LATEST DEVELOPMENTS IN MECHANICAL PROPERTIES AND METALLURGICAL FEATURES OF HIGH STRENGTH LINE PIPE STEELS

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Abstract: In response to the increasing demand to improve both transportation efficiency and performance, the steel pipe industry has conducted extensive efforts to develop line pipe steel grades with superior metallurgical and mechanical (strength, toughness and ductility) properties in order to allow exploitation in hostile environments. This paper aims to give an overview of recent developments of high strength pipe steel grades as API 5L X70 and beyond, providing a detailed understanding of the continuous improvements with respect to a strain-based design context. Information regarding the metallurgy and processing, such as chemical composition, microstructural design, thermo-mechanical controlled process (TMCP) and accelerated cooling process (AcC), to achieve the target strength, ductility and toughness properties are discussed.

Keywords: High Strength Line Pipe Steel; Development; Strain Based Design; Mechanical Properties.

1 INTRODUCTION

1.1 Latest developments of high strength line pipe steels

The trend in the demand for large diameter pipe, in order to improve transportation capacity, is well-established by the contemporary onshore energy industry. The need to achieve higher strength accompanied with sufficient toughness and ductility has pushed the development of high strength steels (HSS) aiming at performance and durability to operate in harsh environments. These new steel grades for high pressure purposes (between 12 to 20 MPa) can be seen as an advanced variant of high strength low alloy (HSLA) steels. HSS steels typically contain very low carbon content and small amounts of alloying elements (microalloyed), such as Nb, V, Ti and Mo [1-4].

High strength steels such as American Petroleum Institute (API) 5L X70 and beyond, possess highly refined grain and high cleanliness. They are characterized by the low sulphur content and reduced amount of detrimental second phases such as oxides, inclusions and pearlite. Figure 1 shows the continuous evolution of HSS line pipe steel grades in terms of strength and toughness over the last decades, as well as a short description of the main alloying elements and processing applied [4-6].

The determining factor responsible for improvements in mechanical properties for currently used high-strength steels relies in the complex thermomechanical controlled processing (TMCP) routes followed by accelerated cooling (AcC). By this method, the rolling mill has become an important metallurgical tool not only able to achieve the final product shape, but also to produce higher strength microalloyed steels by grain refinement, having reduced carbon content and thereby excellent field weldability [1-2].

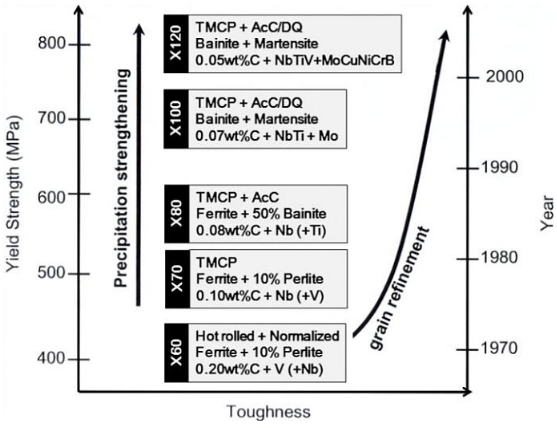


Figure 1. Evolution of line pipe steel grades as an example of HSLA steel development [4].

1.2 Line pipe steel mechanical properties for strain-based design applications

Hostile environments as well as pipeline installation conditions may impose plastic deformations (strains) to the transport pipeline. In such situations, where the conventional stress based design is an insufficient basis for pipeline integrity assessment, strain based design (SBD) concepts must be considered. The extent of the imposed tensile strains is quantitatively expressed as ‘strain demand’ (global strain), which mainly origins from seismic activity and permafrost effects [1, 3, 7].

To ensure the pipeline integrity it is important to define the maximum allowable global strain. This so-called strain capacity has to be greater than the imposed strain demand, in order to sustain the plastic deformation imposed by hostile environments [3]. As a consequence, a deeper understanding of the pipe strain capacity is a fundamental aspect to be discussed. High strength line pipe steels belong to the large category of metals that exhibit two stages of strain hardening (also called ‘double-n’ behaviour) [8]. An accurate description and determination of this stress-strain behaviour and the toughness properties of line pipe steels is a key point in performing a strain based assessment [1, 7].

