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An overview on pipeline steel development for cold climate applications

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ABSTRACT

For some decades, the resources within the northern hemisphere have been studied for possible exploration. The need for reliable infrastructures in such extreme cold climatic condition is constantly on the rise. There is an imminent need to develop pipeline steels that can retain good characteristics under extremely low temperature. The focus of this review is to evaluate the basic requirements for producing steels designated for application in extreme cold polar regions. This study includes construction steels and the high strength pipeline steel grades used in sub-zero temperature applications. The emphasis is on the role of mechanical properties, chemical composition, and microstructure in designing steels for cold region. How these factors influence failure is critical, especially in terms of cracking behavior. Therefore, additional details about the synergy between low temperature and corrosive degradation are also discussed.

1. Introduction

Declining petroleum in many existing wells is driving the interest in oil and gas exploration from uncharted parts of the world. There are many uncertainties about undiscovered natural resources within the arctic circle. The region with its oceans offers great potentials for economic exploitation. Reasonable exploration of natural resources has already commenced in the arctic. This trend is primarily promoted by the increased accessibility created by reducing ice coverage across the northern hemisphere. An appraisal on the extent of circum-arctic natural resources done by the United States Geological Survey confirmed the following: (a) one-third of the arctic circle is above the sea level, (b) another one-third encompass the continental shelves, while (c) the remaining resources are placed in deep oceanic basins enclosed in ice sheets (Gautier et al., 2009). Their statistics show that over 400 fields already developed in the arctic area as of 2007 contain 40 billion barrels of oil and 1136 trillion cubic feet of natural gas. However, the future contributions of resources from the arctic is tied to the global supply of petroleum. The deep portions of the arctic ocean are less likely to be explored for natural resources compared to the continental shelves with more viable sites for oil and gas exploration. Estimates have shown that the undiscovered arctic petroleum accounts for 22% of the unexplored fraction across the globe (Lindholt and Glomsrød, 2011). Specifically, the arctic petroleum represents 15% of oil and 30% of gas which is undiscovered worldwide. The distribution of these untapped oil and natural gas resources across the arctic region is shown in Fig. 1. It is evident that Russia has the largest quantity of both oil and gas relative to other countries within the region. Significant arctic petroleum deposits are present in Alaska (USA), while the remaining are located in Canada, Greenland, and Norway.

The interest in harnessing arctic natural resources present significant financing challenge, because of environmental concerns. A report by Ernst & Young (2011) identified problems associated with arctic development as listed: (a) high cost of construction, operations and logistics, (b) competition created by cheaper gas supplies, (c) long project durations caused by environmental difficulties, (d) controversies related to sovereignty claims by nations in the region, and (e) regulations and political issues. Also, a market research conducted by Deutsche Bank on the financial benefits accruable to selected arctic countries are summarized in Table 1. It is important to mention that the arctic sea route offers shorter access for the transportation of goods to international markets. Even though the arctic sea may not necessarily provide a faster option, a reasonable argument will be that it serves as an alternative to the Panama and Suez canals (Lasserre et al., 2017). Cost is considered as the major issue with most aspects of business in the arctic. Another problem is lack of access to existing framework to support further developments. These limitations generally slow down the deployment of new infrastructures into the area. Consequently, the USA is favorably positioned because of its already constructed Trans-Alaska Pipeline System. Exploration of oil and gas in Norway is concentrated along the continental shelf, which creates easy market entrance for natural resources obtained from the Norwegian arctic. Although the arctic zones of North America (i.e., USA and Canada) and Russia show great potential for large scale discoveries, countries such as Norway and Greenland are probably most advantaged and can easily benefit from their arctic resources.

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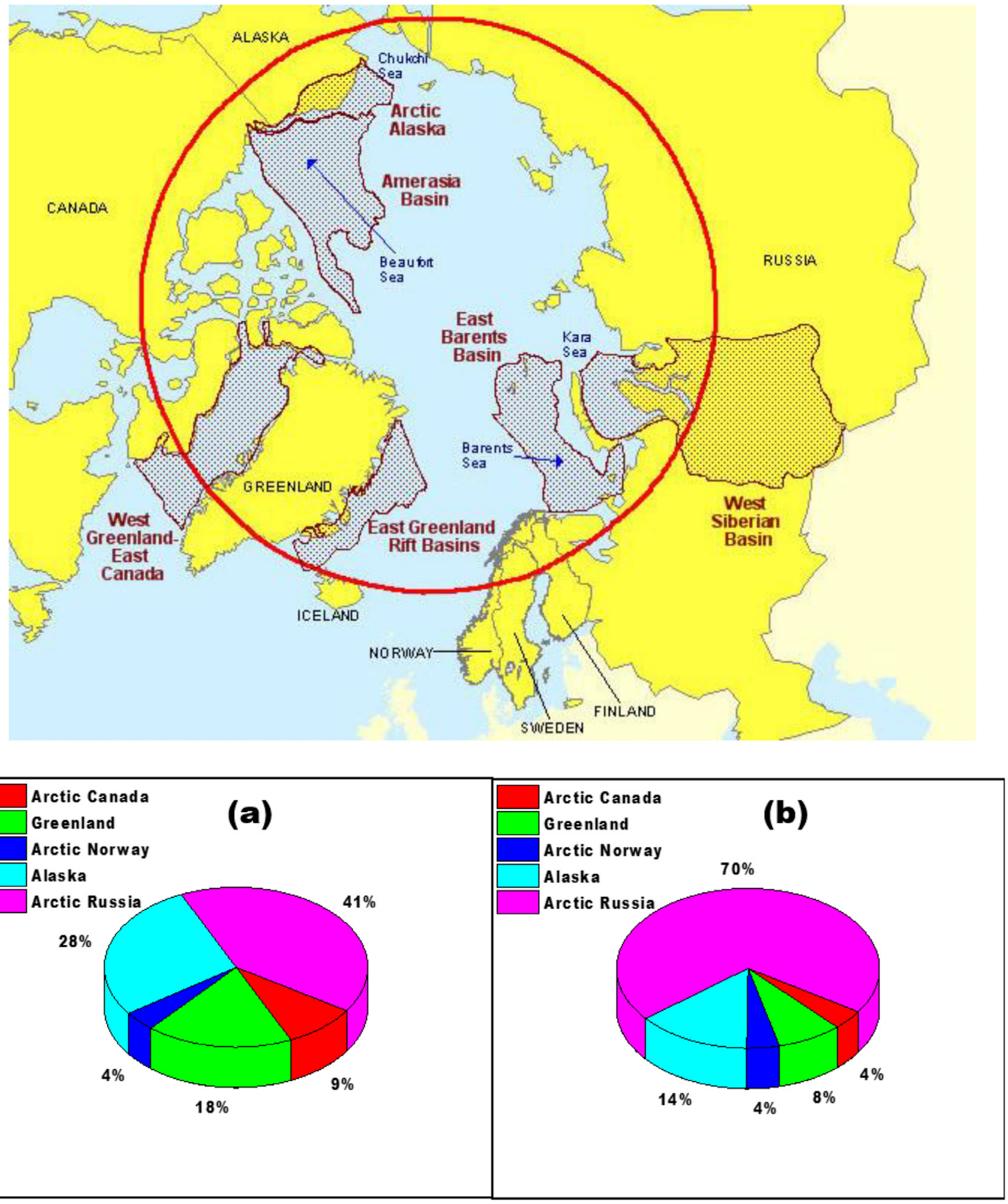

Fig. 1. Statistical estimate of undiscovered distribution of (a) oil resources, and (b) natural gas resources (adapted from Lindholt and Glomsrød (2011)) Geographical map indicating resource basins within the arctic circle (source: United States geological survey).

Developing suitable materials and/or modifying existing ones for use in the cold arctic climate is very critical. Currently, high strength steels of different grades are used for various engineering constructions such as pipelines, bridges, platforms, or marine vessels. These structures have traditionally been designed for other climatic conditions. Therefore, it will be unsafe to use the same materials in extremely low arctic temperature without ensuring their reliability. Such increasing demand for specialized arctic steels is prompting research and development in this field. It is imperative to produce steels that are capable of withstanding sub-zero temperatures without the risk of sudden failure. The remote arctic region is characterized by a wide temperature range of +30 to −70 °C, plus heavy wind depending on the time and location. Such changes in metrological conditions can induce thermal shocks in poorly designed materials. In addition, seasonal weather changes may result in cyclic temperatures and ice loading on structures. This situation can transform minor flaws into cracks, thereby causing unexpected fracture of materials. Other reasons for steel failure in the arctic may include effects of corrosion, hydrogen embrittlement, and forces (e.g., static, dynamic, and cyclic). Therefore, the overall performance of steel in cold regions can be negatively impacted by environmental factors. The current review is aimed at identifying the important characteristics of steels designated for use in the polar (arctic) regions.

1.1. The arctic terrain

The most northern part of the earth is described as the arctic. Scientists generally refer to the region captured within the latitude of about 66.5° towards the north of the equator as the arctic circle. As indicated in Fig. 1, the northern territories of Scandinavia (Norway, Finland, Sweden), Canada (Yukon, Northwest Territories and Nunavut) Russia, Greenland, Iceland, and United States (Alaska) surround the arctic ocean basin. The geographical zones of resource within the arctic

Table 1
Benefits of arctic development opportunities to different countries in the region (Ernst and Young, 2011).

Countries	Prospects for material value creation	Potential for materials discoveries	Access to markets	Access to infrastructure	Existing infrastructure	Competition for resources	Access to resources	General fiscal terms
Russia	Moderate	Very favorable	Moderate	Moderate	Unfavorable	Moderate	Moderate	Very favorable
Norway	Favorable	Moderate	Very favorable	Unfavorable	Unfavorable	Moderate	Moderate	Moderate
Greenland	Favorable	Favorable	Moderate	Very unfavorable	Unfavorable	Moderate	Favorable	Moderate
Canada	Very unfavorable	Moderate	Moderate	Very unfavorable	Very unfavorable	Moderate	Moderate	Favorable
Unites States	Unfavorable	Very favorable	Moderate	Very favorable	Unfavorable	Unfavorable	Moderate	Favorable

circle are highlighted to show territories of various countries that are located within the area. Although the major arctic nations benefit from these resources, other non-arctic nations also seek to profit from the economic opportunities that exist within the region. The uniqueness of the arctic has made it the most pristine part of the world consisting of mostly frozen features (e.g., icebergs, glaciers). For many centuries, there was no form of human activities within the arctic area. The quests for resource exploration combined with the need for shorter transportation route has created a lot of interest in the region. A typical example is the potential of having seasonal shipping passage across the northwest Canadian arctic archipelago (Stephenson et al., 2011). It is predicted that by the mid-century, maritime accessibility across the arctic region will change significantly. The data collected from 1990 to 2015 suggest an increase in shipping activities through the arctic region (Pizzolato et al., 2016). The authors used an empirical sea ice-shipping relationship to explain the implications of declining ice concentration on the physical and socio-economic aspects of human life. Another study (Masterson et al., 2000) categorized the level of ice formation in the arctic with respect to offshore climatic conditions and the number of freezing days. The projected level of access to the four main international shipping routes in the arctic are summarized in Table 2. There is no doubt this will result in unprecedented economic activity around the northern hemisphere in the future. For instance, the global mining, fishing, tourism, timber, and energy industries will experience shorter transportation time to target markets across the world. Also, the construction of pipeline infrastructure will become necessary for conveying liquids and gasses from far-north locations to already existing storage and processing facilities. It is noteworthy that the efficiency of pipelines is unrivaled for transporting liquids from one place to another. Nevertheless, the risk of environmental damage and subsequent loss of containment is possible. Therefore, the emphasis should be on making sure that materials used for all arctic structures are properly designed for high reliability. It is expected that various grades of steel will be used in the process of harnessing resources from the arctic. Hence, the necessary materials property requirements should be validated prior to deployment in the arctic.

