confines of academia and are being adopted in industry to support advanced product development, i.e. they are beginning to reach a level of maturity with good predictive accuracy of microstructure and mechanical properties from any starting chemistry and hot rolling practice. They are now being used to design alloying and rolling practices to meet specified property targets[10].

Pipe Strength

Skelp producers have developed various techniques to calculate pipe strength from skelp strength, ranging from pilot scale pipemaking jigs to statistical techniques to computer models. However, models for the prediction of pipe strength are generally not as sophisticated as rolling models. Frequently, simple regression techniques relating pipe YS to skelp TS or Y/T ratio are still used to guide day-day processing decisions in hot rolling mills, e.g.

Pipe YS = a + b (plate TS or Y/T) ……………………….(3)

where Plate TS is predicted by a linear equation such as (1), earlier

For example, Figure 20 shows that a linear relationship exists between the plate-to-pipe strength change and skelp Y/T ratio, regardless of microstructure. The relationship is solid, but different for each alloy route; however, it can be a practical in-mill tool.

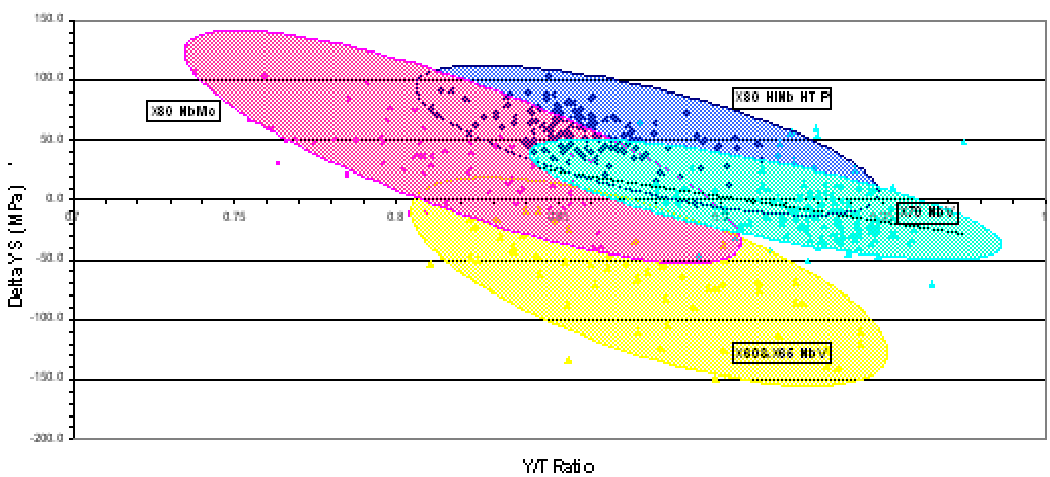


Figure 20. Dependence of plate-to-pipe strength change on skelp Y/T ratio

These simple relationships are very mill- or steel-specific and were replaced first by empirical equations that better describe the steel's yielding behavior (e.g. see section 4) and its strain path during pipemaking and tensile testing, e.g.

$$\text{Pipe YS} = a_0 + a_1\text{*plate YS} + a_2\text{*yield point elongation} + a_3\text{*forming ratio} + a_4\text{*expansion} + a_5\text{*test method} \quad \ldots\ldots\ldots\ldots(4)$$

This form of equation is quite robust if a large database of skelp and pipe properties and pipemaking variables is available, which usually restricts its use to one integrated manufacturer. Again, though, with the increasing trend of the skelp supplier not being the pipe-maker, more fundamental approaches need to be used that actually model the steel's yielding behavior through the pipe forming path. Such generalized models can then be used to predict pipe strength for any type of steel and pipe making process[11,12]. An illustration of the accuracy of one such model is shown in Figure 21[7]. The model requires good measurement of the yielding behavior of the skelp (i.e. its stress-strain curve) and some knowledge of the subsequent pipemaking process, expansion rate and strength test method. The Bauschinger effect is handled by statistical relationships. The overall accuracy is ~ +/-10-15MPa.