HSS steels are designed to provide better mechanical properties and/or greater strain capacity to sustain imposed plastic deformation [3]. In fact, higher strength line pipe steels tend to have lower uniform elongation, resulting in a lower deformability. This is obviously an opposite trend regarding to what is desired of the application of high strength pipelines. Therefore to promote a high strain capacity, HSS line pipe steels for strain-based design applications must have sufficient toughness and high deformability as well as higher strain hardening, which mean a lower yield to tensile (Y/T) ratio and, also a higher uniform elongation (e_m). High work hardening accounts for the ability of a material to distribute the strain more uniformly in the presence of a stress gradient which restricts the onset of strain localization. Usually, steels that have such properties possess a well-defined round-house type stress-strain curve (continuous yielding behaviour) [1, 9, 10]. Figure 2 (a) shows the main stress-strain parameters, which are relevant to a strain based assessment [1]. Stress-strain curves of dual-phase (DP) steels produced on laboratory scale (‘developed’) are shown in Figure 2 (b) by comparing with steels manufactured on industrial scale (‘conventional’). All ‘developed’ line pipe steels have lower Y/T ratio, higher strain hardening and longer uniform elongation [9].

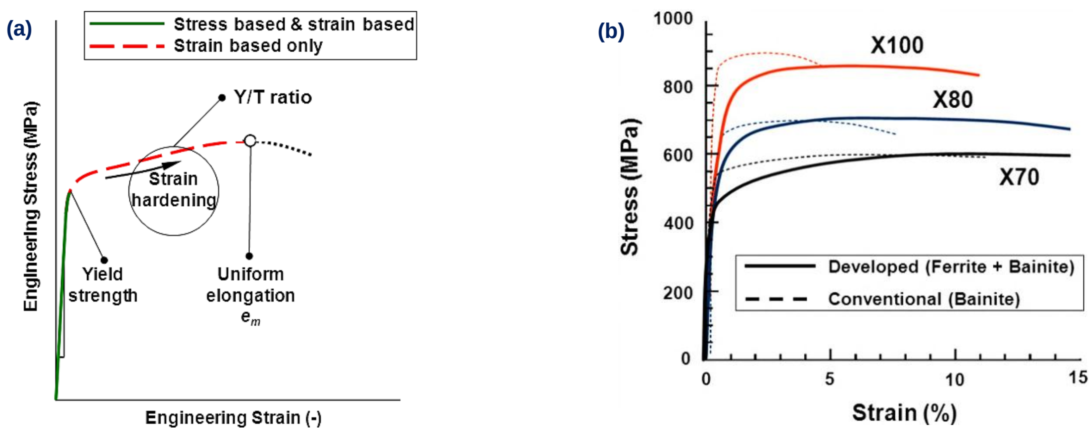


Figure 2. Relevant stress-strain parameters and stress-strain curves of ‘developed’ line pipe steels and ‘conventional’ ones (longitudinal direction) [1, 9].