1.2. Climatic and geological consideration for arctic structures

Physical changes commonly observed within the arctic terrain are either related to the climate or geology of the region. Saito et al. (2013) presented an overview of the important terrestrial components found across the far northern hemisphere and discussed how they interact to create the large scale arctic eco-climate. They identified snow covers as the most significant physical factor affecting the overall arctic climate. In addition, permafrost occupies approximately 24% of the arctic surface area. Both snow and permafrost cover reasonable portions of the north pole region (Park et al., 2015). These features exist interactively with each other on seasonal basis. In the cold winters, snow falls can alter the sub-surface thermal and hydrological characteristics of permafrost . Such effects often last until the summer season. Sometimes, permafrost would not thaw for two consecutive years (Dobinski, 2011). When steels are exposed to average yearly temperatures below freezing within unfrozen soils a phenomenon known as frost heave may occur. Therefore, understanding the challenges associated with snow-permafrost relationship is critical when planning operations in the arctic. Pipelines that are extremely cold can cause surrounding unfrozen water to freeze (Oswell, 2011). Consequently, the following situations may facilitate frost heave on arctic pipelines: (a) migration of water towards surrounding freezing zones, (b) freezing within unfrozen soil, and (c) frost-prone soils that allows permeation of free water through it. The pattern of interactions between frozen soil and pipelines embedded in cold onshore regions has already been established in the literature (Li et al., 2019). Although pipelines are deformed due to frost heave, there is also a counter restrain to soil heaving imposed by the pipeline. Therefore, a state of dynamic equilibrium exist between pipeline and the soil during freezing (Huang et al., 2020). The schematic diagram in Fig. 2 represents the influence of ice formation on pipeline frost heaving.

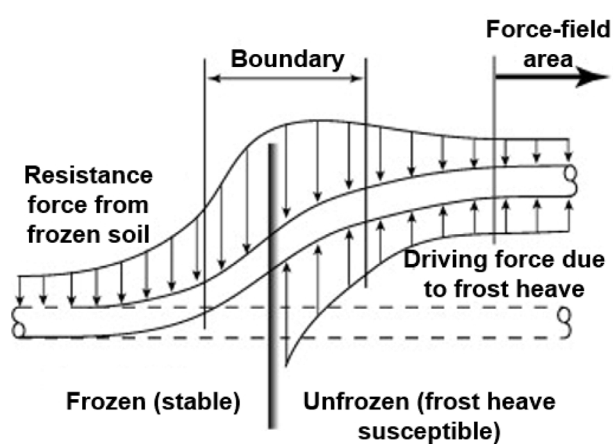

Fig. 2. Differential heave pattern along pipeline in permafrost indicating driving forces for and against pipeline frost heaving (Kim et al., 2008).

Table 2
Expected accessibility changes across arctic shipping routes until the mid-21st century (Stephenson et al., 2011).

Arctic route	Length (km)	Baseline accessibility between 2000–2014	Accessibility changes between 2045–2059	Change in accessibility relative to baseline	Expected travel time by 2045–2059 (days)
Northwest passage	9,324	63%	82%	30%	
Northern sea route	5,169	86%	100%	16%	11
North pole route	6,960	64%	100%	56%	16
Arctic bridge	7,135	100%	100%	0%	15

Such layers of ice created by the migration of moisture through rocks or soils are often described as *ice lenses*. Notice that the non-heaving section of the pipeline in Fig. 2 is made up of stable soil, while the heaving portion comprise of frozen areas within unfrozen soil. The displacement of pipeline in the frost heave susceptible region is due to the action of forces indicated in Fig. 2 (i.e., unfrozen section). Also, a lot of strain is induced at the interface between the stable (non-heaving) and the unstable (heaving) portions of the pipeline. The highly strained portion is marked as the boundary. Note that stable soil is identified as frozen, whereas the unstable soil is largely unfrozen (Fig. 2). Moreover, the heaving forces generated within the unfrozen section are primarily induced by the evolution of frost bulbs inside the neighboring soil. Selvadurai and Shinde (1993) have earlier demonstrated the difficulties associated with performing a comprehensive analysis on the entire soil-pipeline interactions that leads to frost heave. This is mainly due to complexities involved in linking all the temperature and time dependent non-linear mechanical systems. The authors identified some examples of such complicated processes as follows:

(1) Mechanical response of the unfrozen soil.
(2) Issues related with the motion of frozen/unfrozen soil interface due to increased freezing.
(3) The nucleation and growth of ice lenses inside the unfrozen soil
(4) The type of boundary that exist between the soil and pipeline.
(5) Heat transfer and moisture diffusion between frozen and unfrozen soils.

The degradation of permafrost poses severe threats to developments around the arctic (Hjort et al., 2018). It is believed that thawing of near surface permafrost will negatively affect up to 70% of current arctic infrastructures. Even pipelines can experience buoyancy related problems in thawing permafrost. This is often associated with increased pore-water pressures created by rapidly thawing ice within the soil. Unwanted consequences could be uplifting of buried pipelines from their design location. The resistance of pipelines to upward heaving is highly dependent on the soil strength along the stable region. Therefore, applying specialized systems of embedding pipelines inside cold arctic soil is highly recommended. In extreme cases of frozen soil, pipes can be insulated or installed overhead (i.e., above ground) (Yu et al., 2020). Other practical means of minimizing frost heave in the long term involves operating pipelines under carefully controlled cyclic temperature conditions. Another study (Morgan et al., 2006) demonstrated potential benefits of employing cyclic temperatures towards reducing strain on large diameter chilled gas transmission pipelines. This approach is beneficial for ensuring the structural integrity of pipelines embedded within discontinuous permafrost. The goal is to minimize the probability of frost-induced bending strain along the pipeline through sudden temperature elevation.

2. Design considerations for cold climate steels

Strategies for developing new materials are often based on experiences gained from prior industrial operations or existing limitations. Unfortunately, the arctic region is yet to host significant number of engineering projects. Some generally accepted offshore design standards such as the NORSOK and ISO 19,902 are widely adopted in the arctic. However, only few steel research results from the region are available. More specific material requirements are necessary when producing arctic steel. Solving this problem requires understanding the geology and climatic condition in the region. The arctic weather affects heat transfer in metals, facility operations, hydrology and hydraulics (Jansto, 2018a). Thus, knowing the least expected service temperature is important to ensure that steels retain sufficient toughness to overcome brittle fracture throughout their design life. It is recommended to consider temperature as a variable parameter for arctic applications. The suitability of base metals and welds at temperatures as low as −60 °C is required in the arctic. The reason being that temperature may fluctuate throughout the year, especially around submerged structures, buried structures, and equipment located at splash zones (Horn et al., 2017). According to Goli-Oglu (2015) the underlying criteria for manufacturing low temperature resistant steel plates with thickness above 70 mm are as follows: (a) high quality slab macrostructure, (b) well controlled elemental composition, and (c) adequate methods for developing a uniform microstructure consisting of refined grains. In addition, equipment and infrastructures situated in the complex arctic climate require reliable and cost-effective welds.

The production of arctic steel entail controlling the rolling schedule and other related processing criterion to achieve high quality. This requires strict adherence to proper planning, improved rolling processes, and identifying any conditions that may affect the overall outcome of the chosen parameters (Murugabhoopathy et al., 2019). Ultimately, arctic steels are expected to undergo ductile structural response prior to failure. Therefore, the following strategies have been recommended to overcome brittle type of material failure (Ostby et al., 2015).

- Ductile material approach: This requires ensuring that the materials fail in ductile mode under arctic conditions, hence all property requirements should facilitate ductile behavior.
- Plastic collapse approach: This method requires that the material experience extensive plastic deformation before the initiation of brittle failure. It is dependent on a quantitative definition of the tolerable amount of plastic deformation.
- Fracture resistance method: Here, extensive understanding of fracture mechanism is used to understand the effects of applied loads, internal defects, and material toughness towards evaluating acceptable risk of brittle failure.

In addition, Orlov et al. (2014) outlined other processing requirements that must be considered in designing any arctic steel production technology.

- Impurities such as non-metallic inclusions and gasses must be at the minimum to avoid anisotropy of mechanical properties. All forms of inclusion aggregation must be eliminated or have their sizes reduced as low as possible. Alternatively, they must be made more globular in shape using rare-earth metals. This will ultimately enhance steel performance under low temperature, static and dynamic loading conditions.
- Alloying content such as carbon and manganese should be kept within narrow limits to reduce unwanted segregations and improve weldability.
- Thermomechanical processing parameters (specifically rolling temperature and heating duration) must be carefully controlled to achieve proper austenite homogenization, dissolution of carbides/carbonitride precipitates, restrict excessive grain growth, and increase deformability. The roughing temperature should be such that minimizes excessive grain enlargement during recrystallization but facilitates uniform growth of austenite.
- The start and end finishing temperatures, number of passes, and the amount of rolling reduction per pass must be strictly regulated to achieve at least 50% overall thickness reduction. This is necessary to create optimum lattice defects and nucleation sites for an evenly dispersed structure after cooling.
- Limited cold working of the austenite grains should be adopted for bainite-martensite structured steel. Rolling should stop at temperature not less than 150–200 °C below the onset of static recrystallization. In certain situations, direct quenching and subsequent tempering may be required after the rolling process.
- To obtain ferrite-bainite structured steels, sub-grains must be generated within the austenite towards the final stages of rolling deformation close to A_{r3}. The structural defects in the hot deformed austenite are inherited by the bainite, hence increasing resistance to brittle failure. There might be cases where tempering is recommended for this type of steel.

- For ferrite-pearlite structured steel, high dislocation density is used to strengthen the ferrite when the rolling process is ended towards the upper inter-critical temperature range.
- The final cooling temperature must be such that prevents excessive pearlite or bainite formation, minimize grain growth, and ensure structural hardening.

The most reliable approach for developing arctic steel is through thermo-mechanically controlled processing (TMCP). This often involves manipulating alloying composition and the application of direct quenching to manage plastic deformation.

