LOW TEMPERATURE TENSILE PROPERTIES OF LINE PIPE STEELS

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Abstract: Given the expected increase in Arctic oil and gas exploitation, there is a demand for high-strength line pipe steels able to cope with the Arctic climate. The state-of-the-art of the tensile properties of API 5L steels at low temperatures is reviewed and discussed. Well-known characteristics such as an increase in strength and Young's modulus with decreasing temperatures are confirmed. The Y/T ratio is fairly unaffected by changes in temperature. Lüders elongation manifests itself at low temperatures where the Lüders plateau tends to increase. Conflicting statements about the relation between ductility and temperature were found. Altogether, quantifiable test results are scarce, especially for the high strength grades from API 5L X90 grade onwards. The urgent need for more tensile strength and ductility data of these steels at low temperatures is stated and defended.

Keywords: strength; ductility; Arctic temperatures; line pipe steel

1 INTRODUCTION

In recent years, the world has taken interest in Arctic oil and gas reserves. It is estimated that about 25 % of the global oil and gas reserves are located above the Arctic Circle [1]. The increase in energy demand and the loss of Arctic sea ice has made the exploitation of these reserves both economically and technologically feasible. More oil and gas platforms will be constructed in the Arctic in the near future, both onshore, offshore and further north, thus exposing the infrastructure to a severe environment. The harsh Arctic climate necessitates the use of materials capable of coping with all sorts of environmental factors unique to the Arctic region. Temperatures in the Arctic are known to vary from about -70 °C to 30 °C depending on the location and time of year [2]

Pipelines in particular are a key component in oil and gas infrastructure, nonetheless they are very vulnerable and failure often results in prolonged downtime. Offshore pipelines are prone to ice-gouging and onshore pipelines can cause thawing of the permafrost soil. This thawing jeopardizes the support function of the soil, resulting in the introduction of additional stresses and strains within the line pipe steel. Unforeseen operating temperatures in buried pipelines lead to thermal expansion of the pipe which is severely restricted by the surrounding soil. This causes the pipeline to arc upwards as a result of bending stresses. In worst-case scenarios, the pipeline breaks out of the topsoil where it is even more susceptible to ice-gouging. Other risks for pipelines include frost heaving and hazards that are not restricted to Arctic environments.

Not only are these phenomena capable of inducing intense stresses in the line pipe material, possibly resulting in structural failure. They can also cause unacceptable amounts of deformation, exceeding strain limits. This is especially relevant when faced with displacement controlled loads such as frost heaving or soil displacement in general. Since thousands of kilometres of pipelines are expected to be constructed in polar regions in the future, it would be advantageous to scrutinize the mechanical properties of these materials in an Arctic setting, notably at low temperatures.

The goal of this article is to investigate the state-of-the-art on the low temperature mechanical properties of high-strength steels and API 5L steels in particular. The focus is on key tensile test properties such as strength and ductility. A profound understanding of these properties and their correlation with temperature would be of great help to design engineers.

2 PUBLISHED DATA ON TENSILE PROPERTIES AT LOW TEMPERATURES

In the following sections, past research and publications on high strength steels focussing on strength and ductility at low temperatures will be reviewed and reoccurring events will be explicitly stated. Comparing these properties is, however, a precarious undertaking since test results are highly dependent on a variety of parameters. Different publications do not necessarily use the same experimental methodologies since standardisation of mechanical tests at low temperatures is often lacking. Results are also influenced by the specimen properties. This shall be discussed in detail in section 4.

Figure 1 was published by Akselsen et al. [3] in a study on the fracture toughness of X80 girth welds at low temperatures. The examined steel was API 5L X80 grade; the base material was tested at 0 °C and -60 °C using smooth round specimens with a diameter of 10 mm extracted in the axial direction of the pipe.

