CANADIAN HSLA STEEL PIPELINES: HISTORY AND TECHNOLOGY DEVELOPMENTS

Mohsen Mohammadijoo[1,2], Laurie Collins[2], Hani Henein[1], Douglas G. Ivey[1]

[1]Department of Chemical and Materials Engineering, University of Alberta, Edmonton, AB, Canada T6G 1H9

[2]Research & Development, EVRAZ North America, Regina, SK, Canada S4V 3P6

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Abstract

Pipeline failures can be severe events that impact both society and industry. The oil spills in North Battleford, Saskatchewan in 2016 and the gas rupture in Beardmore, Ontario in 2011 are examples of recent pipeline failures in Canada. Pipeline failures have led to pipe fabricators developing new precursor steels and manufacturing processes to improve the final product properties. This paper is aimed at summarizing historically the advancements made in manufacturing of steels used for pipelines. High strength low alloy (HSLA) steels are used extensively to manufacture these pipelines. After the introduction of the first generation of HSLA steels, i.e., X42 in 1948, various classes of HSLA steels, such as X52 and X60, were developed to improve the mechanical properties. In 1970, X70 and X80 HSLA steels were developed to further improve the properties and to improve weldability. Even higher strength grades, such as X100 and X120, have been introduced in recent years.

Introduction

Over the past several decades, pipelines have been extensively utilized by industry as the most economically efficient and the fastest means to transport oil and gas and their by-products. In Canada, there are more than 840,000 km of gathering, transmission and distribution oil and gas pipelines - including 117,000 km of large-diameter transmission pipelines - with significant pipeline infrastructure in most provinces (Figure 1a). Of this amount, about 73,000 km of pipelines are federally regulated and these are primarily transmission pipelines. Pipelines crossing provincial borders are generally regulated by the federal government, whereas the pipelines that are entirely within one province are regulated by the respective provincial authority. There are more than 450,000 km of the local small diameter natural gas distribution pipelines in Canada, which are provincially regulated (extracted from “http://www.nrcan.gc.ca/energy/infrastructure/18856”). Pipelines are laid above ground and underground and operate in both remote and populated areas. Figure 1b shows the major oil pipelines regulated by the National Energy Board (NEB) of Canada.

Pipelines may be subjected to failure during their service. Oil pipeline spills in Refugio (California) in 2016, Red Deer River (Alberta) in 2012 and the Gulf of Mexico in 2010 and the gas pipeline rupture in Beardmore (Ontario) in 2011 are some of the recent failures which result in contamination of the environment. Pipeline failures also cost the transmission pipeline industry 5.4 to 8.6 billion dollars annually (extracted from “https://www.activehistory.ca/2012/oil-pipeline-spills”). According to the National Energy Board (NEB) of Canada (extracted from “https://www.neb-one.gc.ca/sftnvrnmnt/sft/pplnrptr/ indexeng.html”), the failure of Canadian pipelines from 1992 to 2014, were mainly due to cracking and materials/manufacturing effects (more than 45%), geotechnical failure (~8%), metal loss (~29%) and other causes (18%). As such, from the view point of pipeline manufacturing, besides reducing manufacturing cost, in the past decades, a major concern of the pipe manufacturers has been to improve the mechanical properties, particularly fracture toughness, of the precursor steels and the pipe welds. Owing to the advancements made by the pipe manufacturers and researchers in the improvement of mechanical properties of the HSLA steels and their welds, the number of pipeline failures caused by steel imperfections has significantly decreased over the years. Figure 2 illustrates the ratio of pipeline failures per 1,000 km in Alberta, Canada over a 5 year period (2006-2010), which shows a decline during this time frame.