2.1. Processing criteria for steel designated for cold climate

The procedures adopted during thermo-mechanical processing can directly affect microstructure development in arctic steels. It is possible to improve the fracture toughness of steels while retaining their high strength. This entails proper control of steel treatment processes such as reheating temperature, rolling reductions, inter-pass time, rate of cooling and so on (Jahazi and Egbali, 2000). A strategic choice of hot deformation and rolling temperature determines the properties of steels. Obtaining refined ferrite grains requires controlling the following operations during steel processing (Rezayat et al., 2021): (a) austenite coarsening at reheating and roughing step, (b) size and morphology of austenite grains prior to finishing rolling in the non-recrystallized region, and (c) final austenite transformation induced by cooling and coiling. The contributions of key processing parameters towards obtaining optimum steel characteristics are described in the subsequent sections.

2.1.1. Considerations for slab reheating

There is a profound effect of slab or billet reheating temperature on quality and microstructural homogeneity throughout an entire steel. The choice of steel reheating temperature controls austenite grain size and the quantity of solid solution alloying elements (Zhao and Chen, 2018). The authors suggested that reheating temperature required to achieve the desired structural properties in steel can be estimated with Eq. (1).

$$T = \frac{B}{A - \lg([M][X])} \tag{1}$$

The values for A and B in Table 3 represents the coefficients of solid solubility products of some carbonitride precipitates found in austenite, while $[X]$ and $[M]$ are the respective amounts of alloying elements. Using Eq. (1), it was determined that carbides are completely dissolved at temperatures above 1,140 °C (Fig. 3(a)). The consensus is that reheating steel above the dissolution temperature of Nb(C, N) enhances the mechanical properties of steels through grain refinement, reduced austenite to ferrite transition temperature, and precipitation hardening (Ebrahimi et al., 2010). Among all these identified benefits, the creation of refined grains is most favorable towards achieving an excellent balance between toughness, strength, and ductility. Sufficient heating is recommended to allow the dissolution of carbonitrides precipitates (i.e., Nb, Ti, V (C, N)) within the austenite.

Table 3
Solid solubility product coefficients for precipitates in austenite (Zhao and Chen, 2018).

Precipitates in austenite	A	B
TiN	0.32	8,000
TiC	5.33	10,475
NbN	3.7	10,800
NbC	2.04	6,500
Nb(C,N)	2.26	6,770
VN	3.63	8,700
VC	2.72	6,080

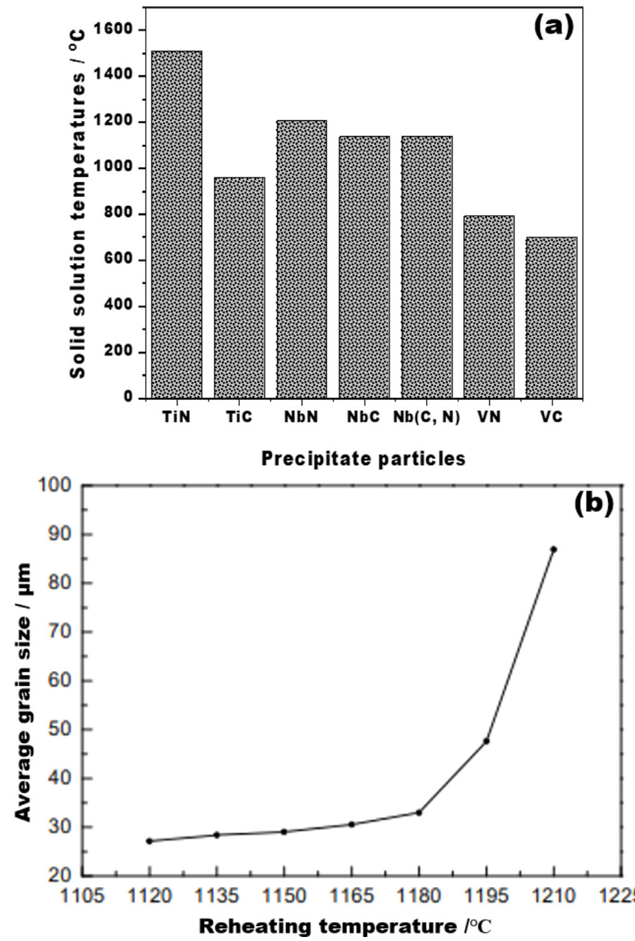

Fig. 3. (a) solid solution temperatures of typical carbonitride precipitate particles obtained from Nb, Ti, and V (b) influence of reheating temperature on average austenite grain size (adapted from Zhao and Chen (2018)).

Notice in Fig. 3(b) that a gradual increase in average austenite grain size is observed between 1,120 and 1,180 °C. Afterwards, significant austenite grain enlargement continues above 1,200 °C. This indicates that a temperature value between 1,140 and 1,180 °C will be most desirable for reheating X70 pipeline steel. Similar results were observed in Nb micro-alloyed steels by Ebrahimi et al. (2010). They concluded that increasing reheating temperature from 1,180 to 1,240 °C minimizes pearlite content and promotes acicular ferrite in the rolled steel. Altogether, the increased ferrite presence plus carbonitride precipitates combine to improve strength and toughness in steels. Another investigation into the effect of reheating temperature on steel indicates an increase in hardenability at higher temperature of 1,175 °C compared to 1,075 °C (Di Schino and Rufini, 2018). They attributed their results to increase in the size of austenite grains at relatively higher reheating temperature, which affects the extent of grain refinement in the end microstructure. Furthermore, dminished impact toughness was linked to enlarged austenite grains . It is important to mention that the optimum reheat temperature may vary for different types of steels depending on their alloying composition.

Elsewhere, Jahazi and Egbali (2000) demonstrated the relationship between reheating temperature and mechanical properties of steel. Their results presented in Fig. 4 shows an increase in strength and absorbed impact energy with respect to reheating temperature up to 1,100 °C. Thereafter, a significant drop in yield strength, tensile strength, and impact energy occurred at 1,200 °C. For the samples reheated at 980, 1,050, and 1,200 °C, the authors obtained average grain size values of 11, 6 and 20 μm, respectively. This confirms that reheating

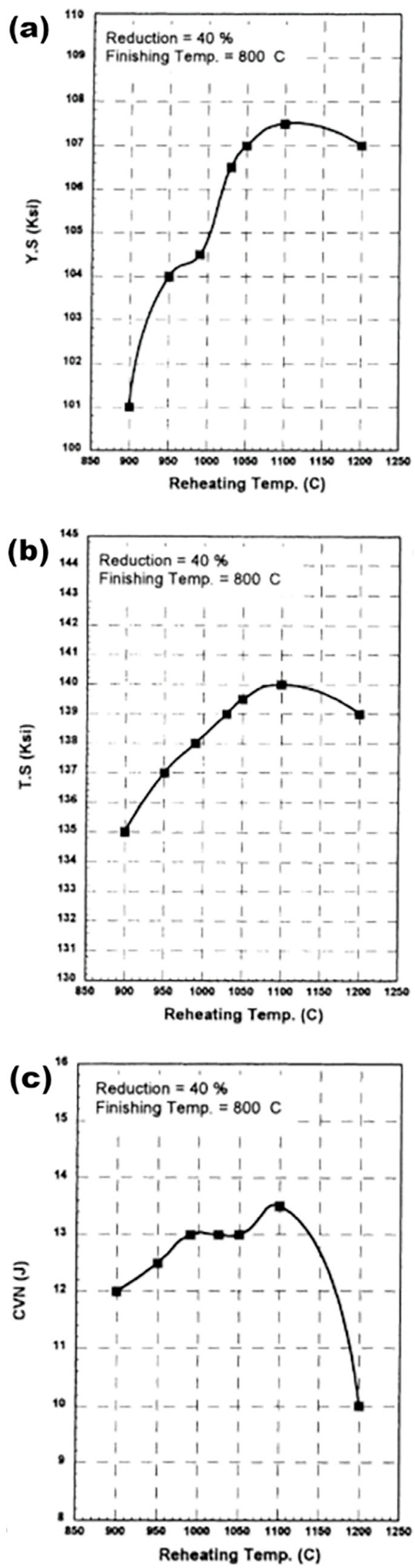

Fig. 4. Effect of reheating temperature on mechanical properties of AISI 4130 steel (a) yield strength vs. reheating temperature (b) tensile strength vs. reheating temperature (c) impact energy vs. reheating temperature (Jahazi and Egbali, 2000).

at 980 ˚C does not allow complete dissolution of carbonitrides. Meanwhile, precipitates were absent within the boundaries of austenite grains after reheating at 1,200 ˚C. It was suggested that the total dissolution of precipitates allowed the formation of large austenite grains, which ultimately impeded grain refinement during subsequent hot deformation. The reason for having the well refined ferrite grains after reheating at 1,050 ˚C is not far-fetched, given that sufficient dissolution of nitrides and carbides occurred without abnormal austenite enlargement. Furthermore, the formation of fine carbonitride precipitates during hot rolling helps to restrict recrystallization of austenite and facilitate solid solution strengthening. Controlling the thermodynamics, kinetics, and combustion parameters helps to achieving uniform reheating. Certain flaws that might be detrimental towards homogeneous heat transfer across the steel during the reheating stage are as follows: (a) sub-optimal flame temperature due to broken burner orifice, (b) air entrance into the furnace from an opening in the roof or sidewall, (c) formation of oxide scale resulting in minimal exposed surfaces, especially at the bottom area of steel slab, (d) reduced furnace pressure because of mechanical fault or poor combustion, (e) imbalance in oxygen accumulation around the tip of combustion burner (Jansto, 2018b).

2.1.2. Implications of thermo-deformation

Altering the properties and internal structure of arctic steel depends primarily on plastic deformation. The level of energy accumulation and/or dissipation during thermo-deformation can either strengthen or weaken steel by changing dislocation density. The hot rolling process entail mostly dynamic recrystallization with subsequent evolution of equiaxed grains. However, it is common to observe progressive reduction in grain size as rolling temperature decrease. This is mainly because of the increase in dislocation density at lower deformation temperatures.

The crucial consideration for processing arctic steels is ensuring the formation of fine-grained ferrite and bainite microstructure in significant proportion. This implies that an optimum austenite grain refinement is necessary to achieve the desired extent of recrystallization. Under industrial conditions, such properties can be obtained by rough rolling at temperatures above 950 ˚C with a total deformation of approximately 70% (Sych et al., 2018). Decreasing the amount of deformation for each pass below 10% could lead to the formation of coarse austenite grains, and further transformation into lath-like bainite as rolling temperature reduces. This increases the chances of creating anisotropic microstructure in steels, which makes them unsuitable for extreme cold application. Furthermore, finishing rolling temperatures can be manipulated for better steel properties. Researchers (Decaux et al., 1998; Carretero Olalla et al., 2014) have suggested lowering hot rolling temperatures as a means of enhancing toughness. The reason being that reduced rolling temperatures will minimize recrystallization and austenite grain enlargement. The authors (Decaux et al., 1998) proposed finishing rolling arctic steel to a temperature of approximately 625 ˚C, which is greater than or equal to the dynamic transformation temperature. Fully formed sub-grain austenite structure formed by isothermal rolling below recrystallization temperature aids grain refinement. In general, having a sub-grain structure with low angle boundaries and degree of misorientation less than 5˚ favors higher strength at low temperature. Especially if the spread in temperature at the surface between passes stays below 20 ˚C with rolling reduction per pass of 10%–15%. In a separate study, Sych et al. (2018) observed that keeping the steel surface at A_{r3} or slightly above by 10–15 ˚C during finishing rolling resulted in a temperature of A_{r3} + (50 to 60) ˚C at the mid-thickness and a homogeneous structure in the rolled plate.