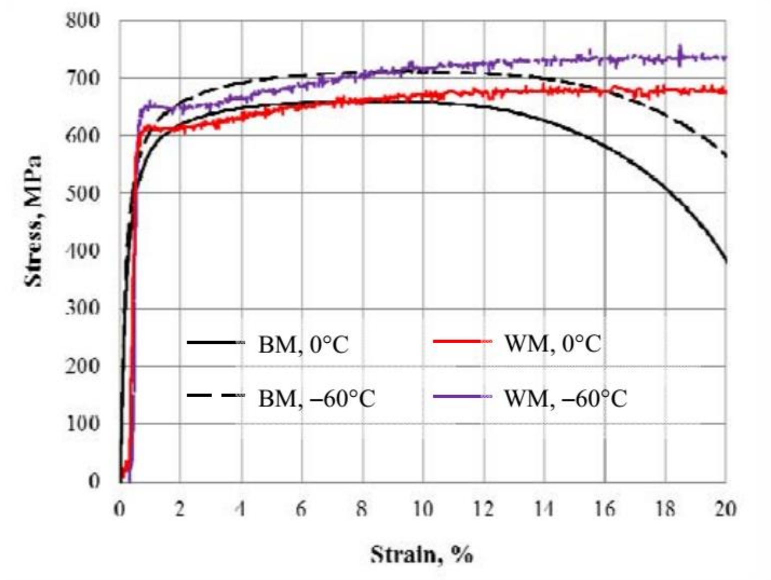
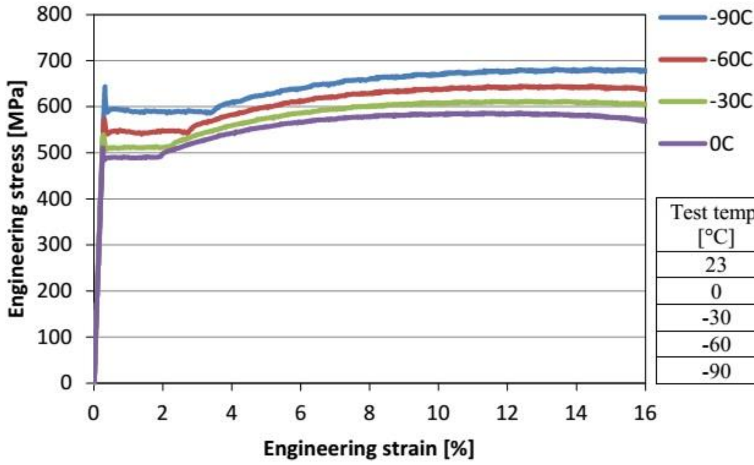


Figure 1. API 5L X80 stress-strain curves at different temperatures [3]

Explicit values of the tensile properties were not provided, nonetheless it is obvious that some of the general characteristics of low temperature material behaviour are confirmed. The rise in yield and tensile strength is very conspicuous. For the 0 °C and -60 °C tests, the yield strength is estimated to be 510 MPa and 530 MPa, respectively, using the stress at 0.5 % total strain definition. The tensile strength is estimated to be 660 MPa and 710 MPa, respectively. The uniform elongation value (uEL) increases from 8 % to 9 % when the base material is cooled from 0 °C to -60 °C. The elastic moduli are virtually identical although a negligible increase can be seen for the specimen at -60 °C. Both specimens fail in a ductile mode but the stress-strain curves do not include the fracture stress nor its corresponding strain, hence a fracture strain comparison cannot be made. It is also noticed that in both cases the base material experiences continuous yielding. [3]

Heier et al. [4] investigated the influence of pre-deformation during pipeline installation on the resistance to ductile tearing of pipeline girth welds. The API 5L X65 grade base metal was also subjected to low temperature tensile tests. These tests were performed on undeformed base material with a longitudinal cut orientation at five different temperatures ranging from 23 °C to -90 °C.



Test temp. [°C]	Longitudinal tensile test			
	$R_{p0.2}$ [Mpa]	$R_{t0.5}$ [Mpa]	R_m [Mpa]	A_{gt} [%]
23	478	480	569	11
0	490	490	587	11
-30	511	509	612	12
-60	545	547	645	14
-90	594	594	681	14

Figure 2. X65 stress-strain curves and tensile testing results at different temperatures, adapted from [4]

Figure 2 shows the stress-strain curves of specimens at various temperatures, the corresponding test results are summarised in the accompanying table.

The table shows a clear increase in the strength values for decreasing temperatures. When applying simple linear regression on the strength and temperature data, an R^2 of 0.95 can be found for the $R_{p0.2}$ values with respect to temperature. The R^2 values for $R_{t0.5}$ and R_m are 0.95 and 0.99 respectively, suggesting a possible linear relationship between strength and temperature in this particular temperature range. A significant increase of uEL from 11 % to 14 % can also be noticed at low temperatures.