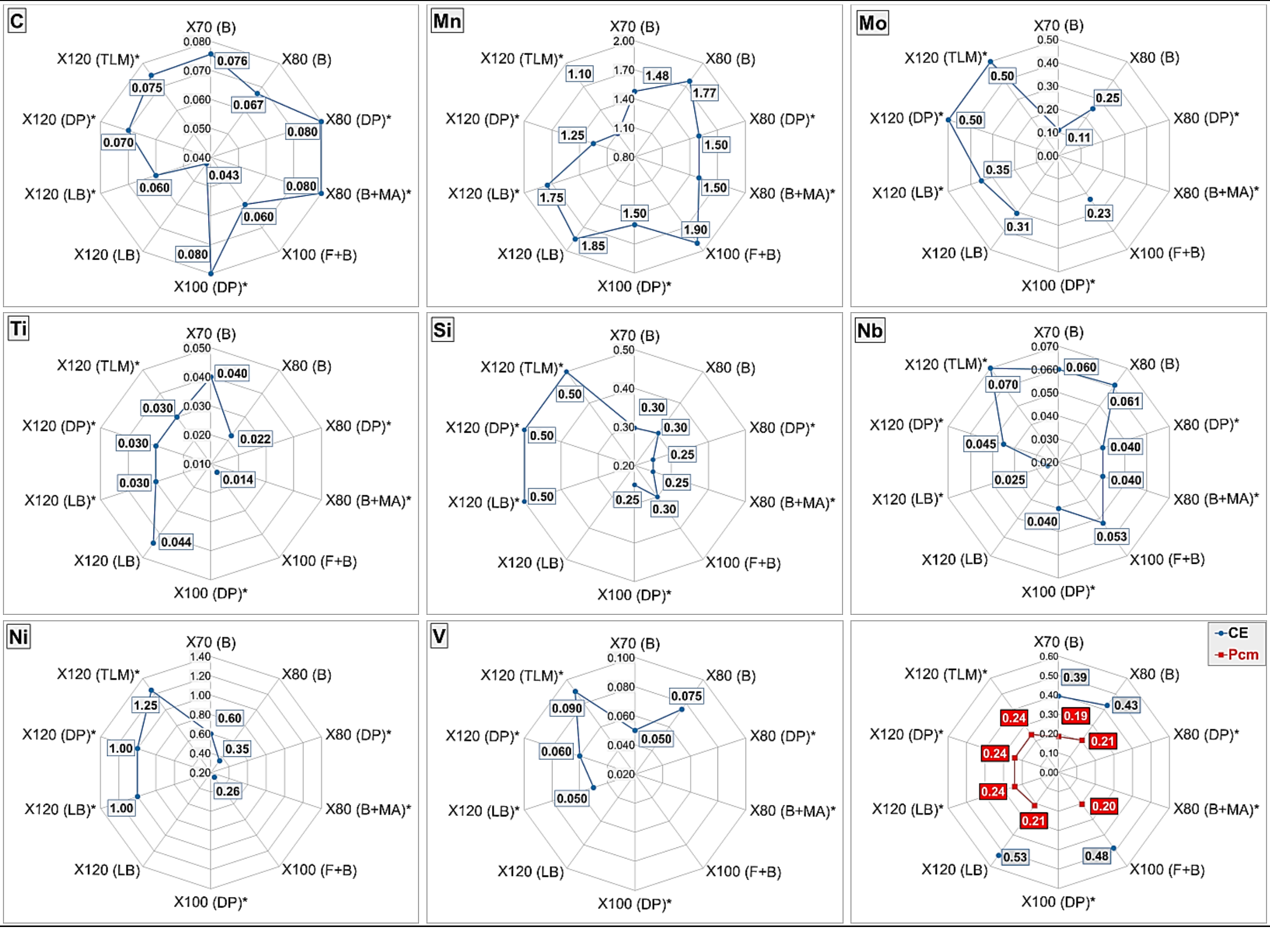
2 MECHANICAL PROPERTIES OF HIGH STRENGTH LINE PIPE STEELS

The abovementioned key material parameters are governed by both steelmaking (metallurgical design) and further processing (final mechanical properties) [4, 7, 11]. Both are separately discussed below.

2.1 Metallurgical characterization

2.1.1 Chemical composition

The chemical composition of HSS steels may vary for different product thicknesses to meet particular mechanical property requirements. Usually, they have a manganese (Mn) content up to 2.0 wt% in combination with very low carbon content (< 0.10 wt% C) and also minor additions of alloying elements such as niobium (Nb), vanadium (V), titanium (Ti), molybdenum (Mo) and boron (B). The main function of the alloying additions is strengthening of ferrite through the following mechanisms: grain refinement, solid solution and precipitation hardening. Solid solution hardening is closely related to the alloy element content, whilst precipitation hardening and grain refinement depend on the interaction between chemical composition and TMCP process. Thus, each individual element coupled with the cooling rate will determine the type and volume fraction of phases that will form in a given steel processed under given conditions [4, 25]. Figure 3 presents an overview of chemical compositions for ‘conventional’ and ‘developed (marked with an asterisk *) API line pipe steel (from X70 to X120) [3, 5, 7, 9, 11-24]. The same figure also shows the parameters that characterize good weldability, known as carbon equivalent (CE) and critical metal parameter for weld cracking (Pcm).



B: Bainite	LB: Lower Bainite	MA: Martensite-Austenite
F: Ferrite	DP: Dual Phase	TLM: Tempered Lath Martensite

Figure 3. Overview of chemical compositions of ‘conventional’ and ‘developed’ API 5L steel grades and weldability parameters (CE and Pcm). Average results in %.
Note: X120 (LB) = 0.0010 wt% B; X120 (LB/DP/TLM) = 0.25 wt% Cr.

The increase of steel strength is related to an increase of the following alloying elements: molybdenum (Mo), silicon (Si) and nickel (Ni). There is no clear trend regarding the other elements. However, CE and Pcm values are kept almost constant even for increasing steel grades.