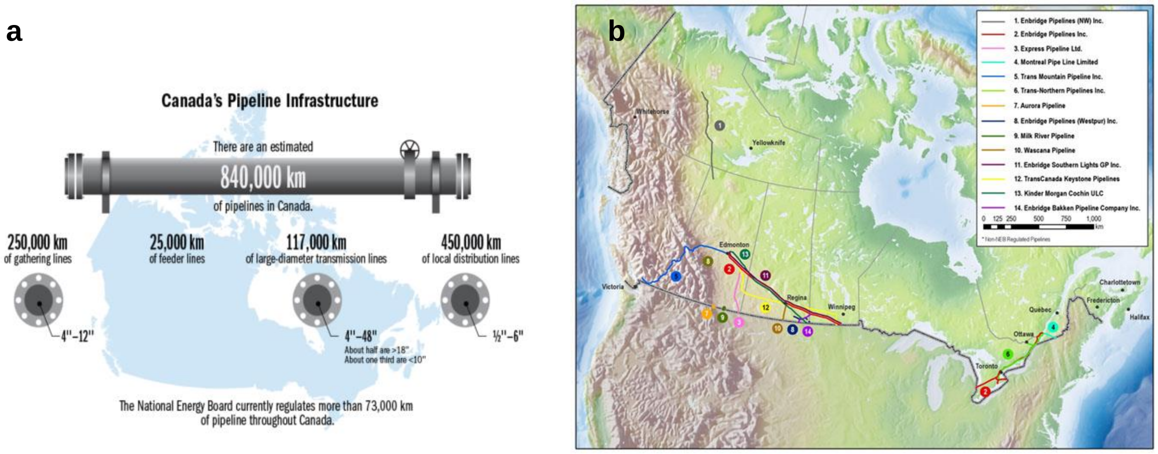

Figure 1. (a) Total length of oil and gas pipelines in Canada and (b) major oil pipelines regulated by the NEB of Canada (extracted from “https://www.neb-one.gc.ca/nrg/ntgrtd/trnsprttn/”).

With reference to the precursor used for pipeline fabrication, steel has been globally used for manufacturing of oil and gas transportation pipelines. Throughout history, significant advancements have been made in the development of steels through the application of fundamental knowledge to alloy development, e.g., chemical composition, microstructure design and manufacturing processes. In the past century, the mechanical properties of steels, particularly strength and toughness, have progressively increased due to advances in the metallurgy and manufacturing techniques in response to market demand for lighter and stronger steels [1]. The drive to achieve higher strength and toughness, with improved corrosion resistance and weldability and sufficient ductility, has resulted in the development of high strength low alloy (HSLA) steels. These steels typically contain 0.05 to 0.2 wt.% carbon and small additions (in amounts less than 0.1 wt.% of each element) of Nb, Ti and V. The steels may also contain other alloying elements, such as Mn and Mo, in amounts exceeding 0.1 wt.% [2]. HSLA steels have high strength and excellent toughness, which are attributed in part to grain refinement and the presence of precipitates, especially nano-size precipitates. The precipitates can affect the recrystallization behavior and subsequent grain growth of the austenite and induce precipitation hardening in the final matrix. The advantageous properties of HSLA steels are not only due to their chemistries, but also to the thermo-mechanical treatments they undergo throughout processing [3]. These steels are classified by the American Petroleum Institute (API) in terms of their strength (e.g., X42, X46, X52, X56, X60, X65, X70, X80, X100 and X120). The designation X corresponds to a pipeline grade and the digits correspond to the minimum specified yield strength in ksi.

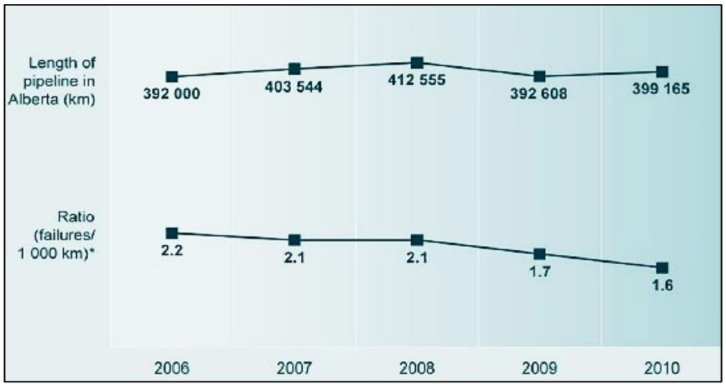

Figure 2. Historical perspective of oil pipeline spills in Alberta, Canada (2006-2010).

