Weldability of Niobium-Containing High-Strength Steel for Pipelines

The investigated steels showed no tendency to cold cracking in the heat-affected zone, even with low heat input

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ABSTRACT

The presented study contains an assessment of weldability based on careful investigation of two niobium-containing industrial steel grades X70 and X80, with 0.056 and 0.094% Nb, respectively. Characteristics of their resistance to brittle fracture in the heat-affected zone (HAZ) were evaluated on simulated samples after rapid heating to high temperature followed by cooling at various rates corresponding to different heat inputs. As shown, the HAZ of both investigated steels ensure performance down to –30°C in submerged arc welded thick-walled pipes welded with high heat input. Investigations of phase transformations at cooling from 1300°C and microhardness measurements have shown that investigated steels with Nb content up to ~0.1% do not have a tendency for cold cracking in the HAZ during welding, even with very low heat input.

Introduction

The high working pressure of modern gas pipelines up to 100–120 MPa require high-impact toughness [Charpy V-notch (CVN)] of the material (at least 180–250 J/cm^2) at relatively low temperatures down to –20° to –40°C, depending on the specifications for the pipelines. Designed steel grades actually have higher CVN values; however, the most critical area of pipelines is the weld heat-affected zone (HAZ). The HAZ undergoes recrystallization, grain growth, followed by (at cooling) a large scope of austenite transformation, thus destroying the attractive thermomechanical-controlled processing (TMCP) microstructure, and often is the site of the lowest fracture resistance.

The microstructure of high-strength low-alloy (HSLA) steels depends on the steel composition and thermomechanical processing route. With the recent trend toward lower carbon (C) contents, niobium's (Nb) effect on transformation behavior has been noted with the emergence of acicular or bainitic steels. Under certain conditions, such as utilizing low interstitial contents and high austenitizing temperatures, small Nb additions increase hardenability by depressing the A_{r3} transformation temperature.

Microalloying with Nb is an integral part of the composition of modern high-strength steels for pipelines because of its significant and simultaneous effects on retardation of recrystallizaton, precipitation hardening, and hardenability of austenite facilitating the formation of a grain-refined structure of favorable acicular ferrite/bainitic ferrite and contributing substantially to the strength of low-C steels (Ref. 1).

At the same time, there is considerable disagreement on the effect of Nb on HAZ toughness. Some controversy exists in the literature concerning the influence of Nb on HAZ properties under certain conditions that is discussed by pipeline construction companies and steel producers.

In the study of the effect of Nb in the presence of nickel (Ni), chromium (Cr), vanadium (V), and molybdenum (Mo), it has been shown that the microalloying Nb steels with V and Mo leads to embrittlement of the HAZ (Ref. 2). Negative effect of joint microalloying pipeline steels by V and Nb was also noted in other studies (Refs. 3, 4).

In a study performed at heat inputs ranging from 1.5 to 6 kJ/mm using steel with various C contents, it was shown that Nb additions can have a detrimental or beneficial effect at low heat inputs, depending on the C level (Ref. 5). Investigating HAZ embrittlement in Nb-containing C-Mn steels, it was shown that 1) C content dominates in the control of the toughness properties and is particularly detrimental to HAZ toughness at higher C levels (0.19% C) in combination with Nb; 2) Nb does not have a significant effect on HAZ toughness at low C levels (0.06% C) at high welding heat inputs up to 6 kJ/mm; 3) good toughness properties can be obtained at intermediate C levels of 0.12% with intermediate to high Nb additions at lower heat inputs in the range 1.5 to 3 kJ/mm; 4) high C levels (0.19% C) combined with a low heat input result in the formation of untempered brittle martensite and lower bainite with poor toughness properties regardless of Nb content.

Numerous publications have discussed the effect of Nb addition on the properties and microstructure of the HAZ in low-C microalloyed steels. Niobium is reported to be beneficial as it expands the nonrecrystallization temperature range, which is useful not only for plate rolling, but because it increases hardenability, which, in turn, leads to retardation of the grain boundary ferrite network, thus enhancing intragranular ferrite formation in low-heat-input HAZ (e.g., Ref. 6). The positive effect of Nb was found in another study, where it was noted that at higher C contents Nb facilitates the formation of carbides, decreasing the martensite-austenite (MA) fraction (Ref. 7).