The alloying elements also exert influence on transformation temperatures, as for example reducing the temperature at which austenite begins to transform to ferrite and/or pearlite during cooling (known as T A_{r3}), resulting in a finer-grain microstructure [4, 25]. Table 1 presents an overview of the relevant alloying elements for high strength line pipe steels and their respective effect and reason of adding [4, 25, 26].

Over the past few years the steelmakers have pursued some strategic alloying combinations to meet the increasing demands on strength and toughness without compromising weldability, namely [19]:

- V+Mo+Nb: to produce secondary hardening by forming carbides, nitrides and carbonitrides;
- Ni+Mo: effective addition of microstructure refinement by suppressing austenite recrystallization during controlled rolling and steel strengthening by precipitation hardening and enhancement of hardenability;

- Ni+B: synergistic improvement of hardenability;
- Nb+V: increase strength properties. However, steels based on this combination may require relatively high carbon equivalent design, which can compromise the capability for preheat-free field welding;
- Mo+Nb+Ti:
  - More effective (compared to the formerly applied Nb+V steels) in achieving the strength requirements of X70 and X80 (high Mn steels) particularly in thicker pipe walls;
  - A significantly finer ferrite grain size;
  - Low temperature transformation constituents such as bainite (B) containing acicular carbide needles in leaner alloyed X70 steels and martensite/austenite (MA) in highly alloyed X80 steels;
  - Enhances precipitation hardening. A synergistic benefit attributed to Ti addition.

In particular, the microalloying of B (< 0.002 wt%) has some particular contributions to API 5L X120, such as: improvement of hardenability by formation of strengthening constituents (e.g. bainite and/or martensite); retards formation of softer ferrite and pearlite constituents during cooling; allows the use of low CE steel compositions to produce high plate strength and enhance grain boundary strength [26].

Table 1. Major effects of alloying elements in High Strength Line Pipe Steels.

Element (wt%)	**Effect and reason of adding**
C (0.03 - 0.10)	• Matrix strengthening (by precipitation).
Mn (1.6 - 2.0)	• Delays austenite decomposition during AcC; • Substitutional strengthening effect; • Decreases ductile to brittle transition temperature; • Indispensable to obtain a fine-grained lower bainite microstructure.
Si (up to 0.6)	• Improvement in strength (solid solution).
Nb (0.03 - 0.06)	• Reduces temperature range in which recrystallization is possible between rolling passes; • Retard recrystallization and inhibit austenite grain growth (improves strength and toughness by grain refinement).
Ti (0.005 - 0.03)	• Grain refinement by suppressing the coarsening of austenite grains (TiN formation); • Strong ferrite strengthener; • Fixes the free Ni (prevent detrimental effect of Ni on hardenability).
Ni (0.2 - 1.0)	• Improves the properties of low-carbon steels without impairing field weldability and low temperature toughness; • In contrast to Mg and Mo, Ni tends to form less hardened microstructural constituents detrimental to low temperature toughness in the plate (increases fracture toughness).
V (0.03 - 0.08)	• Leads to precipitation strengthening during the tempering treatment; • Strong ferrite strengthener.
Mo (0.2 - 0.6)	• Improves hardenability and thereby promotes the formation of the desired lower bainite microstructure.

2.1.2 Microstructural design

Since the final microstructure is a key variable in determining material properties, it must be specifically designed to ensure safe and optimal performance under operating conditions [3]. Most modern line pipe steels have different and complex microstructural arrangements depending on their chemical compositions and processing routes (i.e. TMCP + AcC). However, prevails a general tendency to reduce carbon content in industrial ‘conventional’ plates [3, 27]. In this case the microstructure basically corresponds to lower bainite [27]. On the other hand, the new steel grades developed for strain-based design applications can have various microstructures consisting of different forms and combinations of bainite, martensite and ferrite in order to achieve the target strength, toughness and ductility. These qualities are based on a careful design of steel chemistry and processing in order to control austenite phase transformations, such as lower bainite and lath martensite [11].

Three primary microstructure concepts are reported in this work for the following steel grades (see Figure 4): (a) X80 bainite single phase (volume fraction ≈ 100%) obtained when the AcC starts above T A_{r3}, (b) X80 ferrite-bainite dual-phase obtained when the AcC starts below T A_{r3}, (c) X80 consists of pancaked lower bainite-lath martensite obtained when the AcC starts above T A_{r3} and the cooling stops at an intermediate temperature (T_{Stop} between 600 < 850 °C) [9, 11, 18, 28].