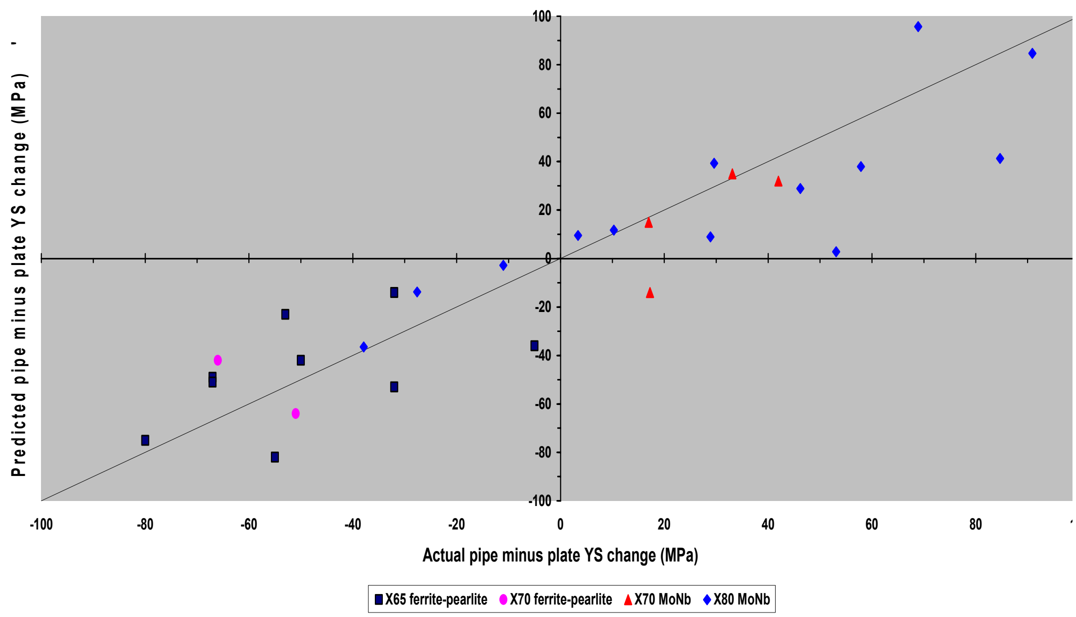


Figure 21. Pipe strength prediction model

As with any model, its accuracy is only as good as the accuracy of the equations and the supporting theories and data used to develop them. There have been tremendous strides made in this area over the past decade. Advanced mathematical models of most steelmaking, rolling and forming processes are mature and are becoming readily available on desktop computers to support alloy and process design studies by mill engineers and metallurgists.

Comparison of Microstructure/Alloy Approaches

When deciding which microstructure/alloy approach should be used for a given pipe specification, several variables need to be considered:

- Total steel cost
- Steel and pipe mill productivity
- Ease of manufacture
- Skelp property behavior during pipe production
- Physical property requirements of skelp and pipe

Table 7 illustrates advantages and disadvantages to the different microstructures and alloy approaches.

Table 7. Comparison of advantages and disadvantages of microstructure/alloy approaches

Microstructure	Strength Range	Chemistry	Alloy Cost Rollability Productivity	Advantages	Disadvantages
F/P	X42-X70	C (≤0.10) V, Nb (<0.065)	Alloy Cost – Lowest Rollability – moderate (mill capability dependent) Productivity – moderate for TMCP, mill dependent	Can use higher C Lowest alloy cost Toughness good to -29 °C	Strength loss during pipemaking. Low temp TMCP rolling Higher mill loads
F/AF-Mo-based	X65-X100	C (≤0.06) Nb (<0.08) + Mo (+Cr,Ni,Cu)	Alloy Cost - high Rollability – challenging Productivity – low due to mill loads and required finish temperature	Air-cooled AF structure for X80<13mm X70<17mm Strength pickup during pipemaking	Low temp TMCP to Ar3 or even 2 phase rolling. Mo is an austenite strengthener – higher mill loads ACC required for heavier thickness
F/AF- Nb based HTP	X65-X100	C (≤0.06) Nb (<0.11) (+Cr,Ni,Cu ≥X80)	AlloyCost – moderate (lowest cost to produce F/AF) Rollability – good due to high processing temperatures Productivity – moderate for TMCP	Higher FT (Ar3+80 °C) Lower mill loads Strength pickup during pipemaking Lower alloy cost Easier to roll F/AF	ACC ≥ X80

In choosing a microstructure/alloy approach the general guidelines can be used:

- **F/P** – low cost requirements, strength requirements ≤X70, rolling mill capability is not an issue, severe low temperature toughness not required, and pipemaking property behavior is not a concern.
- **F/AF**
    - **Mo based** – strength requirements ≥X70, rolling mill capability may be an issue, severe low temperature toughness is required, low YT and pipemaking property behavior is a concern.
    - **Nb based HTP** – strength requirements ≥X70, rolling mill capability maybe an issue, severe low temperature toughness requirements, low YT, pipemaking property behavior is a concern, and lower cost requirements.