Other works reported that the increase in the hardenability by Nb enhances not only the Widmanstätten ferrite and upper bainite but also MA formation in the re-

KEYWORDS

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Weldability Testing
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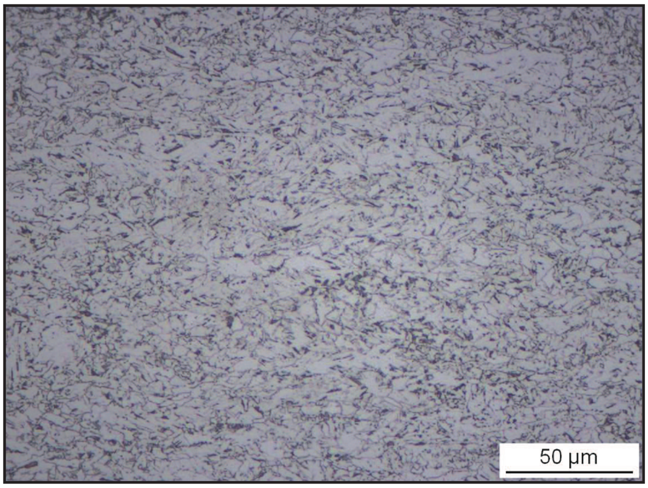

Fig. 1 — Microstructure of the X80 base metal (250×).

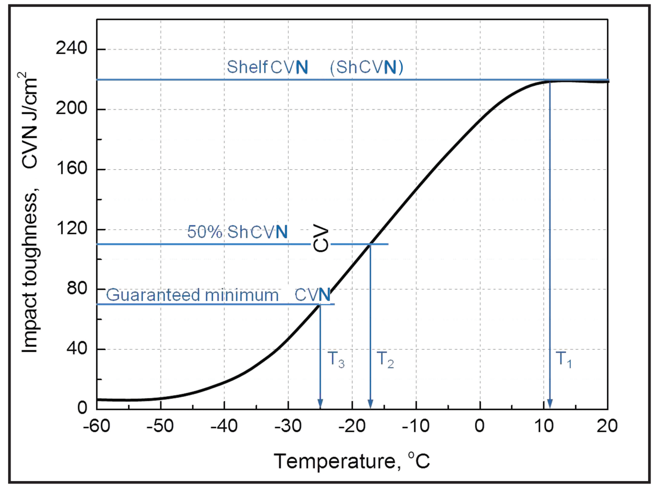

Fig. 2 — The proposed criteria for brittle fracture resistance.

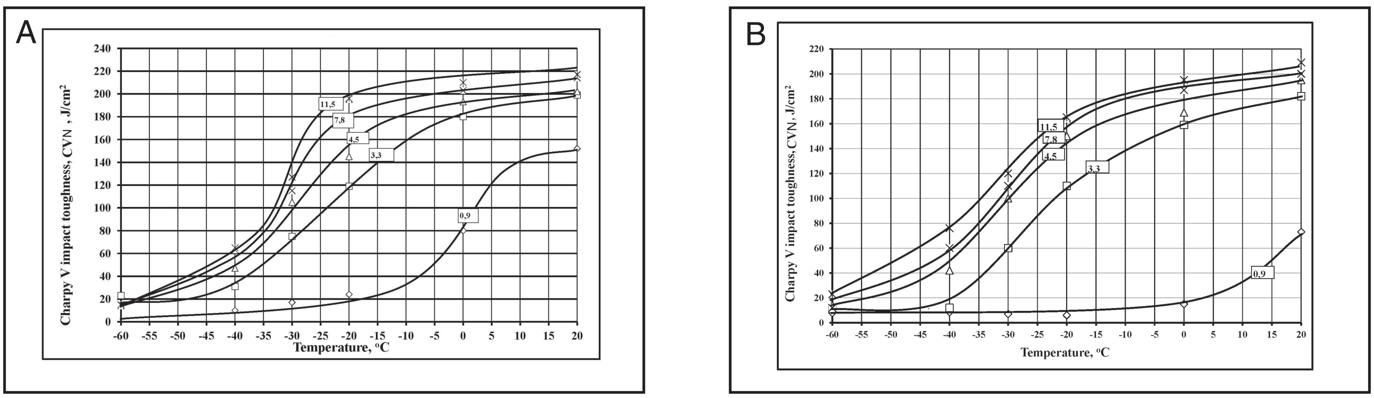

Fig. 3 — The temperature dependence of the impact toughness in the HAZ of the following: A — X70; B — X80 grade steels depending on the cooling rate (shown on the curves), corresponding to a different heat input at welding.

heated region. Some researchers pointed out a linear increase in MA with an increase in Nb content, but this effect has been found at rather high C content (Ref. 8). The corresponding hardness increase was attributed to precipitation of fine Nb(C, N) formed at cooling after the redissolution of Nb (Ref. 5).