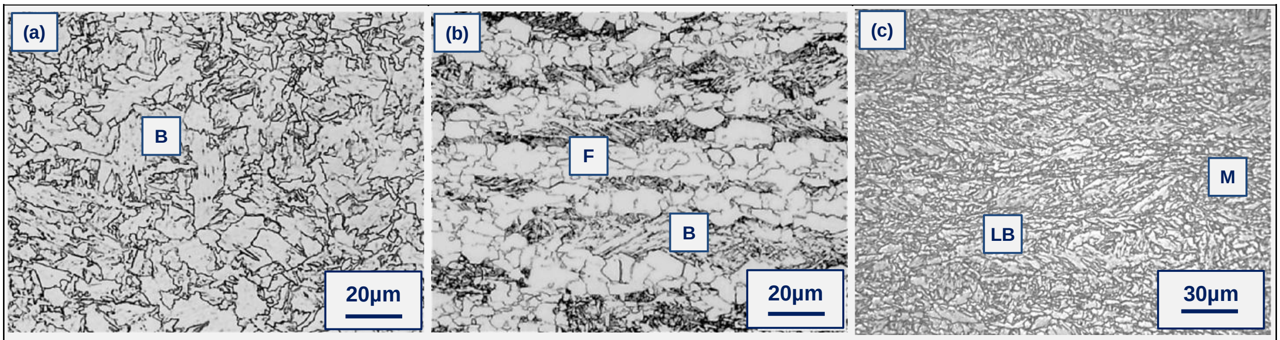


Figure 4. API 5L X80 steel with different microstructural compositions (longitudinal section).

A bainitic microstructure is produced with precise chemical composition (microalloying) and low carbon content, aiming at a low Pcm value. The basic alloying system contains Cu, Ni, Cr and Mo and microalloying elements such as V, Nb, Ti and B [13]. Subsequently, the rolling and cooling procedures are very effective in achieving a grain structured (low angle boundaries) microstructure which hinders the dislocation mobility, resulting in a perfect combination of strength and toughness. This microstructure is also developed to ensure fully ductile failure behaviour and high crack arresting behaviour at temperatures as low as -40 °C (arctic conditions) [14, 30].

Regarding dual-phase steel, it is important to clarify that what makes a steel be classified as dual-phase is mostly its volume fraction between the phases present. The microstructure is composed of a soft ferrite matrix and 10 – 40% of hard bainite and/or martensite-austenite particles. Some of the important features influencing mechanical properties of DP microstructure comprise morphology, size, amount and distribution of ferrite and bainite, the carbon content of bainite, and volume fraction of ferrite and/or retained austenite. The role of ferrite on the microstructure is preventing the brittleness of hard grain boundaries through nucleation of ferrite at the edges of prior austenitic grains in order to suppress possible crack propagations [29]. The dislocation mobility within the ferrite phase (of DP steels) provides the deformability characteristics that are desirable for high strain capacity applications [22]. This type of microstructure can exhibit the following advantageous strain-based features over the 'conventional' high strength steels [31]:

- Microstructure-strengthening controlled by the amount of hard phase/constituent and ductility by grain size and distribution of this phase;
- Exhibits a round-house yielding;
- Possesses low Y/T ratio and high strain hardening behaviour, notably at the onset of plastic deformation.

The X80 microstructure constituted by pancaked lower bainite-lath martensite presents highly deformed and refined domain sizes. This microstructural design provides small domains (average pancake thickness < 6 μm) and high dislocation density (> $10^{12}/cm^2$), which are effective to reach higher strength and toughness properties. Lower bainite has predominant volume fraction in order to avoid detrimental effects on the Charpy toughness. Additionally, it offers higher upper shelf toughness due to the precipitation of carbon out of solid solution into finely dispersed carbides (secondary strengthening). The carbon retained in interstitial sites of lath martensite is responsible to promote high solid solution strengthening [11, 18].

2.2 Steel processing

As previously mentioned, grain refinement is the most effective metallurgical mechanism able to improve both strength and toughness in high strength pipe steels. The development of the so-called thermo-mechanical controlled process (TMCP) in the 1960's was the reasonable cost answer found by the steelmakers to these demands. TMCP steels can reach a precise microstructural control which enables to obtain higher strain hardening capacity and ductility [1, 4, 26]. After rolling, a particular cooling process also known as accelerated cooling process (AcC) is performed to meet the higher requirements for strain based design, with respect to strain hardenability, toughness as well as high strength [1, 9, 14]. However, in some cases the steel plate is first hot rolled and soaked (held at a temperature until the desired microstructural changes take place) and then submitted to an inline quenching and tempering (QT) process. Such QT treatment is performed to produce a bainite-martensite microstructure without applying AcC process. By tempering it is possible to reduce the brittleness of martensite and improve ductility and toughness [11; 29]. Different types of microstructures can be produced by these processing routes, such as: bainite single phase, ferrite-bainite dual phase and lower bainite-lath martensite [3, 9, 11].