Other reports correlates the extent of rolling reduction applied during thermo-deformation to mechanical characteristics. Again, Jahazi and Egbali (2000) determined the influence of varied rolling reductions on yield strength, tensile strength and absorbed impact energy. They noticed a continuous improvement in strength as rolling reductions increased from 15% to 60% (Figs. 5(a), (b)). It is obvious that rolling reductions above 40% did not significantly increase absorbed energy (Fig. 5(c)). This suggests that an excellent balance between strength and toughness was achieved with 40%–50% rolling reduction. Reducing the amount of deformation creates fewer sites for ferrite nucleation and allow sufficient time for grain enlargement. However, increasing the percentage of reduction facilitates the formation of higher ferrite fraction. Additional features such as high volume of (a) pancaked austenite, (b) dislocations, and (c) deformation bands are also formed as rolling reductions increases. These factors increase the rate of ferrite formation and further refine the microstructure of hot rolled steel. Table 4 shows the effect of finishing rolling temperature on the mechanical properties of steel sheets and fully formed pipe. The researchers (Decaux et al., 1998) proposed the reduction in hot rolling temperature as a means of enhancing toughness. Their results depict high toughness and ductility in steels rolled at lower finishing temperatures (830 ˚C) compared to higher finishing temperature (930 ˚C). It is not surprising that the pipes have higher strength compared to the sheet steels in Table 5. This shows the effects of different forces that act on a steel plate during the pipe forming (i.e., the U-ing and O-ing) processes. Making a pipe involves subjecting the outer layer of the steel sheet to tension while the inner layer experience compressive forces (Jo et al., 2017). Therefore, the increased strength in pipes can be attributed to higher strain energy induced by additional forces applied throughout the forming process. Also, it is notable that lower rolling temperature led to reduction in strength across the longitudinal and transverse axis. This is indicates that deforming steel at lower temperatures will potentially minimize recrystallization and austenite grain enlargement. Furthermore, the authors found that coiling at reduced temperature hinders excessive ferrite grain growth but promoted microstructural refinement through more uniform distribution of carbides within the steel. It was concluded that finishing rolling at temperatures greater than or equal to the dynamic transformation temperature of the steel and coiling at reasonably lower temperature is recommendable for arctic steel. It is noteworthy that the fine isotropic ferrite-bainite microstructure obtained by the authors guarantees only yield strength values of up to 355–390 MPa. Elsewhere (Gorynin and Khlusova, 2010), the creation of nanostructured bainitic steel without altering micro-alloying composition has increase strength (by 15%–20%) and brittle fracture resistance (up to 1.5 times). The need to obtain even higher balance between strength and toughness in cold resistant steels remain largely unsolved.

The balance of roughing and finishing rolling reductions play an important role in the properties of arctic steel. There is rather limited systematic research relating rolling reduction patterns to final microstructure and crystallographic texture of steels. A recent study (Tian et al., 2020) determined that varying the rolling reductions within recrystallization and non-recrystallization regions affects low temperature toughness in steels. Various types of microstructural features were obtained by manipulating the rolling reductions in the recrystallized region (i.e., rough rolling) and non-recrystallized region (i.e., finishing rolling) as indicated in Fig. 6. They suggested an optimum rolling deformation

Table 4
Influence of finishing rolling temperature on impact toughness and ductility (Decaux et al., 1998).

Material	Finishing temperature (˚C)	Energy absorbed		Shear area (%)	
		−55 ˚C (J)	−30 ˚C (J)	−55 ˚C	−30 ˚C
Steel Sheet	830	92	114	89	97
Steel Sheet	930	64	94	64	85
Steel pipe	830	66	92	85	94
Steel pipe	930	38	76	43	93

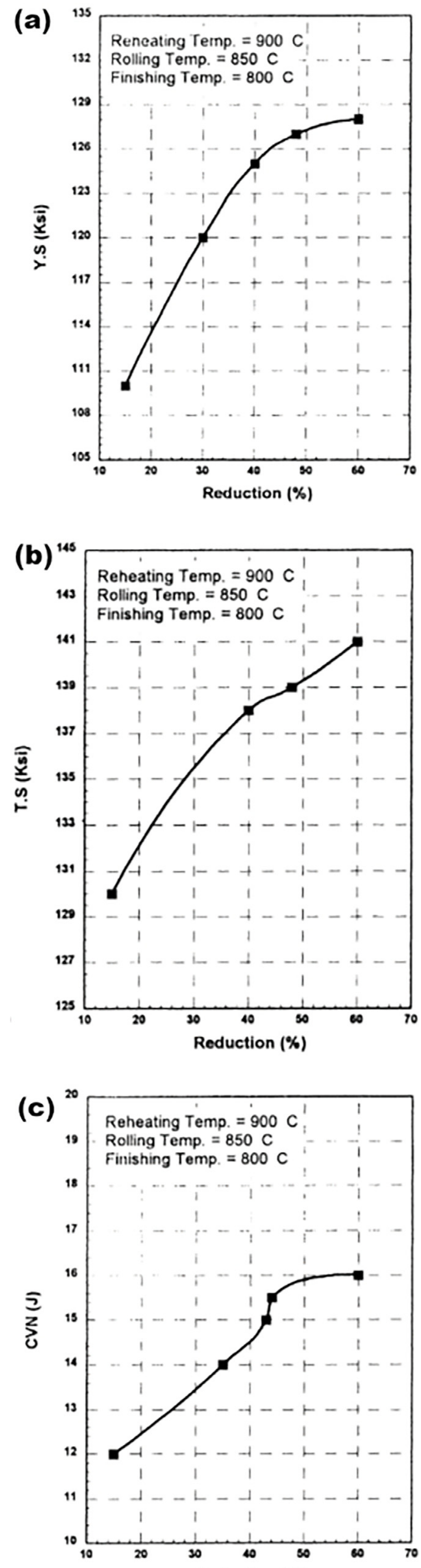

Fig. 5. Schematic representation of TMCP with the resulting EBSD micrographs obtained after applying different rolling reductions above and below T_{nr} (Tian et al., 2020).

Table 5
Influence of finishing rolling temperature on tensile properties of steel (Decaux et al., 1998).

Materials	Finishing temperature (°C)	Longitudinal axis		Transverse axis	
		Yield strength (MPa)	Tensile strength (MPa)	Yield strength (MPa)	Tensile strength (MPa)
Steel Sheet	830	441	537	469	551
Steel Sheet	930	455	551	482	565
Steel pipe	830	496	551	510	565
Steel pipe	930	503	579	524	579

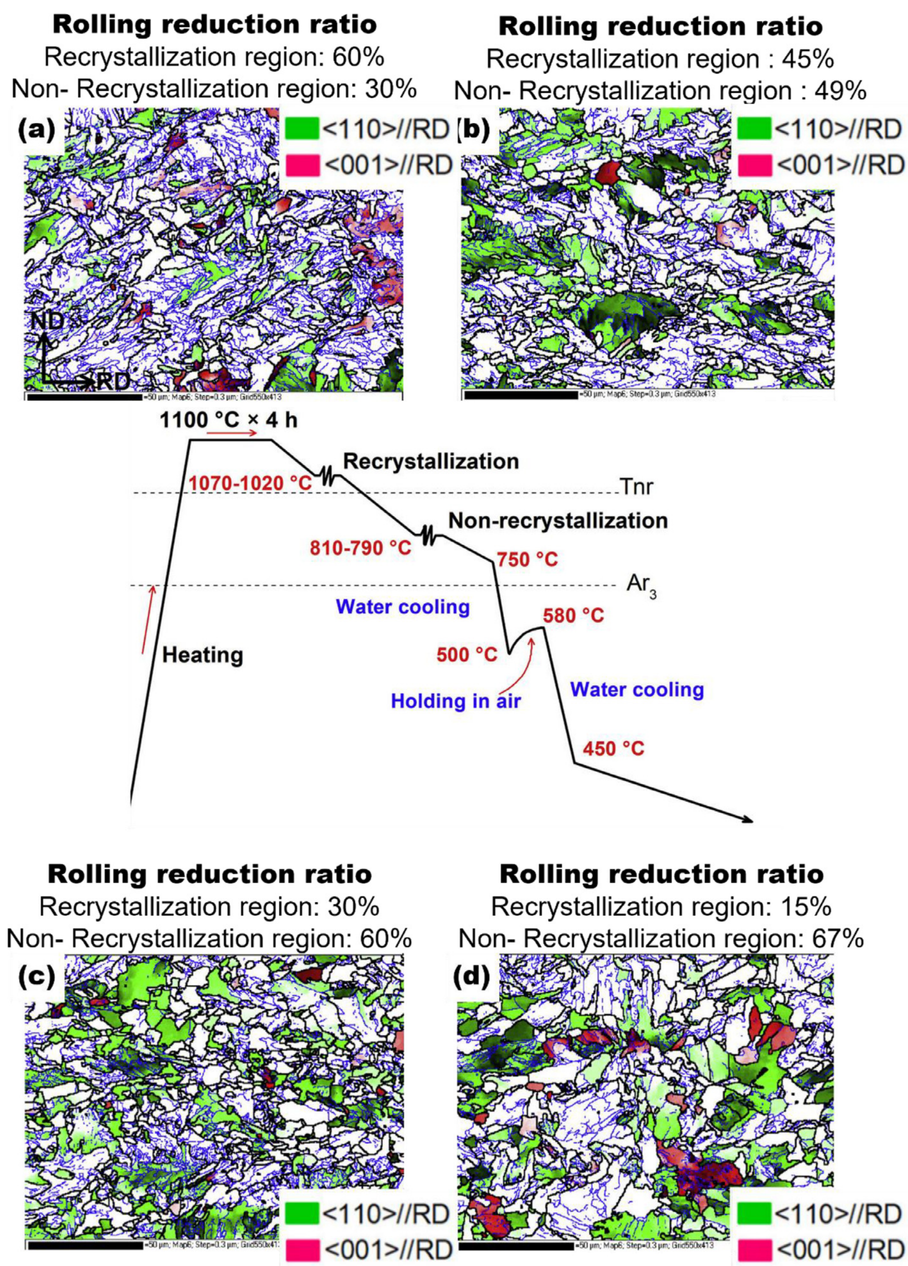

Fig. 6. Effect of rolling reduction on mechanical properties of as hot rolled AISI 4130 steel (a) yield strength (i.e., Y.S) vs. percentage rolling reduction (b) tensile strength (i.e., T.S) vs. percentage rolling reduction (c) absorbed impact energy vs. percentage rolling reduction.

amount of 60% in the non-recrystallized region (below T_{nr}) as a means of developing desirable texture (such as {112}⟨110⟩, {332}⟨113⟩) components in steel. Most importantly higher fraction of the {110}||RD grains (colored green) are visible in Fig. 6(c) compared to other steels (Figs. 6(a), (b), (d)). The authors believe that the optimized rolling process promoted grain refinement, which ultimately enhanced low-temperature impact toughness.