An investigation of the HAZ microstructures of two steels with 0.04% C and 0.07–0.10% Nb showed no difference in the prior austenitic grain size and, consequently, in the local hardenability. On the other hand, Nb reduced the size of the bainitic packet in the HAZ leading to an improvement in impact toughness (Ref. 9).

Some researchers found that a small addition of Nb decreases toughness (Ref. 10), while others found either no significant effect of Nb addition in the case of low-C steels (Ref. 11) or increased toughness in very low C (~0.03%) steel (Ref. 12). The importance of very low C to ensure high HAZ toughness in two-pass submerged arc welds is emphasized in a few studies together with confirmation of the fact that without microalloying by Nb the strength of X80 cannot be achieved (Ref. 13). An investigation of coarse-grained HAZ of X80 grade steel with ~0.1% Nb using simulation of a single welding thermal cycle came to the conclusion that the heat input should be less than 30 kJ/cm to ensure good Charpy impact toughness (Ref. 14).

As is well known, all properties including impact toughness are defined by the microstructure. Therefore, all discussions and differences of opinion about the role of Nb, which was often overshadowed or mixed with the dominating roles of C and Mn or Mo content, should be related to

Table 1 — Chemical Composition of the Investigated Steels

Grade	Chemical Composition (%)								
	C	Si	Mn	S	P	Al	Ti	N_2	Ca
X-70	0.05	0.33	1.73	0.0005	0.006	0.033	0.013	0.0051	0.0002
	Nb	V	Mo	Cr	Ni	Cu	B		
	0.056	0.001	0.002	0.17	0.012	0.014	0.0002		
	C	Si	Mn	S	P	Al	Ti	N_2	Ca
X-80	0.06	0.30	1.56	0.002	0.014	0.037	0.014	0.004	0.0026
	Nb	V	Mo	Cr	Ni	Cu	B		
	0.094	0.002	0.01	0.23	0.13	0.24	—		

Notes: H70 (HSLA) is the steel for offshore application in accordance with Standards Det Norske Veritas (DNV) Offshore Standard OS-F101, *Submarine Pipeline Systems*.
X80 (HSLA) is the steel for the Cheyenne Plains Pipeline, U.S.A.

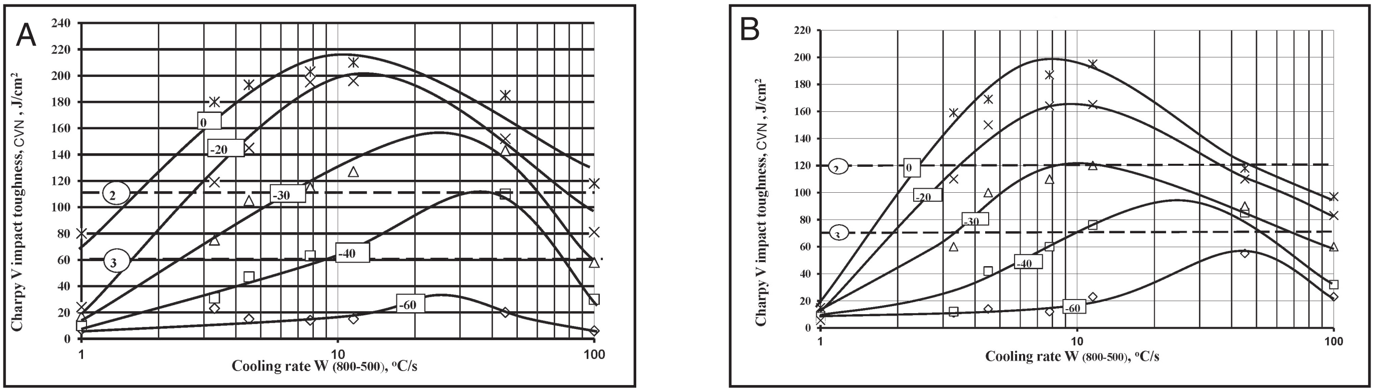

Fig. 4 — The impact of toughness of steel in the HAZ of A — X70; B — X80 at different temperatures of testing vs. the applied cooling rate ($W_{800/500}$): 2 — the line of the average brittleness threshold (T50 CVN); 3 — the line of specified minimum toughness (here 70 J/cm²).

the role of Nb in specific steel compositions on parameters of phase transformation of overheated austenite at specified cooling conditions, defined by specific heat input. In fact, there is a lack of data correlating the thermal conditions of the HAZ, in particular for multipass welding, with Nb effect on phase transformation at corresponding cooling rate.