To determine which hot rolling process route to invoke, the following guidelines can be used:

- **Hot Rolling** (HR) is chosen when tensile (yield/ ultimate) strength is the only end physical property characteristic desired. Moderate toughness properties can be achieved above 0 °C (32 °F) with controlled chemistry selection.
- **Control Rolling** (CR) is chosen when slightly higher tensile (yield/ultimate) strength and/or some intermediate toughness characteristic are desired between -30 °C (-22 °F) and 0 °C (32 °F). In addition, control rolling can be used to enhance formability (bending).
- **Thermo Mechanical Control Processing** (TMCP) is chosen when high tensile (yield/ultimate) strength and/or severe toughness characteristics are desired <-30 °C (-22 °F).

High Temperature Processing Thermo Mechanical Control Processing (HTP TMCP) is chosen when high tensile (yield/ultimate) strength and/or severe toughness characteristics are desired <-30 °C (-22 °F) and/or mill capability limitations are involved. Also well suited to Steckel processing where there is little temperature loss during the final finishing passes.

Rolling Practice

Figure 22 compares the main TMCP temperature setpoints for two X80 steels – HTP and MoNb. For the HTP steel, a 3T hold was specified with a resume temperature slightly below its high calculated Tnr of 1020°C. The MoNb practice used only a 2T hold at around its (lower) Tnr of ~920°C as a less powerful plate rolling mill was being used[13]. The key difference between the two practices is the last pass temperature which is closer to Ar_3 for the MoNb steel. Although the hot flow stress is about the same for the two steels (Figure 23) at the same temperature below Tnr, the lower finishing temperature of the MoNb steel can result in higher rolling forces at the end of rolling with ensuing shape concerns for the lighter gauges.