HLSA steels are preferred over other high strength advanced steels and are broadly used for transport pipelines and pressure vessels, because of their beneficial mechanical properties, excellent weldability and, above all, relatively low cost. Figure 3 compares HSLA steels with other types of steels in terms of ductility and strength. During the past decades, many endeavors have been devoted to improving the properties and safety of pipelines and in decreasing manufacturing cost. As such, higher strength grades, such as API X70, X80, X100 and X120 pipeline steel plates, have been continuously developed. Higher strengths allow pipe thicknesses to be decreased and operating pressures to be increased. Stelco, Canada Pipe Ltd., ArcelorMittal Dofasco and EVRAZ North America are some of the major HSLA steel linepipe suppliers in Canada. The first two companies' products typically include the HSLA steel skelps from 0.075 inch to 0.500 inch thickness which are used for pipe fabrication through electric resistance welding (ERW) processing. ArcelorMittal Dofasco produces X65 steel skelps which are then converted to the pipes through cold formed continuous ERW process. As such, their products are limited to 0.500 inch thickness and 19 inch outer diameter pipes. EVRAZ NA has been known as the main leading supplier of small and large diameter linepipes for oil and gas transmission in Canada. Their large diameter products cover a wide range of HSLA steel pipes from X42 to X100 with the thickness and outer diameter of 0.312 inch to 1.00 inch, and 24 inch to 60 inch, respectively, made through straight seam and spiral submerged arc welding process. The small diameter pipes (2.375 inch to 24.00 inch), also known as ERW pipes, are mainly produced from X70 HSLA steels with the thickness of 0.109 inch to 0.500 inch. All EVRAZ NA products are treated with the external polyethylene, fusion bonded epoxy and abrasion resistant coatings.

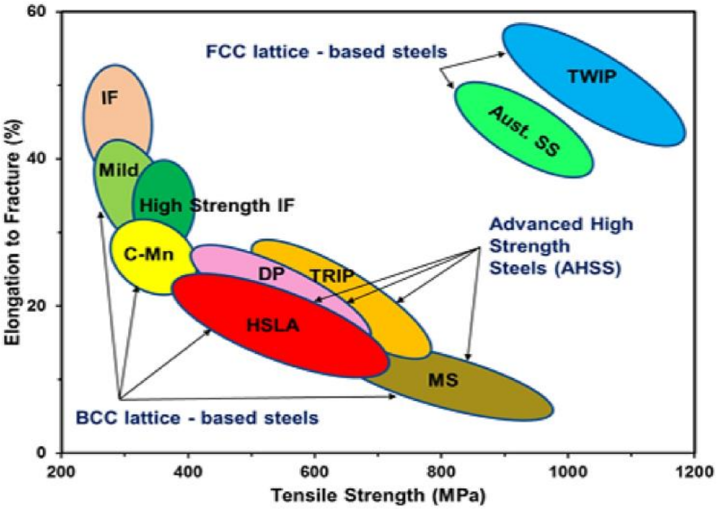

Figure 3. Schematic graph comparing HSLA steels with different types of steels [4]. IF: interstitial free steel; DP: dual phase steel; TRIP: transformation-induced plasticity steel; MS: martensitic steel; TWIP: twin-induced plasticity steel; Aust. SS: austenitic stainless steel.

Thermo-Mechanical Controlled Processing (TMCP)

Thermo-mechanical controlled processing (TMCP) is explained succinctly by Jonas and Sellars [5]: “TMCP in industrial practice involves the production of specific microstructures associated with particular mechanical and physical properties, which differ from traditional deformation processing, which is generally concerned with reductions in thickness and with developing desirable changes in shape.” TMCP essentially involves the control and interaction of fundamental mechanisms, such as dislocation movement, recrystallization, grain growth, phase transformation, precipitation, precipitate coarsening, grain boundary pinning and solute drag. The interest in many of these structural changes lies in whether they take place dynamically (i.e., during deformation) or statically (i.e., after deformation). TMCP is a microstructural control technique combining both controlled rolling and cooling. Figure 4 shows a comparison between TMCP and the conventional normalizing process. In both processes, the post heat treatment (off-line heat treatment) of a slab at about 900℃ is followed by cooling to ambient temperature. Normalizing is used to toughen the steel by generating a refined transformed structure from refined austenite. TMCP comprises thermo-mechanical rolling and accelerated cooling to strengthen and toughen steel plates, essentially by refining the transformed microstructure [2,3]. The nucleation sites for ferrite are increased during cooling by refining the grains and straining austenite. Afterwards, the transformed structure is further refined by accelerated cooling after the controlled rolling step. This involves cooling to a reduced transformation temperature where the diffusion of the atoms is limited, while a large driving force for transformation is provided. The fine microstructure obtained from TMCP generates a steel with high strength and toughness [7]. A typical TMCP process schedule along with the phase transformations that occur through the process is shown in Figure 5.