Thus, the presented study of two high-Nb-containing pipeline steels aims to characterize not only the impact toughness of the simulated HAZ as a function of temperature and a wide range of heat inputs, including two-pass and multipass welding, but also to investigate phase transformations of coarse-grained austenite at various cooling rates as well as the type/microhardness of the obtained structure.

Materials and Methods of Investigation

Material. Investigation of weldability in the current study was carried out on samples of steels with strength of the X70 to X80 classes corresponding to the requirements of Russian and international standards, whose compositions and tensile properties are shown in Tables 1 and 2. Sample thicknesses for steel grades X70 and X80 were, respectively, 25.4 and 16.4 mm.

The low-C steel investigated contained 1.62–1.75% Mn, no V or Mo, and Nb microalloyed in the range of 0.06 to 0.10%. Sulfur (S), and phosphorus (P), aluminum (Al), and titanium (Ti), as well as calcium (Ca) and trace elements, are not significantly different in those two grades: 0.0007–0.001% S; 0.006–0.0013% P; 0.02–0.04% Al; 0.012–0.026% Ti; 0.004–0.006% N_2; 0.0012–0.0015% Ca; 0.0002% boron (B); 0.004–0.005% tin (Sn); 0.000% arsenic (As); 0.05–0.10% copper (Cu); 0.001% cobalt (Co); and 0.003% lead (Pb).

Figure 1 shows an example of the grade X80 steel base metal microstructure.

Simulation of welding. With all existing varieties of evaluation of weldability, the final assessment of the suitability of pipe steels for use in specific conditions is accomplished by testing the impact toughness of the welds. As is well known, the coarse-grained HAZ (CGHAZ) undergoes heating to 1300°–1320°C and therefore has the most reduced, in comparison with the base metal, impact toughness, but a direct investigation of its properties with the necessary localization of fracture in the site of the HAZ is difficult. Simulation of various heat inputs in the current study was implemented by varying the applied cooling rates to samples heated at high heating rates up to 1300°–1320°C, as is widely used in modern studies (Refs. 3, 14). In comparison with those studies, where a Gleeble was used, the authors of this work applied contactless induction heating to samples with the same capability to simulate a real welding process and obtain dilatometric data at cooling. This method allowing the assessment of weldability criteria and investigations of phase transformation in the HAZ based on simulation of thermal welding processes within tubular steels has been developed by the I. P. Bardin Central Research Institute of Ferrous Metals and actively used for more than two decades.The samples for subsequent mechanical testing were subjected to heating and cooling, using thermal cycles that corresponded to typical welding conditions adopted during the manufacture of pipes, as well as in the construction of pipelines. For simulation of the submerged arc welding (SAW) process, when the cooling rate is less than 10°C/s, 10 × 10-mm samples were used. For multipass welding with low heat input and therefore high cooling rates, 5 × 10-mm samples were applied to reduce the temperature gradient over the cross section of the blanks. For normalizing Charpy toughness values, the converting factor of 0.65 was used for smaller samples, which has been established by comparing the experimental results of the impact tests of subsized and traditional full-size Charpy samples of compared steels.

Thermal simulation facilitates not only the investigation of impact toughness and hardness of the HAZ, but also the morphology of microstructures corresponding to specific welding conditions.

In the process of manufacturing pipelines, various types of welding are used including two-pass SAW during pipe production and multipass shielded metal arc (SMA) or other welding processes during the construction of gas pipelines. These welding processes are fundamentally different in terms of the welding heat input and the character of the thermal fields. Calculations of thermal fields are made using two-dimensional field equations, applied to the factory mode of welding pipes with large heat inputs, and three-dimensional ones for multipass welding of butt joints in pipes at low heat-input values.