In 1998 a new conceptual TMCP process (hereafter called 'unconventional' TMCP) was developed in order to obtain not only high strength by transformation strengthening but also high toughness by refinement of transformed microstructure, resulting in a combination of high strength/high toughness steel with reduced alloying elements. The microstructure consists of a bainitic matrix and finely dispersed martensite-austenite constituent (MA) as second phase with a volume fraction above 7%. The process consists of an advanced accelerated cooling device, with the purpose of reaching highest cooling rates and an induction heating equipment for online heat-treatment process (HOP), with high heating capacity to heat thick plates up to 40 mm [32]. This combination enables to reach a novel metallurgical controlling process that cannot be achieved by the 'conventional' TMCP. Some advantages of applying HOP process [9, 32]:

- Precipitation hardening by very fine carbide (reduction of diffusible free carbon content);
- Recovery of the dislocation density;
- Formation of MA constituents which enable the balance high strength / high deformability.

Figure 5 (a) illustrates a schematic TMCP diagram for 'conventional' and 'unconventional' production processes and some morphological changes in the microstructure. In the 'conventional' TMCP process, the steel plate is controlled rolled, accelerated cooled and then air-cooled. On the other hand, in the 'unconventional' TMCP process, the plate is rapidly reheated by the induction coils immediately after accelerated cooling and followed by air cooling. Figure 5 (b) shows a schematic explanation of the microstructural changes promoted during HOP process [4, 9, 17, 32].

Both TMCP processes are typically performed at strictly controlled and relatively low temperatures (i.e. between T_{nr} and T A_{r3}) in order to produce very fine grains. More clearly, the last hot rolling steps are performed below the non-recrystallization temperature (T_{nr}). As a result, the severely deformed ('pancaked') austenite grains do not completely recrystallize, which provides a large number of nucleation sites for the transformation of austenite to ferrite or bainite. Investigation of AcC conditions reports that lowering both, starting and stopping temperatures promote formation of ferrite and MA constituents respectively [9, 11, 32].

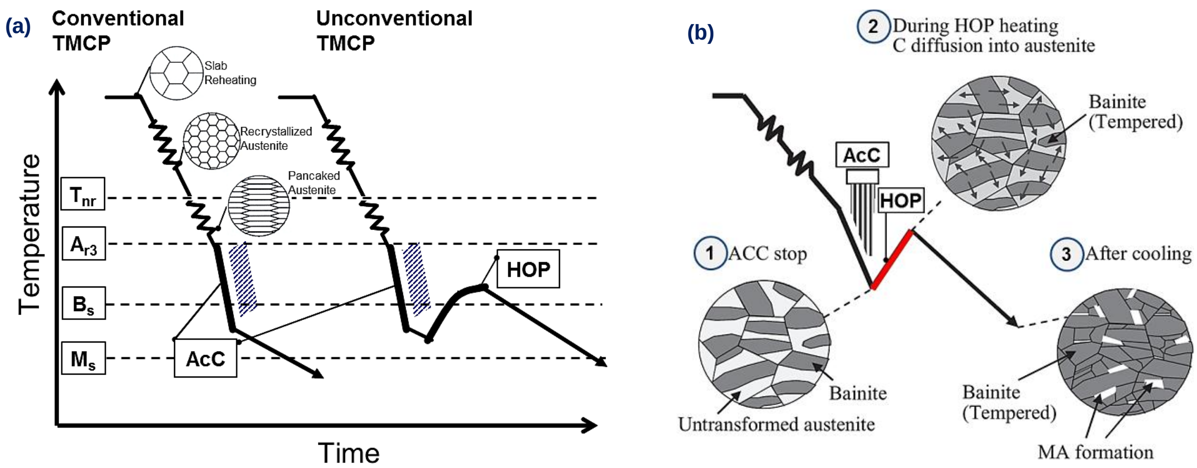


Figure 5. Schematic illustration of (a) TMCP diagram for 'conventional' vs. 'unconventional' processing and (b) microstructural changes promoted by HOP process [32].