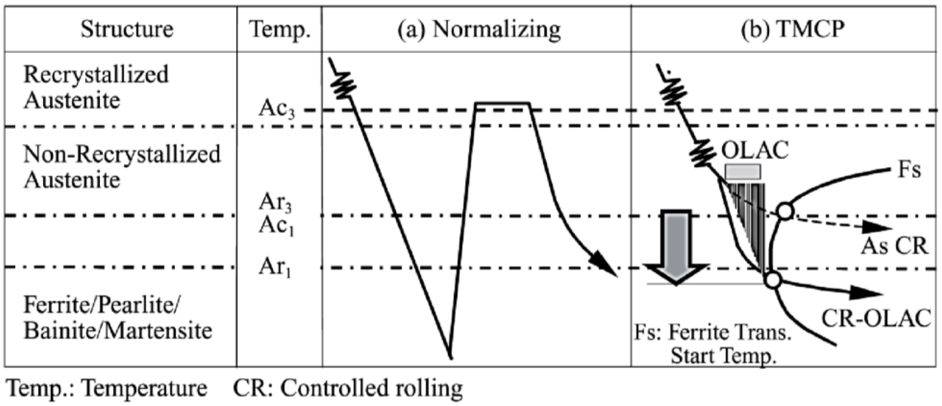

Figure 4. Schematic diagram of (a) normalizing and (b) TMCP processes [3] (OLAC: on-line accelerated cooling).

Development of Pipeline Steels

HSLA pipeline steels are required to have as low susceptibility to crack initiation and propagation as possible in order to prevent fracture during manufacturing or in service. Although, the crack formation typically occurs in the weld region and/or the heat affected zone (HAZ) of the pipe rather than in the base steel [8], the susceptibility of pipeline steels to stress corrosion cracking (SCC) and hydrogen induced cracking (HIC) is a function of the steel hardenability, which is dependent on the steel composition [9]. The resistance of a steel to HIC can be improved by controlling the amount of alloying elements, which are added to prevent the formation of elongated non-metallic inclusions. The good weldability of HSLA steels, compared with traditional pipeline steels with relatively higher alloying elements, is due to the lower carbon equivalent as a result of the low carbon and alloying element content [2]. The formation of a fine grained ferrite microstructure, obtained by the addition of microalloying elements and the use of TMCP, is expected to improve the resistance to SCC, HIC and brittle fracture initiation in the HAZ [10]. As the strength and amount of the hard microstructural constituents increases, the susceptibility of steel to HIC increases. The most susceptible phases (in order of decreasing susceptibility) are twinned martensite, bainite (upper or lower), granular bainite and lath martensite (the least susceptible). Taira et al. [11] and Sampatha [12] believe that the susceptibility to HIC in as-rolled X70 pipeline steel is due to the segregation of Mn to the centerline (segregation band), which promotes the formation of a "hard band" (i.e., low-temperature transformation products) in this zone. They have observed that the HIC susceptibility is high in steels containing 0.05-0.15 wt.% C, when the Mn level is above 1 wt.%. As such, in the recent years, it has been of the main interest to the steel manufacturers to reduce the centerline segregation in the final steel product by modifying the alloying composition and the TMCP rolling sequences.