Calculation of thermal fields and determination of cooling rates for multipass welding and two-pass SAW. Based on the theory of thermal processes (Ref. 16), the

Table 2 — Tensile Properties of Investigated Steels

Grade	Tensile Properties			
η E	$YS_{0.5}$ (MPa)	UTS (MPa)	TE (%)	$YS_{0.5}$/UTS
x-70*	551	631	32.2	0.87
x-80*	614	715	33	0.86

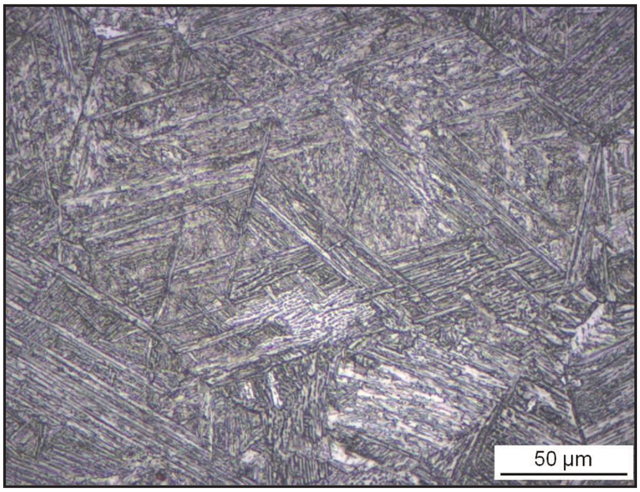

Fig. 5 — Microstructure of HAZ of multipass butt-joint welding, hot pass, preliminary temperature 100°C (250×).

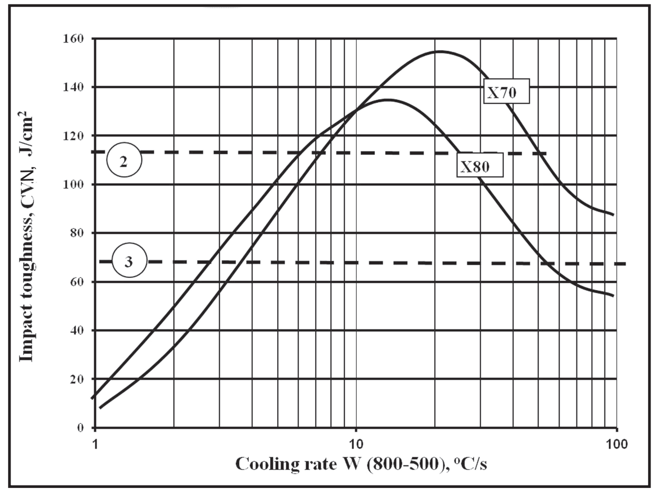

Fig. 6 — Comparison of impact toughness vs. cooling rate dependences for testing the investigated steels at –30°C.

equations of two- and three-dimensional heat-conducting paths are used to estimate the interrelation of modes of welding (heat input) and time of cooling (cooling rate) of welded connections.

In particular, calculations of a three-dimensional thermal field was applied to welding weld roots at low heat input. At a given mode of welding, there is no influence from the pipe wall thickness, d, and the equation reflects only the effect of heat input, E:

$$(t_{8/5}) = (0.67 - 5*10^{-4}*To)*\eta*E*[1:(500 - To) - 1:(800 - To)]*K_3 \quad (1)$$

During welding of pipes using SAW with a large heat input, a two-dimensional thermal zone was considered. The equation demonstrates the influence of both pipe wall thickness and the level of heat input:

$$(t_{8/5}) = (0.043 - 4.3*10^{-5}*To)*\eta^2*E^2/d^2*[1:(500 - To)]^2 - [(1:(800 - To)]^2*K_2 \quad (2)$$

Table 3 shows the symbols and designations for Equations 1 and 2. The charts as presented in Fig. 9, which are based on corresponding calculations and experiments, allow estimations of the cooling rates from the peak temperature for every specific heat input. One of the corresponding charts for multipass welding will be presented later.

During longitudinal welding with high heat input, the cooling rate of the HAZ is affected by the amount of heat input, a wall thickness, and a temperature prior to welding, meaning the temperature of the previous pass during two-pass SAW.

The calculated cooling rate values, depending on the initial temperature of the weld during two-pass SAW are presented in Table 4 for pipes with wall thicknesses of 16.4 and 25.4 mm. During welding of the external joint, each thickness requires a specific optimal level of heat input, which ensures the necessary geometric parameters of the joints. Appropriate cooling rates of the external weld were defined both for the condition of full cooling of the internal joint (20°C), and for its incomplete cooling to 60° and 100°C.