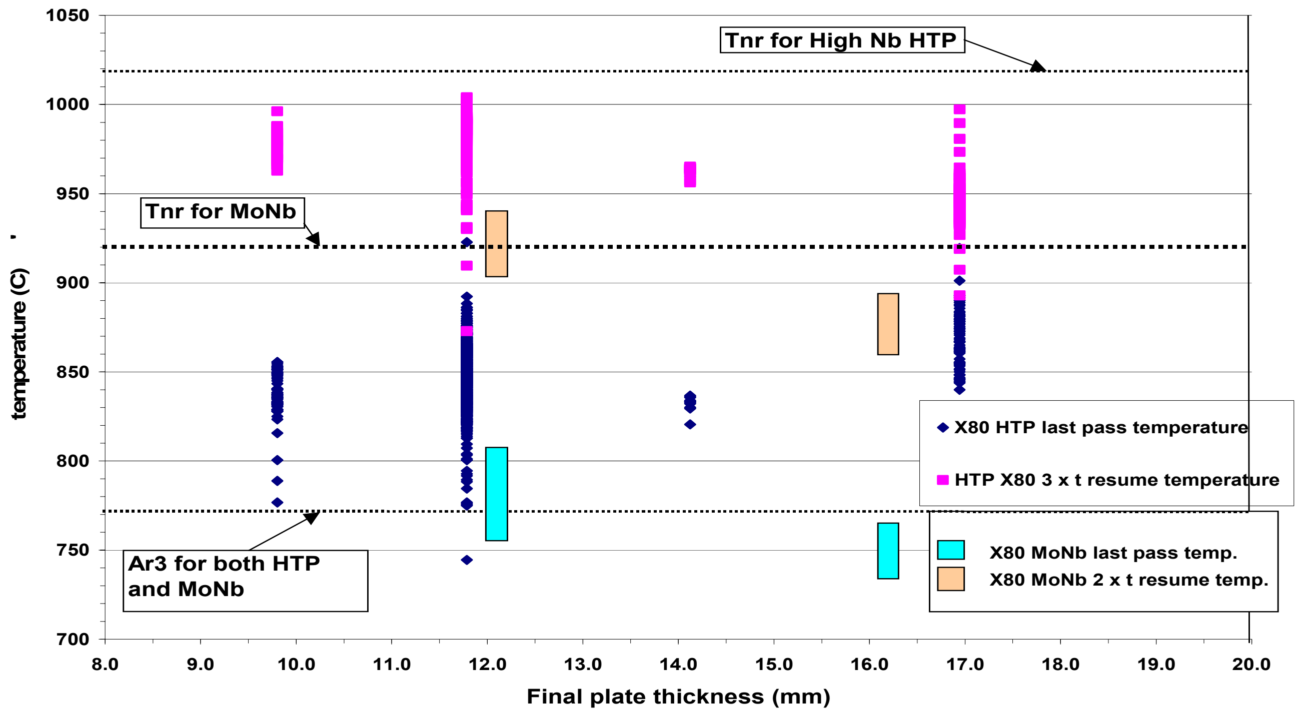


Fig. 22 Comparison of HTP vs. normal TMCP rolling temperature set points for X

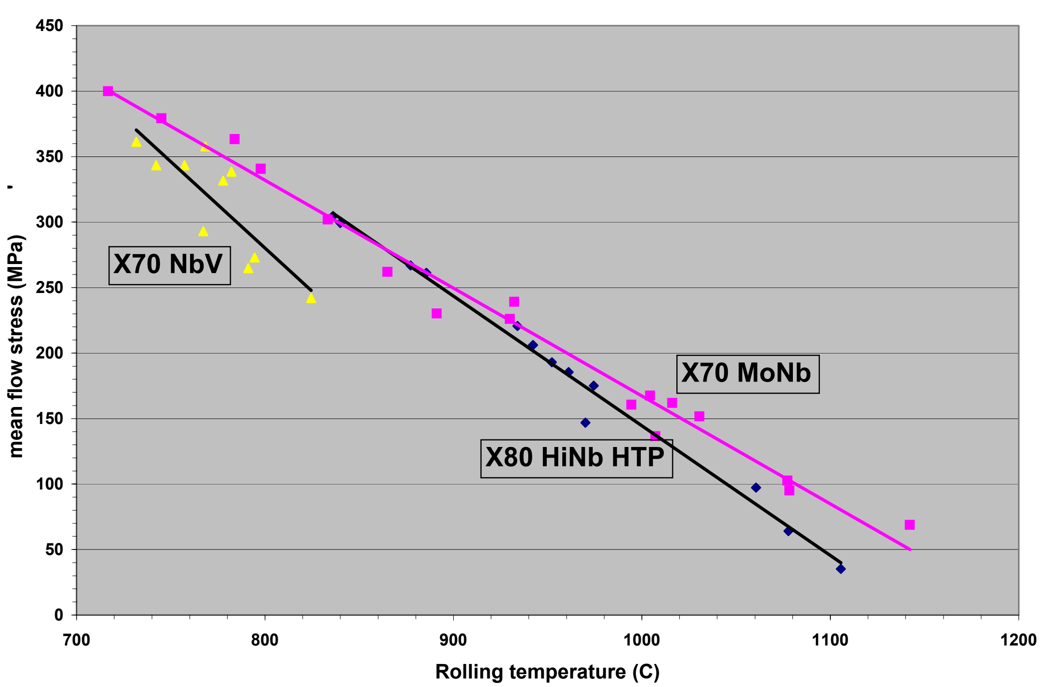


Fig. 23 Comparison of mean hot rolling flow stress - X70 and X80 steels

Results from Recent Projects

Summary results from several recent North American X70 and X80 projects are reviewed in this section to highlight some of the similarities and differences between the basic alloying approaches. First, several actual chemical compositions of recent projects are given in Table 8.

Table 8. Example API chemistry compositions used in past 5 years for NPS36 to 48, ~12-17mm, high toughness linepipe

Grade	µstructure	Chemical composition*							TMCP route
		C	Mn	Mo	Cu+Ni +Cr	V	Nb	Pcm	
X65	**F/P**	0.08	1.55	NA	0.1	0.05	0.065	0.17	Short, intense laminar
X70	**F/P**	0.06	1.55	NA	NA	0.055	0.055	0.15	Air
X70	**F/AF**	0.05	1.5	0.25	0.2	NA	.08	0.18	Air
X80[14]	**F/AF**	0.045	1.75	0.30	0.65	NA	.085	0.2	Air/Laminar
X80	**F/AF-HTP**	0.05	1.6	NA	0.6	NA	0.095	0.16	ACC

*All steels: S<0.003, P<0.015, Ti <0.015

The steels in Table 8 were processed on conventional and steckel plate mills using either TMCP or HTP practices – Figure 6, earlier.

Skelp and pipe strength results are summarized in Figure 24. The figure shows the averages and ranges in measured strength.

In line with Figure 9 earlier, Figure 24 shows the very slight drop in pipe YS relative to plate YS after cold expansion for the F/P X70 versus considerable strength gains for the F/AF projects. There is a significantly higher TS for the MoNb approach, but not too much effect of ~5°C/s laminar cooling rate on the 12mm MoNb X80[13].