The most blatant difference between the API 5L X80 (ref. figure 1), and the API 5L X65 stress-strain curves, is that the latter clearly display Lüders elongation. Figure 2 also shows that the length of the Lüders plateau increases with decreasing temperatures [4] [5]. Why a certain yielding mode manifests itself can be explained by differences in the microstructure of the line pipe steel. This is strongly influenced by processing methods during manufacturing.

A 2011 publication by Akselsen et al. [6] on the low temperature toughness in submerged arc welding of 420 MPa steel again included tensile tests on the base material at low temperature. The specified minimum yield strength (SMYS) is larger than the minimum required 415 MPa for API 5L X60. The tensile test results (ref. Table 1) at room temperature show that this steel is more akin to API 5L X70 strength-wise. This material, however, fails to qualify as any API 5L steel since the nickel content is slightly above the maximum allowable mass fraction. A comparison can be made nonetheless since all other mass fractions comply with the API 5L X70 specifications. [7]

Table 1. Mechanical properties of 420 MPa steel at room temperature (RT) and -60 °C [6]

Test temp. (°C)	Young's modulus (GPa)	$R_{p0,2}$ (MPa)	R_m (MPa)	A_5 (%)	Z (%)
RT	209	565	619	26	71
RT	209	539	604	28	73
-60°C	213	587	673	28	68
-60°C	214	631	694	26	69

The tensile samples were 50 mm long and 8 mm in diameter, and cut from a 50 mm thick plate. A slight increase in Young's modulus can be seen at -60 °C as compared to the room temperature modulus. This confirms the observation that was made earlier while analysing the stress-strain curve in figure 1. No stress-strain curve was included for the 420 MPa base material so the yielding mode is unknown. A_5 and Z are both measures for ductility and while the strain at fracture (A_5) shows no change, there is a small decrease in ductility at lower temperatures if the percentage reduction of area (Z) is considered. [6]

Comparing the results from X65 steel (ref. Figure 2) and the 420 MPa steel (ref. Table 1) that was a X70 equivalent, the following relationship could be established. Between room temperature and -60 °C, the $R_{p0.2}$ increases with 10 % and R_m rises 12 % for the X70 equivalent. For API 5L X65 (ref. Figure 2), these increments were 14 % and 13 %, respectively. Statistically insignificant given the low number of tests and difference in methodologies but it could be interesting to investigate whether higher steel grades tend to experience a relatively smaller increase in strength with decreasing temperatures.

The ductility of line pipe steels at low temperatures is a more ambiguous matter since ductility can be defined as percentage reduction in area, strain at fracture or strain at tensile strength.

Akselsen et al. [6] reported on a lower percentage reduction in area suggesting a decreased ductility whereas no significant change in ductility was measured when based on the strain at fracture.

Heier et al. [4] show an increased ductility for lower temperatures based on the strain at tensile strength definition. This is counterintuitive and probably due to the increasing Lüders plateau at decreasing temperatures. However, figure 1 demonstrates the same increase in ductility for the base material at -60 °C when the same ductility definition is applied even though it experiences continuous yielding.

Yan et al. [2] derived empirical formulas relating strength and elastic modulus of S690 steel to temperature. This construction steel is both chemically and strength-wise comparable to API 5L X100 steel. They also measured a rise in ductility. The fracture strain raised 4.5 % from 30 °C to -80 °C. It should be noted that there was a lot of scatter and the R^2 value was only 0.11 causing the relation between fracture strain and temperature to be unclear. Ehlers et al. [8] confirmed these low temperature ductility increase findings while testing an undisclosed “Arctic material” with API 5L-equivalent chemical composition.

3 TEMPERATURE CORRECTION SCHEMES

Østby et al. [9] specifically addressed the effect of low temperatures on the tensile properties of Arctic steels. They state that the effect of low temperatures on the tensile properties may be accounted for either by conducting experiments or applying correction schemes. Eq. (1) is an example of said correction scheme as proposed in the BS7448-Part 2 standard where $R_{0.2,T}$ and $R_{0.2,T,\ room}$ are the $R_{p0.2}$ values at temperature T [° C] and room temperature, respectively. According to BS7448-Part 2 [10], this equation may be used to estimate the yield strength of ferritic steel at low temperatures. Since the predominant constituent of API 5L steels is ferrite, the use of this equation is justified [11] [12] [13]. It is also noticed by Østby et al. [9] that equations such as Eq. (1) lack general validity.

$$R_{0.2,T} = R_{0.2,T,\ room} + \frac{10^5}{491+1.8T} - 189\ [MPa] \tag{1}$$

In the Arctic Materials research project, tensile tests have been performed on a wide range of high strength steel base metals (BM) and weld metals (WM) at low temperatures. The average change in yield strength and tensile strength is show in figure 3.