Phase transformations and microstructure. The study of phase transformations was performed using a fast operating, high-temperature dilatometer (DB-Chermet) capable of induction heating up to 1350°C at a heating rate from 10° to 300°C/s and cooling capacity with rates from 0.3° to 250°C/s. Microstuctures of dilatometric and weld-simulated samples were investigated using etching in 2% Nital and optical microscope Axiovert 40 MAT. Twelve to 15 samples were used to build each CCT diagram. The diagrams contain microhardness values against each cooling rate and corresponding product of phase transformation so those numbers can be used, in particular, for evaluation of hardness of martensite.

Evaluation of resistance to brittle fracture. The investigated steel samples were subjected to induction heating in accordance with a specific thermal cycle of welding and subsequent cooling at a wide range of cooling rates. Specimens with simulated microstructure of the HAZ were machined to cut a sharp (Charpy) notch and subjected to impact testing in the temperature range 20° to –60°C. The usual determination of the temperature of ductile to brittle fracture transition, based on area fraction of shear fracture, is practically impossible on subsized samples due to the large plastic deformation of thin samples. Therefore, the estimations of resistance to brittle fracture were based on the following set of parameters, schematically shown in Fig. 2.

• The "upper limit," corresponding to the beginning (lowest temperature) of the "shelf toughness" (ShCVN) and signifying the beginning of the transition from ductile to brittle fracture (projection "T1" in Fig. 2).

• The "average threshold" T50 ShCVN (here at ~110 J/cm²) corresponding to the decrease in impact toughness by 50% relative to the maximum (Shelf CVN) values, which corresponds to a mixed brittle-ductile fracture and, as shown by comparison with full-size samples, corresponds to 50–60% of the tear fracture pattern (projection "T2" in Fig. 2).

Table 3 — Symbols and Designations for Equations 1 and 2

Designation	Units of Measure	Parameter
$t_{8/5}$	seconds	Time of cooling from 800° to 500°C
η	Dimensionless factor	Parameter of the process effciency
E	J/sm	Heat-input (E = U*I/V)
U	Volt	Electric voltage of a welding arc
I	Amperage	Electric current of a welding arc
V	sm/s	Speed of welding
To	°C	Temperature of preheating
d	sm	Thickness of pipe wall