2.1.3. Considerations for cooling and coiling

The approach towards cooling and coiling after thermo-mechanical deformation can significantly affect the end properties of steels. Particularly, decreasing the temperature for coiling alongside the accelerated cooling could result in a variety of microstructure and grain size distribution. Different kinds of non-equiaxed ferrite microstructures with unique substructures and morphologies have been identified after varying accelerated cooling and coiling conditions (Lanjewar and Tripathi, 2016) . They obtained relatively higher strength from rapid ferrite transformation with intermediate cooling times and coiling temperatures of 500 and 525 °C respectively. Similarly, Liu et al. (2019) observed that controlling the final cooling temperature improved the overall mechanical properties of V-N-Cr micro alloyed steels.

It is common practice to use cooling rate to determine if steel would have mainly ferrite, bainite or martensite microstructure (Liang et al., 2021). Another study (Kabanov et al., 2019) established that increasing cooling rate while processing X80 pipeline steel resulted in the following: (a) grain refinement, (b) higher acicular ferrite/upper bainite content, and (c) higher martensite/austenite constituents. Carbon diffusion from bainite to non-transformed austenite becomes limited as cooling rate increase, thus promoting refined martensite/austenite formation. In fact, rapid cooling is a critical step in the production of high strength low carbon steel. The progression of pipeline steel development from the X52–X65 even up to the higher strength X70–X120 grades was made possible by applying accelerated cooling (Krasnov et al., 2018). It has been found that finishing cooling at relatively lower temperature promotes lath bainite formation in X100 pipeline steel, while higher finish cooling temperature leads to mostly acicular ferrite (Zhou et al., 2016). The authors identified an optimum range of 535–560 °C for controlling final cooling temperature at a rate of 27–33 °C/s. This indicates that the transition from steels with ferrite-pearlite microstructure to those containing mainly bainitic ferrite can be accomplished by increasing the cooling rate. Table 6 summarizes selected studies on the effect of cooling temperature on tensile properties in different kinds of steels. Overall, the results indicate higher strength for accelerated cooling performed at relatively lower temperatures.

Elsewere, three separate cooling paths were evaluated in HSLA steel (Tang et al., 2013). The results show the effect of each processing route on grain refinement, precipitates formation, and overall mechanical properties. The cooling rates were varied while keeping the other rolling parameters constant for all processing schedules. It was observed that increase in strength depends on the rate of cooling in the order of accelerated cooling, ultrafast and accelerated cooling, ultrafast cooling. In Table 7, the fastest cooling rate (i.e., ultrafast approach) resulted in the highest level of grain refinement. It was found that ferrite nucleation sites and dislocation density increased with increasing cooling rate. This must have led to reduced grain growth and higher strength. Microstructural evaluation confirmed the presence of relatively larger grains and fewer precipitates at the grain boundaries in the accelerated cooled specimen (Figs. 7(a), (b)). Comparatively, higher rate of cooling (specifically ultrafast/accelerated and ultrafast routes) resulted in superior grain refinement as seen in Figs. 7(c)–(f). Precipitates with the smallest average grain size (~5 nm) are present in the ultrafast cooled specimen than those cooled through other routes with up to 30 nm precipitates (Fig. 7(g)). An explanation could be that rapid cooling drastically reduced the phase transformation temperature for austenite to ferrite, thus restricting the time required for precipitates to grow. Craven et al. (2000) made similar observation in Ti-Nb alloyed HSLA. They concluded that larger carbonitride (above 100 nm in size) are often formed at elevated austenite temperatures, whereas the smaller strain-induced precipitates nucleate at ferrite temperatures through the cooling process.

Certain alloying elements can affect the final steel properties by interfering with the cooling and coiling processes. This phenomenon was recently examined by Kong et al. (2015). Recall that the final state of microstructural features is determined at the coiling stage. Therefore, important material characteristics such as grain size and precipitate distribution are controlled with the suitable choice of coiling temperature. Figs. 8(a) and (b) clearly indicates that significant increase in strength can be achieved in TiMo, NbMo, NbW and TiW micro-alloyed HSLA steel by deploying relatively lower coiling temperature (Park et al., 2013). Their results indicate reduction in the average size of grains (Fig. 8(c)), and precipitates (Fig. 8(d)) at 500 °C compared to higher coiling temperatures (i.e., 620 and 700 °C). It is noteworthy that the dimensions of precipitates increased drastically with the addition of W into Ti - Nb containing steel (Fig. 8(d)), especially at a holding temperature of 700 °C. This suggests that W impedes the creation of numerous precipitate nucleation sites. The understanding is that phase transformation at the hot rolling stage followed by formation of precipitates during low temperature coiling results in smaller grains and smaller precipitates. Generally, such behavior can be attributed to the following reasons: (a) high density of precipitate nuclei because of increased thermodynamic driving force created at lower coiling temperature, (b) increased density of dislocations within the ferrite matrix that provides non-uniform carbide nucleation sites, and (c) precipitates tend to grow slower at lower temperatures. Elsewhere, Cheng et al. (2016) made similar findings on X100 pipeline steel coiled at 500, 470, 440, 410, 380, and 350 °C respectively. The authors linked the decrease in strength at elevated coiling temperatures to lower dislocation density and bainitic content. Lower coiling temperatures facilitates excellent toughness through the creation of finer bainite with high dislocation density. In addition, coiling at a re-

Table 6
Summary of the effect of final cooling temperature on mechanical properties of steels.

Sample	T_f (°C)	T_c (°C)	$R_{p0.2}$ (MPa)	R_m (MPa)	E%	YR	KV (−20 °C) (J)	Ref
V-N-Cr steel	835	600 (15 °C/s)	580	844	17	0.69	–	Liu et al. (2019)
	830	450 (30 °C/s)	835	989	15.2	0.84	–	
	830	350 (40 °C/s)	740	969	15.9	0.76	–	
Cr-Ni-Mo-V steel	860	535 (10–15 °C/s)	760	1,185	16.5	0.64	146	Zhang et al. (2018)
	860	501(10–15 °C/s)	825	1,232	13.8	0.67	102	
	860	459 (10–15 °C/s)	928	1,287	12.7	0.72	83	
X80 pipeline steel	745	481(20 °C/s)	613	790	23.5	–	120	Duan et al. (2021)
	740	534 (16 °C/s)	620	800	25	–	118	
	750	584 (13 °C/s)	613	800	23.8	–	102	

T_f: final finishing rolling temperature; T_c: final cooling temperature; $R_{p0.2}$: yield strength; R_m: ultimate tensile strength; E: elongation; YR: yield ratio; KV: Charpy impact absorbed energy.

Table 7
strengthening effects on steel produced by different processing routes (Tang et al., 2013).

Processing route	Grain refinement strengthening (MPa)	Precipitation strengthening (MPa)	Yield strength (MPa)
Accelerated cooling	272	91	619
Ultrafast/Accelerated cooling	293	105	665
Ultrafast cooling	321	145	731

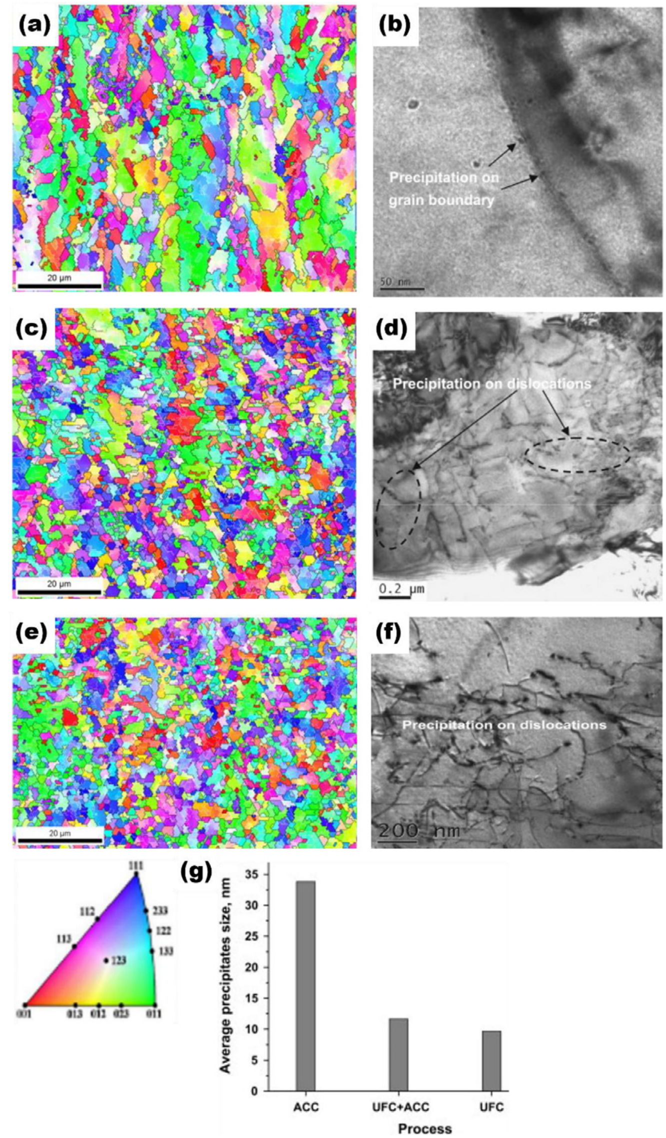

Fig. 7. EBSD and TEM micrographs of microstructure developed in steel using different processing routes (a-b) accelerated cooling, (c-d) ultrafast/accelerated cooling, (e-f) ultrafast cooling, and (g) average distribution of precipitate after cooling (Tang et al., 2013).

duced temperature hinders excessive ferrite grain growth and promote microstructural refinement through more uniform distribution of carbides within the steel.