In modern clean, vacuum degassed low carbon API steels, notch toughness is mainly driven by sulfur and phosphorous content, and by final grain size, Figure 25[15]. For niobium steels, the final grain size, in turn, is driven by the amounts and speeds of the reductions that can be taken on the rolling mill, and post-rolling cooling rate. This is basically a function of mill size and power, and ACC capability. More powerful rolling mills that can deliver high degrees of reduction/pass (e.g. ε ~0.2) with short interpass times will generally produce a better conditioned 'pancaked' austenite leading to a finer ferrite grain size, e.g. ~ 4-5µm. The CVN toughness for several recent X80 projects is shown in Figure 26.

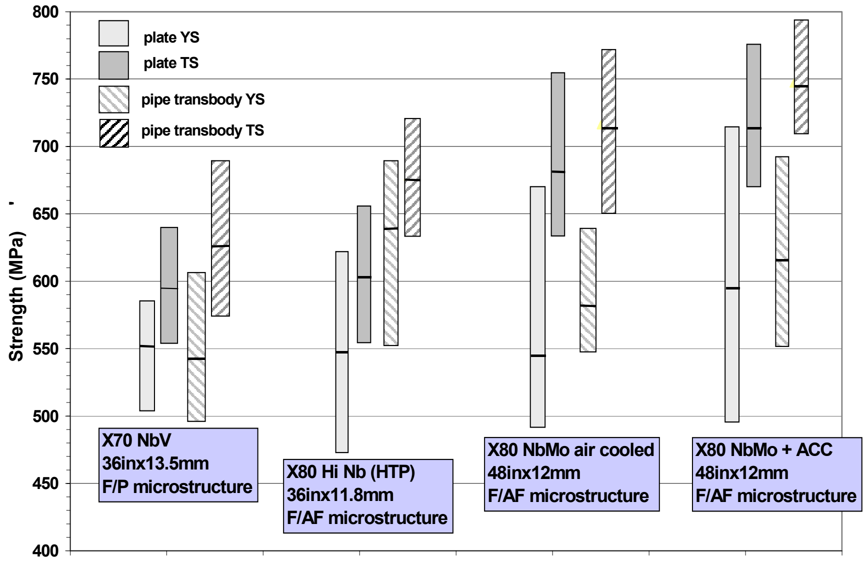


Fig. 24 Plate and pipe strength – recent North American X70 and X80 projects

Figure 26 shows that average -5°C CVN values over 200J are now readily achievable in low sulfur X70 and X80 pipe. In fact, skelp sometimes has to be tested at a very low temperature (e.g. -45°C instead of -20°C) to avoid hitting the limit of conventional Charpy testing machines.

The 50% FATT of these steels is now typically below –45°C, regardless of alloying route, Figure 27.

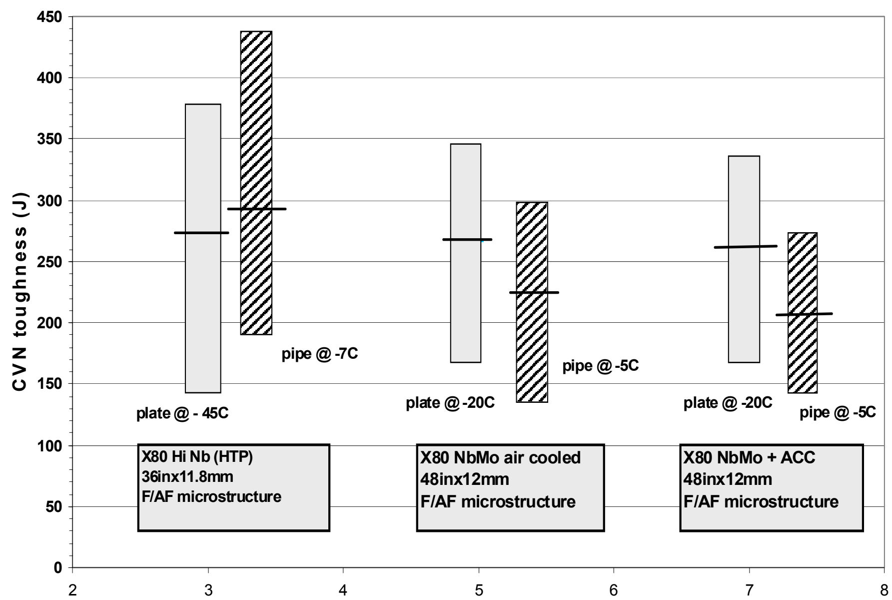


Figure 25 Dependence of CVN toughness on steel sulfur content -11.4mm x 42NPS X70 and 12-13 X80.