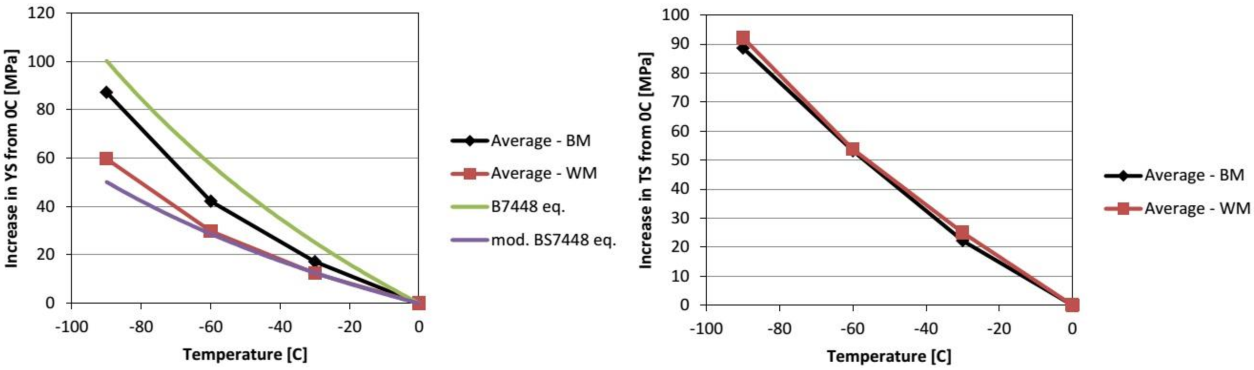


Figure 3. Average change in yield (l.) and tensile (r.) strength at low temperatures, adapted from [9]

Eq. (1) and the base metal test results in figure 3 suggest an inverse proportional relationship between temperature and the yield and tensile strengths. From 0 °C to -90 °C, an average 90 MPa increase is measured for both strengths. The curvature of the hyperbolae are rather small in the investigated temperature range making a crude linear approximation possible. This is especially true for the tensile strength and it explains why a high R^2 value of 0.99 could be found for the tensile strength with respect to temperature after applying simple linear regression on the data from figure 2. In comparison, the R^2 value for $R_{p0.2}$ was only 0.95 since this relationship seems to be less linear.

Eq. (1) was also plotted (ref. Figure 3, left, “B7448 eq.”) and it can be seen that this is an overestimation for the increase in yield strength. Østby et al [9] propose a modified equation.

$$R_{0.2,T} = R_{0.2,T,\ room} + 0.5\left(\frac{10^5}{491+1.8T}\right) - 189\ [MPa] \tag{2}$$

This modified relationship, eq. (2), has also been plotted on Figure 3 (left, “mod. BS7448 eq.”). It is recommended by Østby et al that this equation is to be used until better relations are developed [9]. For the base material, it is obvious that Eq. (1) is a better approximation although it is an overestimation of the real yield strength.

Figure 4 compares Eq. (1) with the data from other publications. It plots the increase in yield strength with respect to the yield strength at room temperature in function of the temperature decrease from room temperature. The data from figure 1 was not included since no room temperature strengths nor data tables were provided for the X80 grade material. It can be seen that Eq. (1) is reasonably accurate to predict the yield strength increase of the X65 grade steel. Eq. (1) predicts a rise in yield strength from 478 MPa at room temperature to about 518 MPa at -30 °C. The measured yield strength is 511 MPa at -30 °C. Less data points for the 420 MPa steel (X70 grade equivalent) were available but at -60 °C, a significant error can be observed for this material.