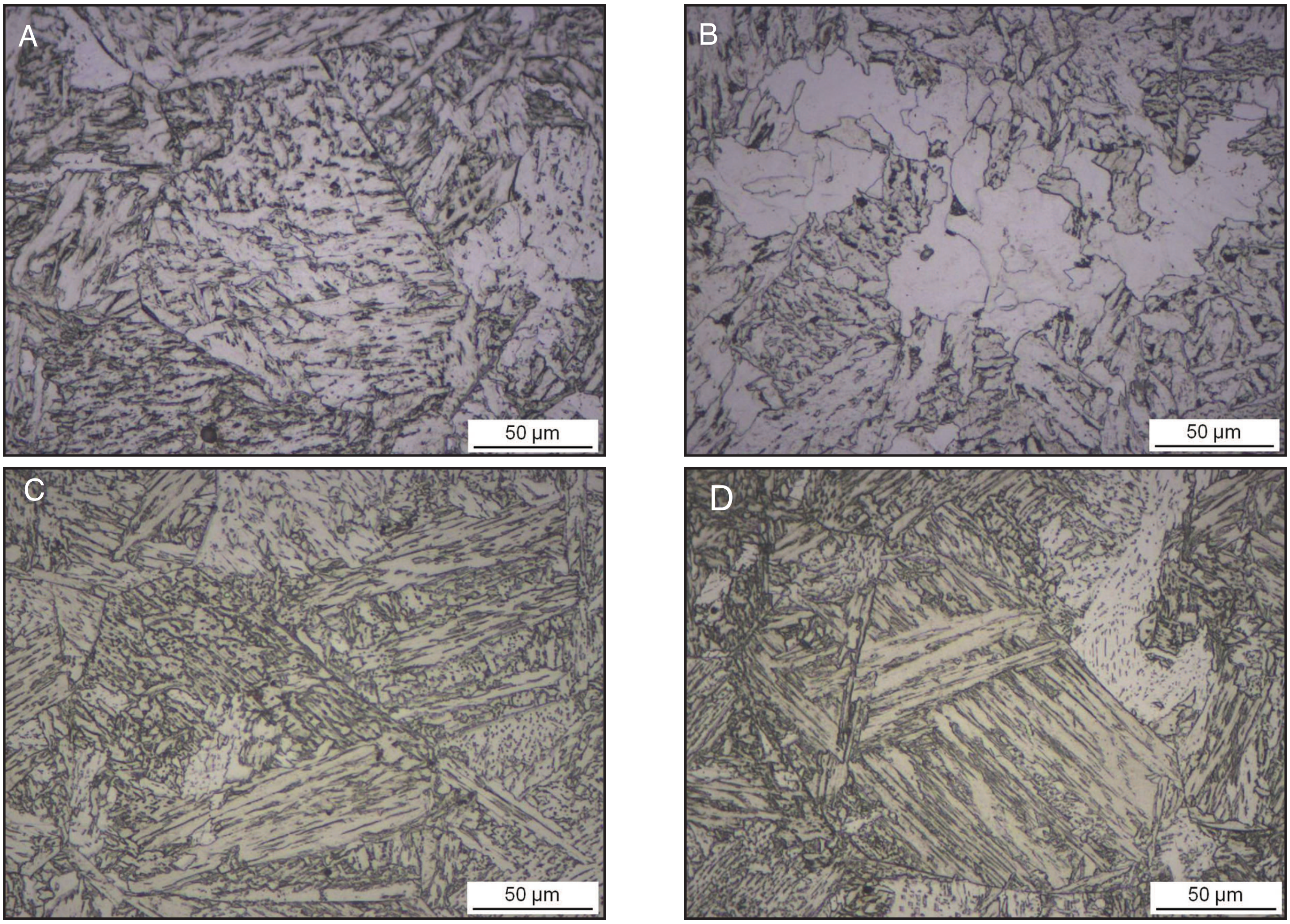

Fig. 7 — Microstructure of HAZ depending on simulated thermal conditions (250×).

• The temperature of minimum toughness required (here 70 J/cm^2), which is usually defined by specifications for gas pipes (projection T3 in Fig. 2).

Results and Discussion

Investigation of HAZ Resistance to Brittle Fracture

Evaluation of weldability of the steel containing 0.056% Nb based on T50 CVN (Fig. 3A) shows that during cooling of the external weld with a rate of 6°–8°C/s corresponding to the condition of complete precooling of the internal weld, the temperature of the average threshold ductile-brittle transition of the HAZ (here corresponding to CVN ~120 J/cm^2) is –30°C (determined for 7°C/s). For welding over the "hot" joint (with its temperature of 100°C) and accordingly for the condition of a reduced cooling rate T50 ShCVN increases only up to –20°C (determined for 3.3°C /s).

Evaluation of weldability of the steel containing 0.096% Nb by T50 CVN presented in Fig. 3B, under the same welding conditions, demonstrates that the ductile-brittle transition temperature (here, too, at CVN ~ 120 J/cm^2) is also –30°C (determined for cooling rate 7°C/s, and for welding over the "hot" joint (again at 100°C) rises also to –20°C. Thus, the increase of Nb content does not negatively impact the brittle fracture resistance of the HAZ during welding with high heat input.

The obtained experimental data were transformed to some diagrams depicted in Fig. 4. These diagrams present the CVN values vs. applied cooling rate at various temperatures of impact toughness measurements and thus allow us to define permissible ranges of cooling rates in the temperature region of phase transformations $W_{8/5}$ (cooling rate from 800° to 500°C), which may ensure a prescribed level of brittle fracture resistance of the steel in the HAZ. As shown, these curves exhibit some extremes, pointing out a maximum possible impact toughness of the HAZ. At present, this possibility cannot be implemented due to lack of technical means to control postweld cooling.

In particular, Fig. 5 presents the HAZ microstructure after simulation of multipass joint welding, the "hot pass" version. When very favorable microstructure with 100% lath bainite was obtained, bainite

Table 4 — Calculated Values of Cooling Rates, Depending on the Preliminary Temperature of the Joint during Two-Pass, SAW

Temperature of Internal Joint before Welding, T, °C	Pipe wall thickness, (mm)	
	16.4	25.4
	Heat input (E), kJ/mm	
	3.4–4.0	4.8–5.4
	Cooling rate ($W_{800/500}$) (°C/s)	
20°C	5–7	6–8
60°C	4–6	5–7
100°C	3–5	4–6