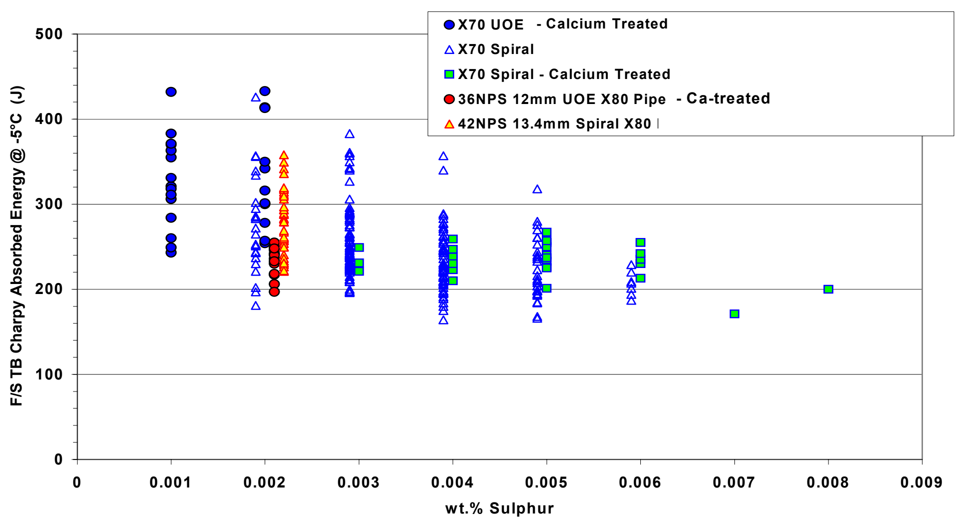


Figure 26. X80 Trans-body pipe notch toughness

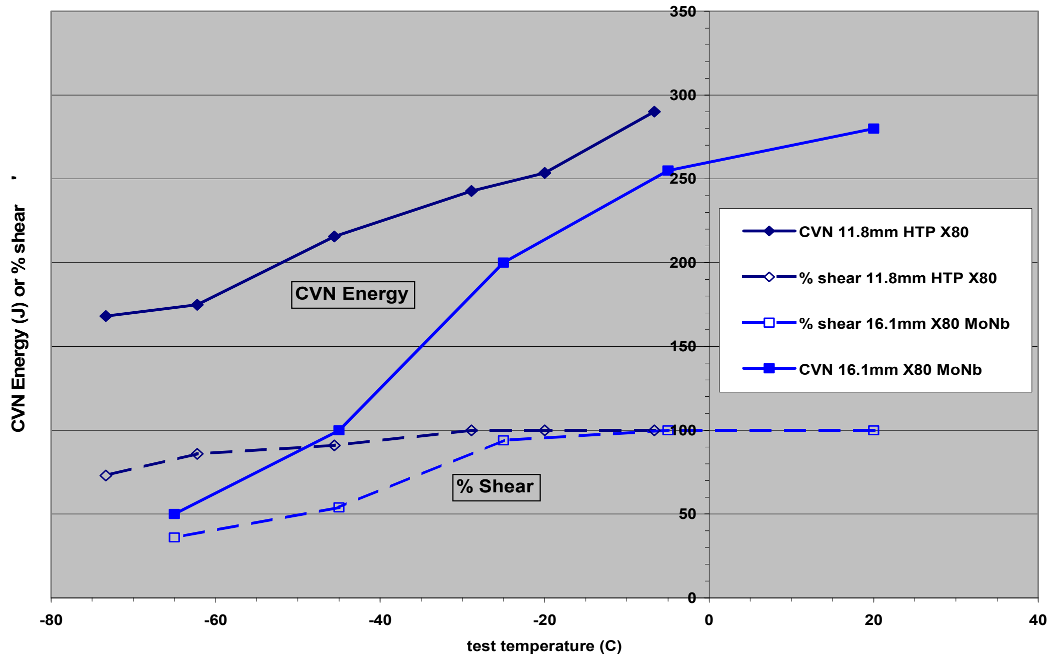


Figure 27. Pipe TCVN toughness-X80

Figure 28 shows example DWTT results from recent API projects utilizing different microstructures/alloy approaches. Good shear values (>80%) are maintained down to about -30°C, and then begin to fall, with the V-added steel dropping the most. In addition, rolling practices can have a major impact on the performance of microstructure/alloy approaches at very low temperatures.