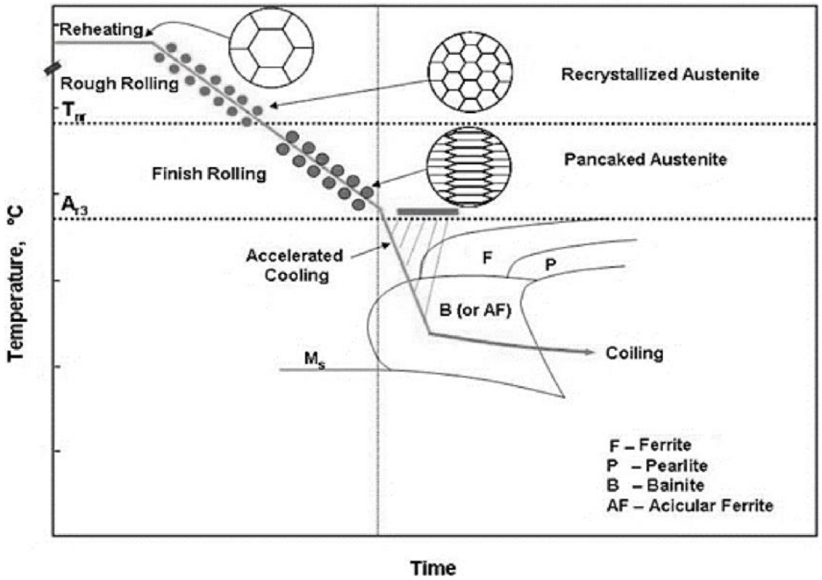

Figure 5. Schematic diagram of a TMCP schedule, superimposed on a CCT diagram, indicating the phase transformations during processing [6].

Since the late 1940s, several classes of HSLA steels have been developed and utilized for oil and gas transport. API X42 and X52 pipeline steels, with a ferrite-pearlite microstructure, were some of the earliest classes of pipeline steels. The steels were initially manufactured by the conventional normalizing and rolling processes. However, in the early 1970s, API X70 steel, produced through TMCP, was proposed to accommodate higher strength and toughness requirements. The historical advancements in pipeline steel yield strength since 1950 are shown in Figure 6. The strengthening mechanisms are mainly precipitation hardening and grain refinement, while ferrite remains as the dominant microstructures [2,3]. However, in recent years, newer generations of HSLA pipeline steels are dominated by bainitic-ferritic microstructures containing finely distributed martensite-austenite (M-A) constituents. Major Canadian pipelines installed in recent decades are made from X70 and X80 steels with low carbon contents (less than 0.05 wt.% and 0.07 wt.%, respectively) and Ti, Nb and V as primary microalloying elements [13]. Recently, newer grades of HSLA steels, such as X100 and X120 have been proposed; however, they have mainly remained at the laboratory research scale. For X100 steel, the microstructure is composed of bainite, with lath and granular morphologies, and M-A constituents. Table 1 gives the mechanical properties for various grades of pipeline steels.

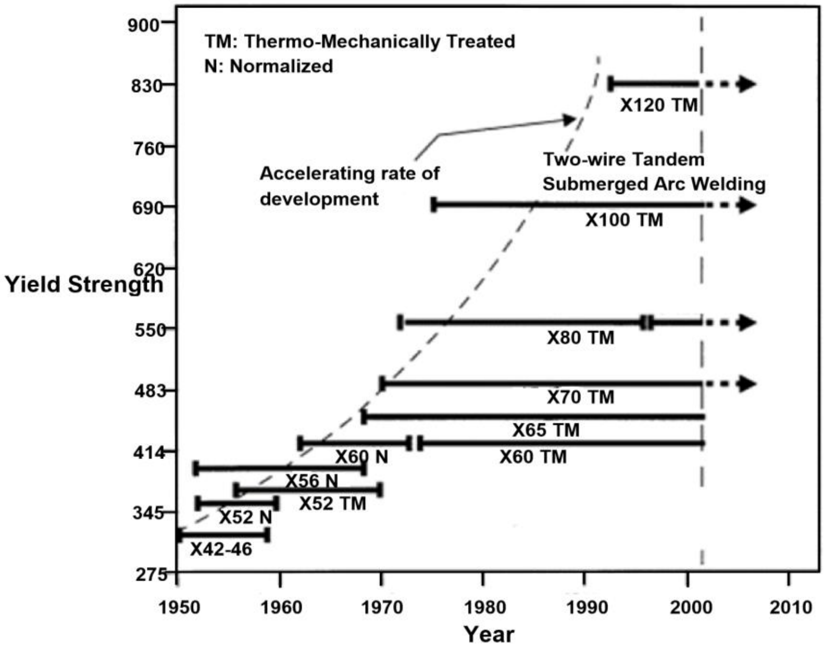

Figure 6. Required yield strengths for pipelines and corresponding years of development.