Table 2 presents a summary of some relevant parameters for several stages of the TMCP process and the respective features related to them [4, 11, 13, 17, 32, 33]. Table 3 gives an overview of different microstructures obtained using various processing routes for 'conventional' and 'developed' (*) high strength line pipe steels.

Table 2. Overview of TMCP stages, typical temperatures and features.

Processing Parameters		Range	Features
Rolling	Reheat Temp.(^oC)	1140-1180	• Dissolution of precipitates; • Produce a fine, polygonal austenitic grain; • Maintain within the range of the T_{nr};
	Reduction ratio (%)	40-75	
	Finishing Temp.(^oC)	760-800	
AcC	Start Temp.(^oC)	730-760	• Enhances grain refinement of ferrite; • Prevents formation of pearlite during cooling;
	Cooling rate ($^oC/s$)	20-50	
	Stop Temp.(^oC)	150-400	
Tempering	Heat Temp.(^oC)	600	• Reduce excess hardness and residual stresses.

Table 3. Microstructures obtained using different processing conditions.

API 5L	Processing	Microstructure	Reference
X70	TMCP	Polygonal Ferrite (PF) + Pearlite Band (P)	[27]
		Bainite (B)	[3]
	TMCP + QT	Bainite (B) + Martensite (M) + Ferrite (F)*	[30]
	TMCP + AcC +QT	Fine-grained Bainite	[17]
X80	TMCP + AcC	Lower Bainite (LB)	[14]
		Ferrite (F) + Bainite (B) Dual Phase (DP)*	[9]
		Lower Bainite (B) + Lath Martensite (M)	[18]
	TMCP + AcC + HOP	Bainite (B) + Martensite-austenite (MA)*	[9]
X100	TMCP	Ferrite (F) + Bainite (B)	[13, 14, 15]
	TMCP + AcC + HOP	Ferrite (F) + Bainite (B) Dual Phase (DP)*	[9]
X120	TMCP + AcC	Lower Bainite (LB)	[11, 13]
		Ferrite (F) + Martensite (M) Dual Phase (DP)*	[11]
		Tempered Lath Martensite (TLM)*	[11]

3 MICROSTRUCTURE - MECHANICAL PROPERTY RELATIONS

Over the last years, the steel industry has made a significant effort towards increasing the purity of steel plates produced (impurities measured in ppm), rather than focusing on raw productivity. In view of this, all subsequent processing routes are metallurgically integrated since they have significant influences on the final mechanical properties of the pipe steel. In consequence, it is important to define and understand the relation between steel making parameters (e.g. chemical composition and processing) and the following mechanical properties: stress-strain properties such as yield strength ($R_{p0.2}$), ultimate tensile strength, Y/T ratio and uniform elongation (e_m) as well as toughness requirements for crack arrest. The latter are often quantified on the basis of Charpy V-notch (CVN) tests and Battelle drop weight tear tests (B-DWTT). Figure 6 shows the average results of the abovementioned mechanical properties for different steel grades reported in the literature [5, 7, 9, 11-20, 26]. The tensile test specimens were extracted in the longitudinal direction. Both toughness tests, CVN and B-DWTT, were performed at a temperature range between -10°C and -40 °C.

As expected, higher steel grades exhibit higher $R_{p0.2}$ and R_m as well as lower uniform elongation (e_m) and total elongation, comprising both 'conventional' and 'developed' steels (Figure 6a, b and c). However 'developed' ones, mostly dual-phase steels, show reduced $R_{p0.2}$ and superior R_m and a lower Y/T ratio (i.e. higher strain hardening) which is, considering the dataset below, an average of 10% less than in 'conventional' steel grades [1, 3, 31]. Such favourable properties are closely related to the characteristics of a dual-phase microstructure as discussed above. The increment in strain hardening can be attributed to the increasing strength difference between soft matrix and hard second phase, which means steels with harder second phase provide higher strain hardening and, apparently, a round-house type stress-strain curve [7, 9, 26, 31].

According to API 5L 2000 (PSL 2), all materials have reached the required minimum average Charpy value of 101 J for longitudinal specimens, at a temperature of 0°C (Figure 6 d). However, some steel grades such as X80 (B) and all X120 did not reach the API requirement of a DWTT shear area equal to 85% or higher, showing a percent variation from 68% to 84%. No clear correlations between stress-strain properties and toughness values, such as Charpy V-notch and B-DWTT are observed [12].