2.2. Optimizing chemical composition of cold climate steels

The chemistry of metals can influence their ductile-to-brittle transition temperature. Steels with excellent mechanical properties at subzero temperature often contain minimal amounts of N, S, and P. Optimum proportions of alloying elements such as Si, Mn, Nb, and C may be added to increase impact toughness. Previous study (Krishnadev and Cutler, 1981) has proposed specific modifications to the composition of low carbon Fe-Cu steel for improved arctic service life. They are as follows: (a) including P and Si (larger than the quantity used in HSLA steels) to enhance solid solution strengthening and corrosion resistance, (b) moderate addition of Nb and Ti for precipitation strengthening and grain refinement. A summary of nominal chemical composition for steel alongside the contributions of selected elements towards the upper shelf fracture energy and transition temperature are presented in Table 8 (Decaux et al., 1998). Similar results were obtained during the early days of arctic pipe fitting development through hot forming and heat treatment (Reisdorf, 1976). The authors observed significant low temperature toughness (at −62 °C) in heat treated constructional alloy steel. It is important to highlight the role of certain alloying constituents in lowering transition temperature. Amongst all the elemental constituents the functions of Nb during thermomechanical processing, especially in austenite conditioning, remains the most important (Deardo, 2003). The addition of Nb enhances the production of suitable hot rolled austenite that guarantees the desired ferritic microstructure. Also, Nb increases the number of crystalline defects that eventually act as ferrite nucleation sites during phase transformation. Achieving a refined ferrite microstructure through austenite conditioning requires high ferrite nucleation rate accompanied by reduced grain growth rate. Substantial amount of fine uniformly sized grains can be obtained through a combination of Nb addition and, proper thermomechanical rolling schedule.

3. Mechanical response of steels in cold climate

Majority of low carbon steels have reduced strength and insufficient toughness to withstand the extreme cold weather. Steels designed for low temperature must not only possess high strength, but excellent toughness is also required. Investigations into the effect of low temperature on the mechanical response of various engineering materials are mostly centered on the risks of cold-induced brittle failure. In addition to the choice of processing parameters and alloying composition, another important factor that affect the anisotropy of mechanical properties in pipelines designed for low temperature is the crystallographic texture. Fracture toughness is an important factor that can be influenced by texture. This is critical towards understanding crack behavior in steels. For instance, it has been revealed that the mechanical property anisotropy along transverse, diagonal and longitudinal directions of X70 and X80 steels is linked to texture (Joo et al., 2014). The highest strength obtained from the transverse direction was attributed to the prominent presence of (110)||RD grains, and the relative difficulty imposed on slip by this orientation. They found that specimens with $\{001\}$ cleavage planes aligned parallel to the fracture plane displayed poor toughness. Large presence of undesirable, $\{100\}\langle 011\rangle$ Rotated Cube texture component predisposes pipeline steels to a phenomenon described as 'splitting' or separation under mechanical load in modern X80 pipeline grade (Gervasyev et al., 2020). The faces of such cubic shaped grains are mostly inclined at 45° to the direction of hoop stress in longitudinally welded pipes and approximately 90° in spirally welded pipes. Since the faces of a $\{001\}$ grain often lie parallel to the pipe outer surface it makes it easier for splitting to occur. However, this type of failure is promoted by the generation of through-thickness triaxial stresses from crack propagation. It is evident that the $\{100\}\langle 001\rangle$ Cube and $\{100\}\langle 011\rangle$ Rotated Cube contribute more towards local yield strength weakening compared to the $\{111\}$ fibers and $\{110\}\langle 011\rangle$ Goss texture components. Recent studies have found the dominance of cube texture as undesirable for pipeline steels (Joo et al., 2012; Nafisi et al., 2012; Gervasyev et al., 2016).

Deforming steel above the non-recrystallization temperature (T_{nr}) allows the conversation of deformation textures into predominantly Cube component after recrystallization. Therefore, it is recommended to avoid recrystallization of austenite towards the completion stages of steel processing. Table 9 shows the role of finishing rolling temperature on after direct quenching and tempering steel (Saastamoinen et al., 2018). The authors acknowledged that intense rolling at non-recrystallization temperatures often lead to higher strength along the transverse direction, whereas no significant changes were observed at relatively lower temperatures (Table 9). Also notice that slight increase in strength occurred on the longitudinal direction at the highest finish rolling temperature, while the opposite is seen at lower finish rolling temperatures. Also, the microstructure obtained after initial thermomechanical processing clearly changed with hot rolling temperature. Mostly martensite was

Table 8
The role of selected alloying elements on steel toughness for arctic application (Decaux et al., 1998).

Alloying elements	Nominal composition (wt.%) for fine grained Si-Al killed steel (Reisdorf, 1976)	Nominal composition (wt.%) for X65 pipeline steel grade	Toughness	
			Transition Temperature	Upper-shelf fracture energy
Carbon	0.08	0.06	Increase	Decrease
Niobium		0.04	Decrease	–
Molybdenum	0.3	–	Increase	–
Chromium	1.0	–	Slight increase	Increase
Nickel	1.0	–	Decrease	Increase
Nitrogen	–	–	Increase	Decrease
Aluminum	–	0.04	Slight decrease	Increase
Silicon	–	0.22	Increase	–
Phosphorous	–	0.008	Increase	Decrease
Sulfur	–	0.005	Decrease	–
Manganese	0.6	1.15	Decrease	–
Calcium	–	0.003	–	–

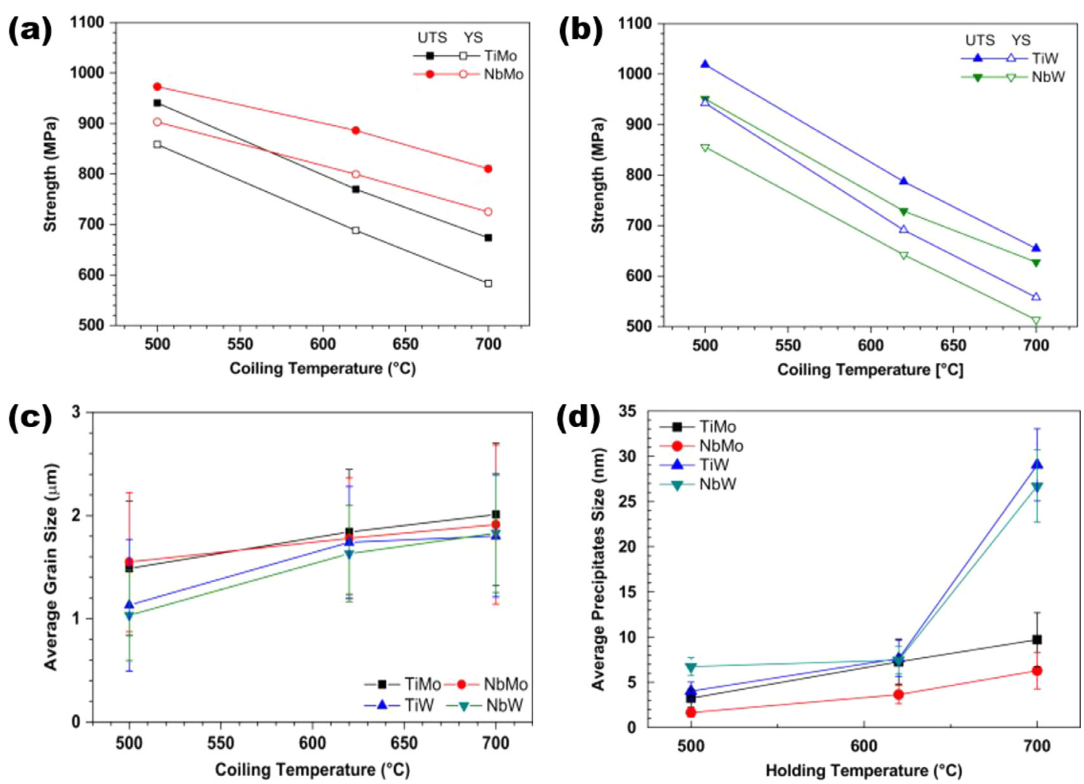

Fig. 8. Effect of simulated coiling temperatures on (a) strength of Ti-Mo and Nb-Mo micro alloyed HSLA steel, (b) strength of Ti-W and Nb-W micro alloyed HSLA steel, (c) average grain size of Ti-Mo, Nb-Mo, Ti-W and Nb-W micro alloyed HSLA steel, and (d) average precipitate size of Ti-Mo, Nb-Mo, Ti-W and Nb-W micro alloyed HSLA steel (Park et al., 2013).

created at elevated finishing temperature of 915 °C. Relatively lower finishing temperatures (specifically 775 and 865 °C) resulted in mixtures of ferrite, granular bainite, upper bainite and martensite phases. This means that achieving the desirable mechanical properties requires strict choice of rolling parameters above and below the T_{nr} temperature.

The unique polar climate makes it difficult to maintain adequate tensile strength in steel structures throughout the year. Special types of steel are often used as reinforcements for constructing cold resistant concrete walls in the arctic. Yan et al. (2014) investigated the mechanical behavior of normal mild steel (NMS) of different thicknesses (4 mm, 8 mm and 12 mm, respectively) and a 12 mm thick high strength steel (HSS) under typical arctic temperatures. Fig. 8 presents the plots of tensile parameters measured at different temperatures. In general, there is an increase in yield strength (Fig. 9(a)) and ultimate tensile strength (Fig. 9(b)) with reduction in temperature. However, the effect of temperature on strength was most pronounced in the NMS-4 mm and NMS-8 mm thick steels compared to the NMS-12 mm and HSS-12 mm thick steel. There is a moderate increase in elastic modulus at lower temperature, especially for the NMS (Fig. 9(c)). Also, a slight increase in fracture strain occurred at relatively lower temperatures as seen in Fig. 9(d). The statistical correlation between fracture strain and temperature is weak due to disparities in collected data. Nonetheless, these findings further validate the tendency of steel to experience brittle cleavage in extremely cold conditions.

Table 9
Variations in tensile characteristic of steel according to processing conditions and sample direction (Saastamoinen et al., 2018).

FRT (°C)	Microstructure	Condition	YS ($R_{p0.2}$, MPa)	UTS (R_m, MPa)	YS/UTS-ratio
Transverse to RD					
775	F + GB + UB	DQ	931±5	1,133±3	0.82
		DQ + T	960±2	1,017±1	0.94
865	Mainly M + minor	DQ	1,078±4	1,249±13	0.86
	UB	DQ + T	1,080±2	1,106±1	0.98
915	Mainly M	DQ	1,051±4	1,212±3	0.87
		DQ + T	1,053±5	1,092±3	0.96
Longitudinal to RD					
775	F + + GB + UB	DQ	900±26	1,118±23	0.81
		DQ + T	946±23	996±18	0.95
865	Mainly M + minor	DQ	1,041±3	1,254±6	0.83
	UB	DQ + T	1,096±7	1,100±5	1.00
915	Mainly M	DQ	1,078±6	1,212±4	0.89
		DQ + T	1,058±6	1,079±5	0.98

Where FRT-finishing rolling temperature; F-ferrite; GB- granular bainite; UB- upper bainite; M-martensite; DQ-direct quenched; T-tempered.