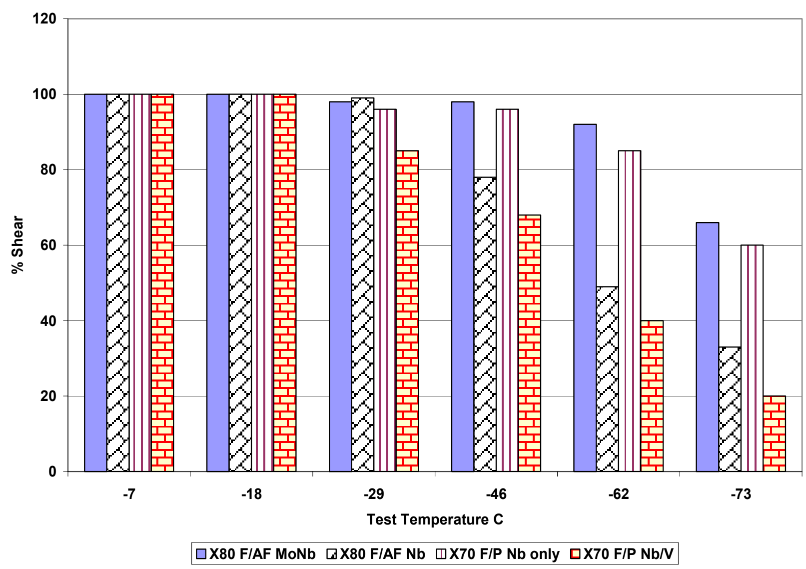


Figure 28. DWTT transition data for F/AF and F?P microstructures and alloying approaches

Resultant hardness during welding is a function of weld wire consumable chemistry, welding parameters and base metal chemistry. As can be seen in Figure 29, the F/P microstructure (lower Pcm) gives the overall lowest average hardness values across the weld. As alloy design becomes richer to produce the F/AF microstructure the resultant hardness also increases. The Mo-based design will yield the overall highest average hardness values due to the fact that molybdenum is powerful hardenability agent. Figure 29 shows average hardness across the weld for some recent API pipeline steels.

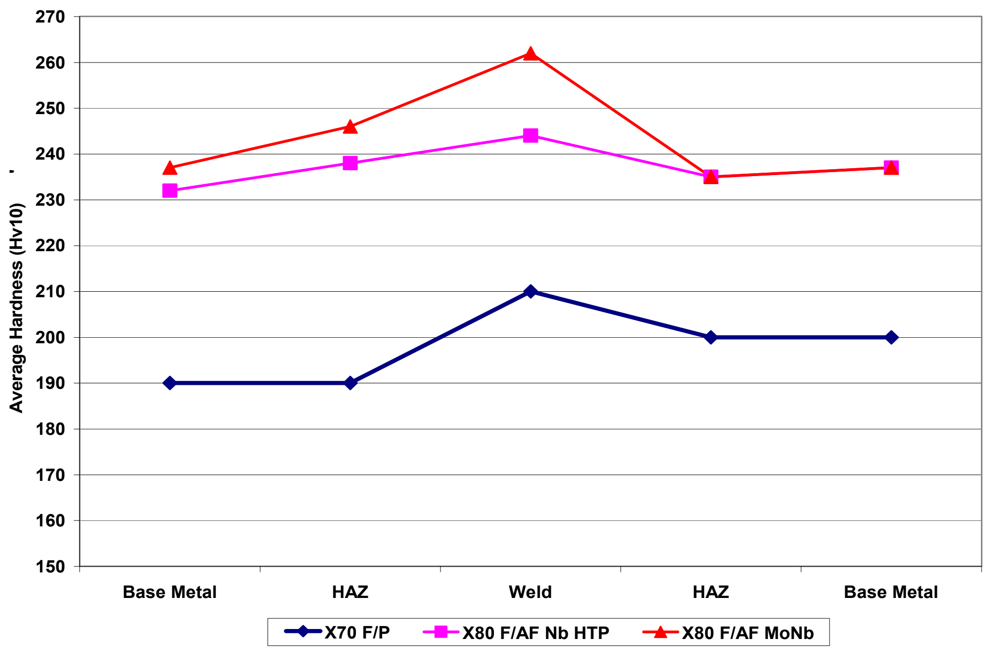


Figure 29. Average cross-weld hardness of recent API pipeline steels.