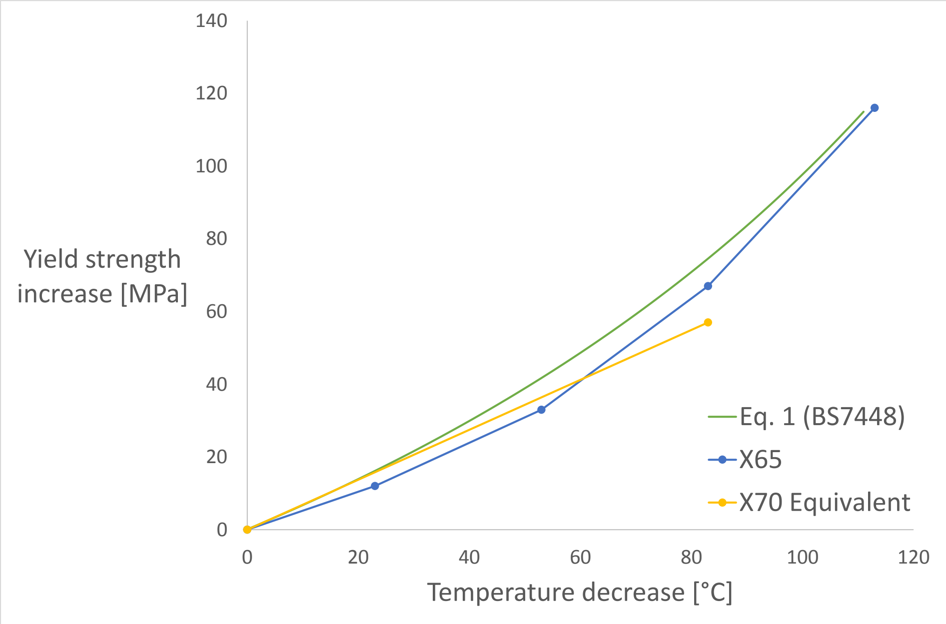


Figure 4. Comparison of Eq. (1) with data from table 1 and figure 2

Eq. (3) is one of the empirical equations derived by Yan et al. [2] as mentioned in section 2. It estimates the yield strength at low temperatures in function of the temperature T [K] and the yield strength at room temperature [MPa] for S690 steel, which is an X100 grade equivalent.

$$R_{0.2,T} = 2.21 * T^{-0.139} . R_{0.2,T,\ room}\ [MPa] \tag{3}$$

Figure 5 uses Eq.(3) to plot predictions for the yield strength in function of the temperature decrease from room temperature. It compares the X65 grade and X70 grade equivalent experimental data with their corresponding predictions. The error for both predictions increases as the temperature drops and the error is much larger than in figure 4. Eq. (3) is therefore not suited to predict the yield strength of these relatively low grade steels at low temperatures. It is unclear if it would provide a better prediction for experimental high (≥X90) grade data at low temperatures since no such data could be found.