3.1. Effective crack arrest strategies

Assessing the brittle crack arrestability in steel has been an issue for the industry since the mid 1,900′s. Pipeline manufactures, and shipbuilders have continued to seek reliable testing methods for evaluating crack arrest properties in metals. The drop-weight tear test (DWTT) is a simplified experimental technique for determining the extent of tolerance of materials to brittle crack propagation at temperatures below zero.

Other concepts such as the temperature gradient brittle crack arrest (BCA) test has also been standardized for the purpose of determining crack behaviour. Another procedure relies on prior local embrittlement of the initiation zone to allow easy simulation of brittle crack propagation under isothermal conditions, which is the crack arrest temperature (CAT) test. Brittle crack propagation in pipelines often follows the isothermal approach. The reason being that the operating temperature plays a key role. Therefore, Sakimoto et al. (2021) compared the isothermal CAT test with the percentage shear area curve of DWTT. They found reasonable correlation with earlier pipeline burst test crack velocities, as well as agreements in terms of shear area fractions after both tests. A recent study (Nishizono et al., 2019) has proposed a less cumbersome testing method for crack arrest assessment using the single edge-notched three-point bending specimen. Since their test results did not perfectly agree with the crack arrest toughness measured from wide-plate tests, the authors introduced elastoplastic FEA to fully analyze the performance of steels. However, more experimental evaluations are required to thoroughly verify the suitability of this method on a wide range of materials.

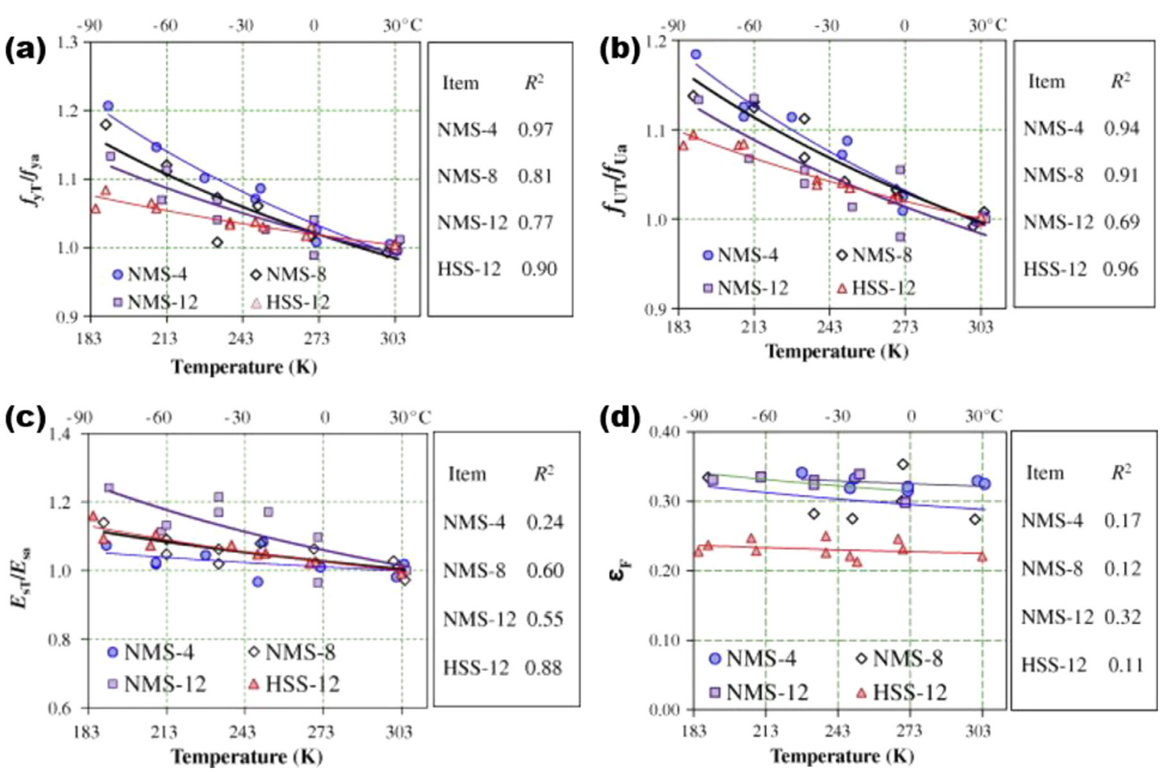

Fig. 9. Effect of low temperature on characteristics of steel (a) yield strength (b) ultimate tensile strength (c) elastic modulus and (d) fracture strain (Yan et al., 2014).

Understanding the correlation between crack initiation and arrest in large metallic structures is vital towards design life assessment. It is particularly important to ensure that pipelines can arrest fast -propagating brittle cracks. Pipelines located in cold climate often experience severe environmental (e.g., wind, wave and so on) and operational loads. Such situations may cause cracks to initiate at high-residual stress regions. For complex steels structures consisting of numerous welds that may serve as potential sites for the onset of brittle cracking, eliminating internal stress concentration is unrealistic. Instead, an alternative will be to rely on the 'crack arrest' concept (Biefer, 1981a). The authors did not find any significant correlation between high fracture or upper shelf Charpy energy and resistance against unstable brittle fracture. Hence, they recommended not to depend only on absorbed impact energy as a crack arrest property in steels. Their strategy is based on the idea that crack may occur around specific regions of high internal stresses when a pipeline is in service. In addition, recent studies (Coburn et al., 1968; Biefer, 1981b) suggest that both experimental and numerical studies aimed at predicting crack arrest in steels are based on the local stress criterion. Therefore, the stress state ahead of the crack tip is critical in determining crack propagation behavior of steels. Low temperature applications require steels with enough toughness to resist crack propagation. In an event of brittle fracture in pipelines, crack may propagate uncontrollably until total failure.

4. Steel degradation in cold climate

4.1. Weld damage in cold climate

Extremely cold temperatures pose a special challenge to welded joints in metallic materials. The steels used in arctic environment are often expected to have excellent toughness, but their welds typically degrade at low temperature. Such loss of mechanical properties is most often noticed around the heat affected zone (HAZ) (Horn et al., 2017). As service condition tend toward sub-zero temperatures steel weldments begin to lose ductility and become more brittle. Recall that large diameter pipelines have both longitudinal and girth welds. These two types of joints are susceptible to damage during service, and low temperature induced cracking remains the main reason for unexpected weld failure. Therefore, the properties of welds impact the overall low temperature toughness of the entire pipeline. The use of dissimilar welded joints to achieve the tensile property requirements of high strength steels in subzero conditions was previously reviewed (Mvola et al., 2016). The following key factors were identified for achieving prolonged welds service life: (a) heat treatment, (b) choice of electrode, (c) weld design, (d) welding process and (e) weld microstructure. Proper design of welding parameters remains crucial for the deployment of steels in low temperature conditions. The choice of electrodes should be such that ensures the optimum integrity at the joints. This means that the metallurgical structure generated in the weld zone must promote excellent tensile characteristics across the entire steel.

In general, needle-like shaped acicular ferrite structures often nucleate from austenite grains. The disorderly arrangement of interconnected acicular ferrite grains improve crack resistance and increase toughness (Zhang et al., 2012). It is known that larger austenite grains provide more intra-granular sites for acicular ferrite nucleation, whereas smaller grains mainly support bainite nucleation at the boundaries. Moreover, weld metal corrosion and/or cracking has been previously linked to joint heterogeneity (Brigham et al., 1988). The authors confirmed the key role of weld chemistry in determining the rate of corrosion. Alloying weldments with Ni and/or Cu were found to be useful in minimizing corrosive attack. Since high Ni content alloys (e.g., stainless steels) are very expensive, recent attention has shifted to the use of Mn as an alternative. The reason is that phase transformation behavior in low-Mn alloys closely resemble that of low-Ni alloys (Morris, 2013). Table 10 describes the contributions of different microalloying elements towards ductile-to-brittle transition temperature (DBTT) in the welds. A study (Hutchinson et al., 2015) used heat treatments to simulate changes in microstructure resulting from the addition of different alloying elements in the weld HAZ. They observed significant increase in toughness for V-N micro-alloyed steel with increased cooling rate. The authors linked slower cooling to high transformation temperature and ferrite grain coarsening within austenite grain boundaries. Elsewhere (Bhole et al., 2006) the effect of adding Ni and Mo to weld material in high strength low alloy line-pipe steel (i.e., API HSLA-X70) designed for low temperature application was investigated. The results indicate that impact toughness at −45 °C increased with higher acicular ferrite fraction in the weld. In addition, higher fractions of Mo facilitated even more acicular ferrite formation. Similar findings have been reported in other literatures (Kim et al., 2004; Guo et al., 2015). Altogether, the authors attributed their results to carbide precipitation, grain refinement and solid solution strengthening. They found that minimizing the amount of C while increasing Ni and Mo contents compensated for any loss in strength that may occur as a result of less C.

Also, precipitates of refined M_2C carbides contributed to improving strength and fracture toughness across weld HAZ and base material. In addition, extra caution is necessary to ensure that alloying constituents of the filler metal are beneficial towards overall mechanical properties of the weld. Overall, elevated heat input is critical in minimizing the potential risks of weld deterioration. These studies indicate the importance of applying advanced welding techniques with well controlled heat input and alloying composition to improve steel welds for low temperature applications. A summary of selected studies on the relationship between welding parameters and the weld property changes is presented in Table 11.

Table 10
Summary of the alloying elements contribution towards DBTT in welds (Mvola et al., 2016).

S/No	Weld alloying element	Description	DBTT pattern	Ref.
1	1% Ni	Enhances weld ductility at low temperature reduces weld metal corrosion	Leftward DBTT shift at −20 °C	Mvola et al. (2016); Bhole et al. (2006); Kim et al. (2004) and Guo et al. (2015)
2	Cu	Reduces weld metal corrosion	–	Brigham et al. (1988)
3	Mo	Enhances weld impact toughness at sub-zero temperatures	–	Bhole et al. (2006); Kim et al. (2004) and Guo et al. (2015)
	Mn	Enhance strength and low temperature toughness	–	
4	Al, Nb, Ti, N and V	Enhances grain refinement and increase ductility at low temperature	Leftward DBTT shift at −40 °C	Mvola et al. (2016)
5	0.1% C	Diminishes ductility at low temperature	Rightward DBTT shift at −25 °C	Mvola et al. (2016)
6	0.1% P	Diminishes ductility at low temperature	Rightward DBTT shift at −55 °C	Mvola et al. (2016)
7	0.01% N in solution	Diminishes ductility at low temperature	Rightward DBTT shift	Mvola et al. (2016)
8	0.01% O in solution	Diminishes ductility at low temperature	Rightward DBTT shift	Mvola et al. (2016)
9	Cr	Degrades impact toughness	–	Mvola et al. (2016)

N/B: V, Cr, Mo, Ni and Mo are essential constituents of any weldment designated for cold service conditions.

Table 11
Summary of selected works on the effects of welding parameters on microstructure evolution and the mechanical properties of welds.