Table 1. Mechanical properties of pipeline HSLA steels

Grade	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation%
X65	≥448	≥530	≥24
X70	≥482	≥565	≥23
X80	≥551	620-827	≥22
X100	≥690	≥760	
X120	≥883	≥1023	

Ferrite-pearlite steels are considered as the first generation of pipeline steels manufactured by hot rolling and normalized conditions. As stated earlier, API X52 steel is comprised of ferrite and pearlite. Gladman and Pickering [14] have reported that the strength and ductile-to-brittle transition temperature of the steel increases as the pearlite volume fraction increases. Moreover, due to the relatively high carbon content of 0.12-0.2 wt.%, the steel has poor weldability. To improve the properties, the fundamental approach was to reduce the level of carbon and thereby minimize the fraction of pearlite and to add some alloying elements, to provide grain refinement and precipitation hardening. In addition to alloying elements, TMCP can improve the toughness of the steel. Acicular ferrite HSLA steels (e.g., X70 and X80 steels) were the next generation of pipeline steels. Intragranular nucleation of the ferrite phase, with non-equiaxed characteristics, occurs on non-metallic inclusions. The term of acicular ferrite was initially introduced by Smith et al. [15] in the 1970s. Acicular ferrite is also known as bainitic ferrite. Because of its fine grain structure and high angle grain boundaries, acicular ferrite steels offer a good combination of strength and toughness. In addition, a uniform distribution of fine precipitates and a high density dislocations provide more benefits to the mechanical properties of acicular ferrite HSLA steels. To develop higher grades of HSLA steels, it was believed that an alternative microstructure based on shear transformation products was necessary to achieve higher strength and toughness. Accordingly, martensite-bainite microstructures, containing lath martensite and lower bainite with high dislocation densities, were developed. Two examples of these types of steels are X100 and X120 HSLA steels with minimum yield strengths of 690 and 820 MPa, respectively. To achieve the desired microstructure, small amounts of boron (B) were added to the steel as B suppresses the transformation of ferrite and promotes lower bainite transformation [16-18]. In addition, depending on B and nitrogen content, Ti is added in an amount sufficient to completely stabilize nitrogen and Mo is added to enhance the hardenability improvement of B [19,20]. Generally speaking, after the HSLA steelmaking process, the steel plates are welded and joined to manufacture long pipes (except for seamless pipe manufacturing). Submerged arc welding (SAW) is commonly used to produce pipes by either spiral welding or UOE techniques; SAW has a high deposition rate and welding speed relative to the other welding processes [8].

Conclusions

High strength low alloy (HSLA) steels are widely used for pipe manufacturing due to their good combination of mechanical properties and weldability. The formation of a fine-grained ferritic/bainitic microstructure containing acicular ferrite, fine martensite-austenite (M-A) constituents, as well as finely distributed precipitates, results in a substantial improvement in the resistance of the HSLA pipes to crack initiation and consequently failure compared with the conventional steel pipes with relatively higher carbon contents and poorer microstructures. In recent decades, much effort by researchers and industries has been devoted to improving the properties of HSLA steel by fine-tuning the steel composition and refining the microstructure through thermo-mechanical controlled processing (TMCP). HSLA steels, particularly X70 and X80 steels, are extensively used across the world, particularly in North America, to manufacture pipelines for oil and gas transport. In addition to their strength and toughness, these steels possess good weldability and corrosion resistance. The first X70 pipeline in North America was manufactured in the mid 1970s for natural gas transport. Recent developments have seen the introduction of higher strength grades such as X100 and X120, which are still at the laboratory research scale.

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