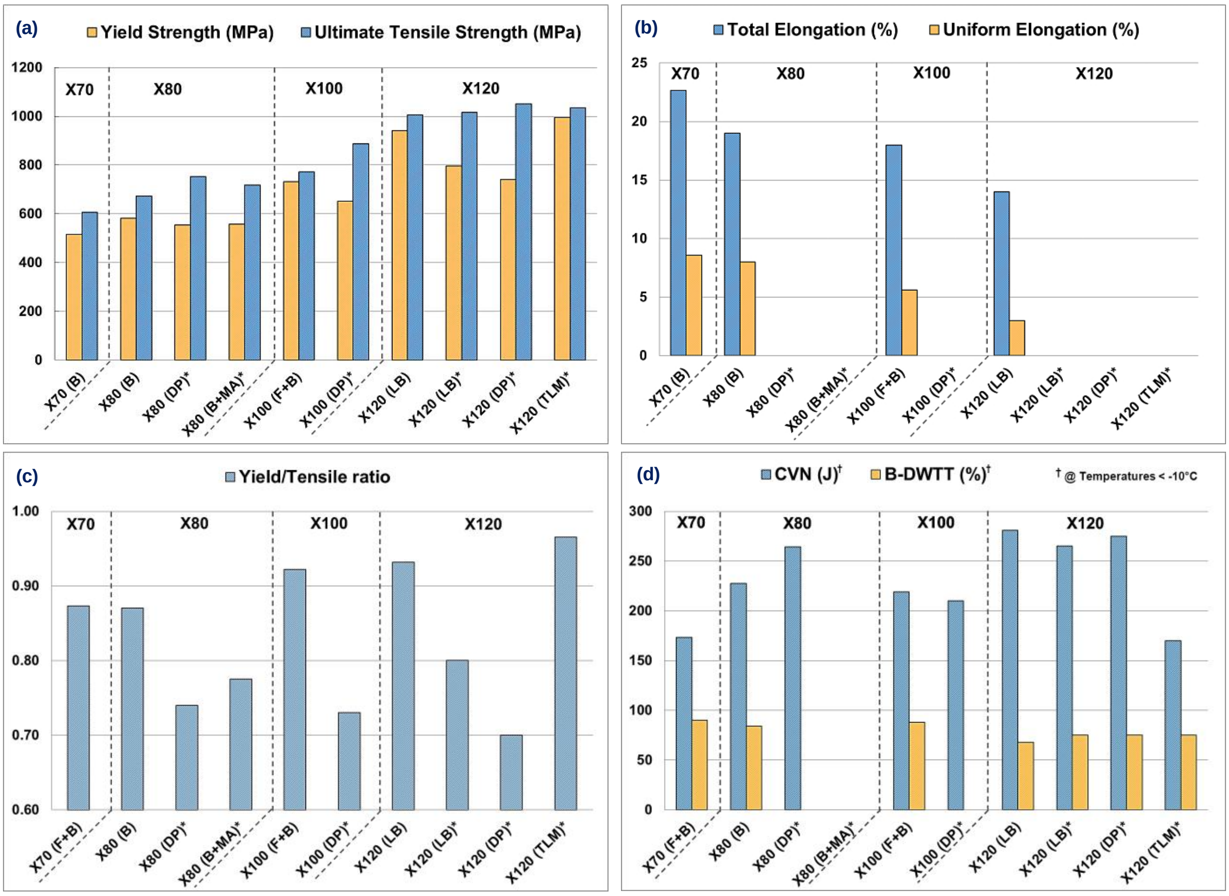


Figure 6. Mechanical properties of various high strength line pipe steel grades with different microstructures. (*) 'Developed' line pipe steels.

4 CONCLUSIONS

A significant progress has been achieved during last years in the development of HSS line pipe steels for strain-based design applications. The main results obtained are the following:

- High strength steel grades are showing improvements in mechanical properties. The limitations on strain capacity were recognized and are being properly addressed;
- Increase of strength is associated with increasing Mo, Si and Ni content;
- Independent of the variations in the alloying element content, the characterizing parameters for good weldability (i.e. CE and Pcm) are maintained practically unchanged;
- Development of optimum microstructures (e.g. ferrite-bainite DP and/or bainite-martensite/austenite) which provide the required mechanical properties for high strain capacity applications, such as higher strain hardening and uniform elongation;
- Both 'conventional' and 'unconventional' TMCP processes showed to be effective processing routes in order to produce steels with lower Y/T ratio and higher e_m, and sufficient toughness.

5 ACKNOWLEDGEMENTS

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