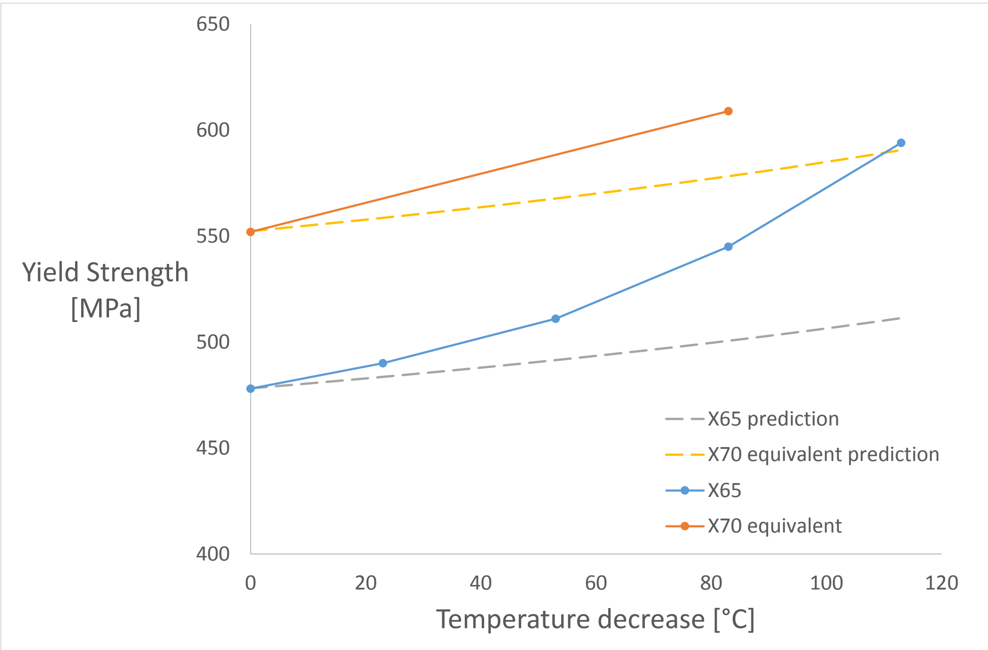


Figure 5. Comparison of Eq. (3) with data from table 1 and figure 2

4 DISCUSSION

Quantitative comparisons made between test results within a single publication are reasonable but relating them with other publications' results as done in section 2 should always be done with caution.

For example, Klein et al. [14] discussed the tensile properties of API X100 line pipe steel at room temperature and demonstrated that results are highly dependent on specimen size and geometry, sampling location and heat treatments. Li et al. [15] conducted a similar research but focussed extensively on the effects of heat treatment. Results are also affected by the lack of consistent assessment methods. For instance, API 5L suggests that the yield strength is to be determined as $R_{t0.5}$ for steel grades up to grade X90, and $R_{p0.2}$ is to be used for grades X100 and up whereas CSA Z245.1 recommends that $R_{p0.2}$ should be used only for grades higher than grade X100. Even the specimen geometry and size is open to discussion, depending on the standard.

The yield strength tends to be lower for strap specimens than for round specimens when cut transverse to the pipe axis (ref. Figure 6, left). This is caused by the common practice of flattening the straps. This effect increases for higher steel grades and for aged specimens. It can be noted that the tensile strength is relatively unaffected. When cut longitudinal to the pipe axis, the yield strength of the flat test piece is slightly higher with respect to the round specimen yield strength (ref. Figure 6, right) due to the shape difference itself and the fact that longitudinal cut straps are often not flattened. Klein et al. also observed that the total elongation at fracture is greater for strap specimens than for round specimens for both cut orientations while the uniform elongations are about the same. [14] [15]

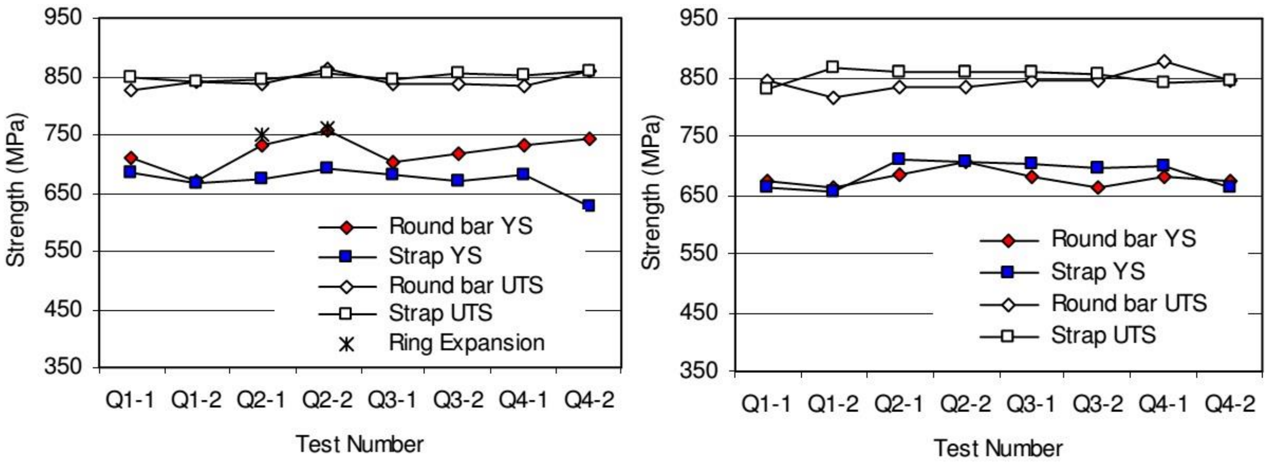


Figure 6. Effects of specimen geometry on strength for TPA (l.) and LPA (r.), adapted from [14]

The yield and tensile strength generally decrease for smaller specimens, regardless of the cut orientation, since small specimen preparation requires the removal of the superficial fine-grained structure [15].