S/No	Material	Weld reheating parameters	Weld microstructure evolution	Weld mechanical properties	Ref.
1	X70 pipeline steel	Initial heating to 1,350 °C and cooling to 150 °C simulated CGHAZ. Later samples were reheated to inter-critical temperatures of 813 °C, 838 °C and 868 °C to simulate IC–CGHAZ. The rate of heating for all thermal cycles were 200 °C/s	Contains bainitic ferrite and a mix of carbides and M/A particles. Higher inter-critical reheating temperature reduced the size and proportion of M/A constituent.	Fracture toughness at–20 °C was generally lower for IC–CGHAZ compared to the initial CGHAZ. Among the reheated steels, toughness increased slightly with temperature	Zhu et al. (2014)
2	HSLA steel	Simulated CGHAZ using continuous thermomechanical cycling. Heat input was 30 kJ/cm and	The deformed CGHAZ poses lower martensite lath size with higher precipitate fraction, while the undeformed CGHAZ larger martensite lath with reduced quantity of complex precipitates	Nano indentation at weld CGHAZ indicate higher hardness in the deformed samples compared to the undeformed ones.	Moon et al. (2011)
3	Low carbon bainitic steel	Weld thermal cycle simulations where specimens are heated quickly to 1,350 °C at a rate of 130 °C/s and held for 2 s. Cooling rate was varied to mimic different heat inputs	The microstructure consists mainly of lathe martensite and bainitic ferrite, which transformed to granular ferrite as cooling increased	–	Kong and Qiu, (2013)

N/B: CGHAZ – coarse grain heat affected zone; IC–CHAZ – Inter-critical coarse grain heat affected zone.

4.2. Environmentally assisted degradation of steel in cold regions

Metals exposed to cold climates degrade just like in other regions of the world. The only exception is that the rate of degradation and consequences of failure may differ profoundly. Other factors associated with fluctuating O_2 levels, water splashing due to tidal waves, and coating abrasion by ice slits may create aggressive conditions for corrosion at the polar regions. An overview by Perrigo (2001), identified the critical effects of external (outside the system) and internal (within the system or equipment) environments on corrosion in cold environments. For the internal factors, proper material selection, design, and inhibitor application were proposed as useful control measures. The external factors are linked to the following: (a) atmosphere around the metallic structure, (b) chemistry of the submerged environment, and (c) soil type surrounding the buried metallic structures. The application of cathodic protection and protective coatings are also helpful strategies against external material degradation. Further research is necessary to fully establish the damaging impact of cold climate on steels. However, caution is required for any construction project involving steel reinforcements in polar regions.

4.2.1. Corrosion in extreme cold climate

The common belief is that materials subjected to severe cold temperatures will corrode less than those in higher temperate regions. Moreover, the polar regions are characterized by pristine air, high winds, very low temperatures, and rain falls. The assumption is that ice sheets covering most metallic structures in cold regions can limit direct oxygen contact and surface wetness on metallic surfaces. White et al. (1983) observed lower rate of carbon steel corrosion in permafrost and a decrease in corrosion potential at reduced temperature. However, water can easily percolate underneath the ice layer and facilitate electrochemical corrosion process. This implies that the significance of environmentally induced material degradation under icy conditions cannot be overlooked. The rejection of ions from the boundaries between ice lattice and solution allows the penetration of ions that are present within the soil. Such accumulated ions will eventually provide intergranular pathways for electrochemical charge transfers to occur within the permafrost. Even at freezing arctic temperatures, salt-rich ice can cause aqueous corrosion on buried steels.

High saline content in the electrolyte limits the freezing process, thus resulting in accelerated corrosion (Morcillo et al., 2004). The author outlined typical corrosion rates observed in both arctic and antarctic zones (Table 12). This is often the case for pipelines buried under permafrost. Such pipelines tend to suffer from the downward migration of concentrated brine from the ice. It is noteworthy to mention that most economic or research activities in the arctic territories occur around waterbodies. Such locations are often characterized by either portable or chloride-enriched ice. Therefore, the exposure of metallic alloys to chloride ions from the sea/ocean can also facilitate corrosion. Timco and Weeks (2010) showed the relationship between changes in sea ice saline content and the depth of ice sheet cover. They found that corrosion trends obtained from the sub-arctic region can be misleading when compared to rates seen outside the arctic regions. For example, a recent study (Chernov et al., 2018) determined an increase of about 60% of the corrosion rate for steel exposed to sub-arctic seawater for an extended period (2–3 years), while shorter exposure time of (6–12 months) resulted in only 25% increase. An explanation for this phenomenon is in the bi-modal nature of high strength steel corrosion after several years under sub-arctic seawater conditions. Similar corrosion degradation pattern was observed in steels buried inside different kinds of soil (Petersen and Melchers, 2018). Earlier corrosion studies (Biefer, 1981a) in the Canadian arctic and sub-arctic regions showed an average rate of metal loss as low as 2 to 5 μm/year in the mainland and the islands. Other sites that are nearer to the arctic sea had higher corrosion rates of about 21 to 34 μm/year. This clearly suggest that moisture and other corrosive species inside the sea must have contributed in accelerating metal loss. Also, most field experimental works are performed over a long time in various corrosive media. Exposure trials conducted in a short time (≤ 1 year) or rapid electrochemical testing techniques are insufficient to describe the severity of corrosion damage in cold climates.

4.2.2. Hydrogen embrittlement in cold climatic conditions

The deterioration of mechanical properties is another form of steel degradation in cold environments. Steel exposed to extreme cold temperature conditions begins to accumulate structural defects that will finally diminish resistance to brittle fracture. A generalized degradation pattern for steel operating in a long-term service situation was established by Nykyforchyn et al. (2010). They identified the two main stages of pipeline steel degradation in Fig. 10(a) as: stage I - work hardening, and stage II - defect accumulation. At the initial stage of operation (≤ 20 years), there is a tendency for steel to experience increased strength

Table 12
Typical corrosion rates measured at selected test stations situated within the arctic and antarctic regions.

S/No	Exposure site	Test description	Distance from sea (km)	Corrosion rate (μm/year)	Ref.
Arctic region					
1	Norman Wells, NWT	–	–	1.43	Morcillo et al. (2004); Coburn et al. (1968); Biefer, (1981)
2	Canadian arctic interior	Test was performed with '*wire on bolt*'steel specimens. Corrosion rate values were converted to those for flat specimens according to ISO 9226	>1	1.14–3.08	
Antarctic zone					
3	Vanda	Test was performed on carbon steel containing –0.25% Cu	80	0.87	Morcillo et al. (2004); Hughes et al. (1996)
4	LGB00		120	0.70	
5	LGB10		186	0.18	
6	LGB35		780	0.13	
7	Vostok		1,200	0.05	
8	Macquarie I. Isthmus		<1	222	
9	Heard I. Spit Bay			55.3	
10	Marion I			31.9	
11	Signy			36.4	
12	Rothera (Antarctic Pen.)			27.1	
13	Mawson			3.35	

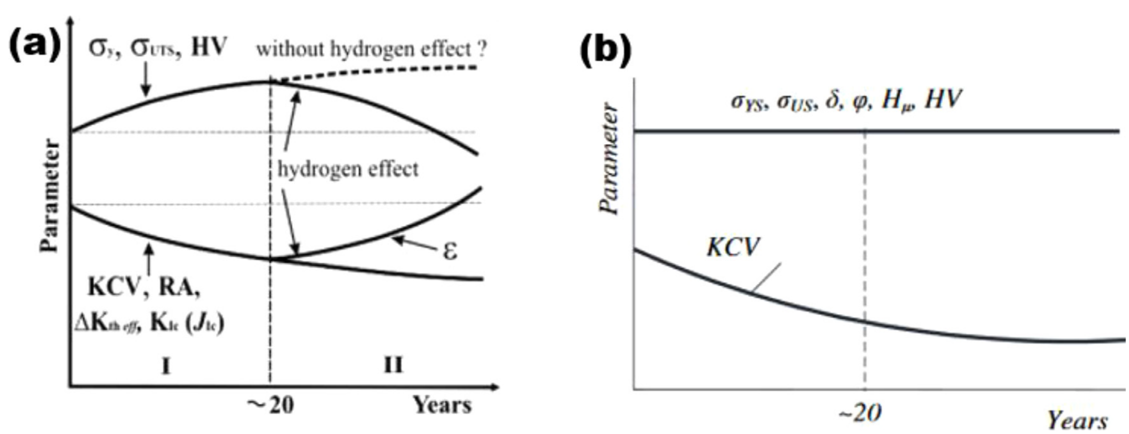

Fig. 10. Degradation pattern for pipelines in (a) temperate or climate (Nykyforchyn et al., 2010; Panin et al., 2017) versus (b) arctic zone (Panin et al., 2017).

at the detriment of plasticity. As time progresses, environmental factors such as hydrogen ingress begins to interfere with mechanical behavior of steel structures. The migration of hydrogen into the steel structure plays a role in the proliferation of defects. From stage II (Fig. 10(a)), it is obvious that the combined effect of hydrogen and stress leads to visible reduction in the lifetime of the pipeline steels. One can clearly notice the reduction in strength, plasticity, and hardness due to hydrogen. similar corrosion degradation pattern has also been seen in steels buried inside different kinds of soil. Meanwhile, strain continues to increase until failure. This confirms the mechanism of long-term metal degradation outside the arctic climate. However, it is not clear whether the failure mode described in stage II (Fig. 10(a)) can proceed without the contribution of hydrogen. Additional investigations are required to properly evaluate this situation. A separate study (Panin et al., 2017) determined the degradation pattern for pipeline steel exposed to north arctic condition over 37 years of operation. They proposed that the process of degradation under prolonged service in the arctic cold environment comprise of cementite fragmentation, carbide formation in the ferrite and finally dislocation generation. This chain of events experienced by arctic steel will ultimately result in decreased fracture toughness and subsequent failure as years go by.

5. Summary

The high risks involved in cold climate steel development has not deterred various countries from embarking on exploratory activities around polar region. Experts in this field must convince the public that their operations will consider environmental safety and create real economic benefits to the world at large. For instance, there has been unprecedented accessibility through the arctic region in recent times. The increase in economic activities around the northern hemisphere require materials that are suitable for severe low temperature applications. There are compelling reasons to develop high strength steels that can retain their mechanical properties even at sub-zero temperature conditions. Perhaps the unique characteristic of steels designated for cold environments is their ability to maintain high toughness under severe low temperatures. Carefully controlled chemical composition and thermomechanical processing parameters are essential for obtaining desirable performance in steels subjected to extreme service situation. It is important to highlight the use of Nb to limit ductile-to-brittle transition temperature in arctic steel. In addition, proper conditioning of austenite during hot rolling creates high volume of nucleation sites for the formation of small ferrite grains during transformation. These strategies could potentially improve the low temperature fracture toughness of steels designated for cold climate use.

Declaration of Competing Interest

Authors declare no conflict of interest.

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