Conclusions

(1) Increasing operating pressures along with challenging environmental locations for oil and gas reserves have added pipeline design attributes that can challenge material design. These attributes brought on by improvements to both stress- and strain-based pipeline designs require increased pipe strength and low temperature toughness, improved weldability/formability, resistance to hydrogen induced cracking - while keeping total costs low.

(2) There are two basic microstructural designs in current commercial grade pipeline steels up to and including X80: ferrite/pearlite (F/P) and ferrite/acicular ferrite (F/AF). Today's alloy designs to produce the two microstructures rely on a low C, Mn-Si base with additions of niobium and V (plus occasional solute alloy additions depending on rolling mill capability) for strength to X70 and lower grades, while X80 and above grades require solute alloy additions of Cu, Ni, Cr, or Mo in some combination. Moderate niobium (<0.08%) with molybdenum and high niobium (>0.09%) with Cr (or other suitable solute strengtheners) are the two basic alloy schemes used to produce F/AF microstructures.

(3) There are five main goals in steelmaking for the production of slabs suitable for API transmission applications: tight chemistry control, good internal cleanliness, minimum centerline segregation, good surface quality and good slab dimensional controls. There are key variables in the LMF, caster, and slab cutting that need to be maintained to meet these goals.

(4) Skelp for API transmission pipelines can be produced as plate, coil/plate, or coil on a hot strip mill, Steckel mill or a conventional plate mill, followed by either air or water cooling. Regardless of processing route, the two main goals in skelp production are to maintain a designed temperature and drafting schedule to meet microstructure, mechanical properties, shape and productivity targets. Key variables during heating, rolling, and cooling must be maintained to achieve the goals.

(5) There are two basic rolling strategies with two subsets each for producing the desired microstructure and mechanical properties: conventional hot rolling used for ≤X52 grades and thermomechanical rolling (TMCP) used to produce X60 through X80 API grades. A TMCP process called High Temperature Processing (HTP) for higher strength grades is gaining popularity. Continuous cooling transformation diagrams (CCT) can be used to determine the requisite post-rolling cooling required to produce the desired microstructures for the different alloy approaches.

(6) Smaller diameter <610 mm and grades up to X65 are routinely produced on electric resistance welding (ERW) pipe mills. Large diameter higher strength grades are typically double submerged arc welded (DSAW) in helical (spiral), UO/JCO, or pyramid rolling mills. Cold expansion up to 1.5% of diameter is typically used for dimensional control.

(7) It is critical for the success of a pipe project that an understanding of the mechanical property behavior from skelp to pipe is understood, e.g. strength during pipemaking changes depending on microstructure. Tensile strength will be neutral or increase regardless of microstructure, while yield strength can increase or decrease for an F/P microstructure depending on various skelp properties and pipemaking practice. In an F/AF microstructure, regardless of alloy approach, yield strength either stays the same or increases from skelp to pipe. Increasing amounts of acicular ferrite forming Mo will increase the yield and tensile strength shifts.

(8) Toughness is also affected by the pipemaking process; therefore, skelp toughness testing is usually done ~15 °C lower than that required of pipe. However, at very high toughness levels, a divergence between the skelp and pipe results is sometimes being seen.

(9) Anisotropy (testing relative to the rolling direction) can play a role in physical property shifts from skelp to pipe. The F/P microstructure design is affected to a greater degree than the F/AF microstructure.

(10) Pipe strength is dependent on skelp yield strength that is modified by the steel's yielding behavior through the strain path during pipe-forming and cold expansion (if applicable) and then tensile testing. Each microstructure behaves differently with a F/P microstructure producing a distinct yield point and yield point elongation, while a F/AF microstructure will produce a more continuous yielding behavior.

(11) Models can be used to determine strength behavior from skelp to pipe. They should be used to help determine appropriate microstructure/alloy design relevant to the steel production and pipe process route to achieve the desired mechanical properties.

(12) There are advantages and disadvantages to each microstructure/alloying approach to API transmission pipeline steels. Guidelines have been established to help determine which approach is appropriate for a given project. A newer concept utilizing high temperature processing (HTP) steels can be a cost-effective approach to producing a F/AF microstructure while reducing skelp rolling issues.

(13) Actual recent API X70 and X80 project results have been shown illustrating the strength, toughness and hardness ranges of the different microstructure/alloying approaches. With modern, clean, low S and P steels, low temperature toughness values between 200 and 300J are now common with 50% FATTs <-45°C.

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