The reviewed publications confirm each other's findings regarding strength at low temperatures. They also show that specimens with a certain yielding mode at room temperature exhibit an identical yielding mode at lower temperatures. The yielding mode is determined by the chemical composition and processing methods since these affect the microstructure of the steel. Han et al. [16] and Fragiel et al. [11] discuss this matter in detail. Comparing the findings of Akselsen et al. (ref. Figure 1) and Heier et al. (ref. Figure 2), a similar chemical composition of both steels was determined. The X65 and X80 grades carbon weight percentages were 0.10 % and 0.07 %, respectively. The most important distinction on a chemical composition level is that X80 grade contains more manganese. which is known to form inclusions with sulphur, giving rise to a ductility reduction [11].

The yielding mode is, however, more affected by the processing methods. Different processing methods lead to different microstructures and it is known that the phase constituents of the microstructure influences the shape of the stress-strain curve considerably [15]. This particular X65 grade was quenched and tempered whereas no heat treatment was specified for the X80 specimens [3] [4].

Horn et al. [17] discussed robust material qualifications for Arctic applications. They also commented on the tensile properties results in the Arctic Materials project as summarised in figure 3. The observation was made that the yield strength increases less than the tensile strength with decreasing temperatures while the Y/T ratios remained constant for rolled plates regardless of temperature. Østby et al [9] also mention that the Lüders plateau increases with decreasing temperatures, confirming an earlier observation in this article.

The influence of low temperatures on ductility is unclear, as contradicting test results have been published. The expected decrease in ductility for decreasing temperatures is the prevalent conclusion but counterintuitive results are also available. Extensive testing to measure the same ductility determinants over a wide range of materials and temperatures would be advisable.

Davis [5] points out the lack of low temperature engineering data and its resulting need for low temperature testing. To quote Østby et al. [9]: *There is a need to develop a better general understanding of how reduction in temperature affects all aspects of the stress-strain behaviour*. Akselsen et al. [3] also mention the limited amount of data available from low temperature testing. Not only do these tests determine the strength and ductility properties, the shape of the stress-strain curve is also essential for fracture toughness assessment. Østby et al. [9] and Horn et al. [17] showed how Lüders elongation exhibits a larger crack driving force than roundhouse elongation after the onset of yielding during CTOD-tests, influencing the fracture toughness values.

Østby et al. [9] and several other publications refer to the lack of standards describing procedures for material testing and qualification, such as tensile testing, below room temperature. This is especially true for fracture toughness assessment, however, for tensile testing at low temperatures the ISO 15579:2000 standard is available. The ISO 6892-3 standard shall revise this norm and is as of January 2015 in its publication stage.

5 CONCLUSIONS

To the authors' knowledge, no publication with the sole focus on the tensile properties of API 5L steels at low temperatures is currently available. General low temperature behaviour such as the increase in strength and Young's modulus are well known. However, detailed quantifiable results of these characteristics are lacking.

There is limited published data available on the tensile properties of low-grade (≤X80) API 5L steel, most commonly conducted within the context of publications concerning fracture or notch toughness assessment. These publications rarely include comprehensive data sets. Both low temperature stress-strain curves and explicit results are scarce and low temperature tensile tests on grade X90 and above have not been found.

Several attempts have been made to devise correction schemes for tensile properties with limited success, accuracy and validity. More data is needed to verify these schemes and/or to improve them.

The limited data that is available confirms the expected rise in material strength at low temperatures. Unexpected trends have also been observed such as the counterintuitive rise in ductility at low temperatures by some definitions.

The combination of the lack of available knowledge, the extensive need for the low temperature tensile data of line pipe steels and of the now available framework provided by ISO standards justifies further research on the subject. The trend towards more Arctic oil and gas exploitation and the increasing application of high grade line pipe steels makes the study of X90 and X100 low temperature stress-strain behaviour most urgent.

6 NOMENCLATURE

R_p	proof strength, non-proportional	MPa
$R_{p0.2}$	0.2 % offset yield strength	MPa
R_t	proof strength, total extension	MPa
$R_{t0.5}$	stress to achieve 0.5 % strain	MPa
uEl	uniform elongation value	[%]
A_5	strain at fracture	[%]
Z	percentage reduction in area	[%]
R^2	coefficient of determination	[-]

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