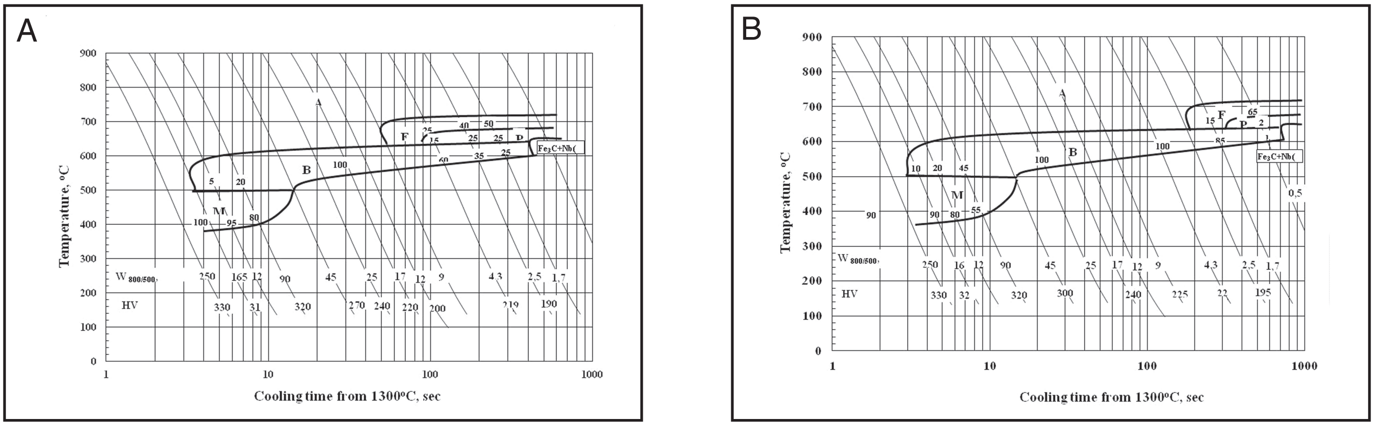

Fig. 8 — CCT diagrams of A — X70; B — X80 steel grades, built at cooling from 1300°C.

lath size is 15 microns, prior austenite grain size is 40 microns.

As shown for X70 grade (Fig. 4A), the studied composition shows a wide range of acceptable cooling rates for welding with large heat inputs, typical for factory-made longitudinal SAW, as well as with low heat inputs applied for field construction joints. Depending on the test temperature for a specific pipeline operation, the allowable range of postweld cooling rates may vary. For example, to guarantee a CVN value more than 120 J/cm^2 at –20°C, the permissible range of cooling rates is from 2.7° to 70°C/s.

It is worth noting that for field SAW at –7°C, all existing working instructions require preheating to 150°C, which means heat input should be 1.2 kJ/mm or higher to ensure a cooling rate no higher than 40°C/s.

As can be seen for X80 grade (Fig. 4B), its high Nb content shows a wide range of acceptable cooling rates for welding with both high and low heat input. Depending on the testing temperature for a specific pipeline operation, the allowable range of postweld cooling rates may vary. For example, for a guaranteed level of toughness of more than 120 J/cm^2 at –20°C, the permissible cooling rate range is from 2.7° to 40°C/s.

Figure 6 presents the comparison of those permissible ranges of cooling rates for both investigated steels for impact toughness tested at –30°C. As shown, the X70 steel with 0.056% Nb can guarantee retaining 50% ShCVN (here 115 J/cm^2) at cooling rates from 8° to 60°C/s, and the specified minimum value (here 70 J/cm^2) at cooling rates from 3.8° to more than 100°C/s. Increase in Nb content results in slight changes of those values. The toughness of 115 J/cm^2 at –30°C can be guaranteed at cooling rates from 7° to 20°C/s, whereas the level of 70 J/cm^2 can be assured at cooling rates from 3° to 70°C/s.

Microstructures obtained at various cooling rates are presented in Fig. 7. Figure 7A corresponds to the HAZ at very slow cooling and contains 50% bainite and 50% polygonal ferrite with the sizes of the bainite packet and ferrite grain of 30 and 35 microns, respectively. Figure 7B presents the microstructure of the SAW HAZ with a "hot pass" (preliminary temperature 100°C): 5% polygonal ferrite and 95% bainite, average bainite packet size is 15 microns, and prior austenite grain size (PAGS) is 70 microns. Microstructure of HAZ at SAW with a "cold pass" (20°C) is presented in Fig. 7C and contains 100% bainite of lath and globular morphology, and the bainite packet size is 10 microns and the PAGS is 60 microns. The microstructure that can ensure the highest low-temperature toughness is presented in Fig. 7D. It is 100% lath bainite with a packet size of 10 microns and PAGS of 45 microns.

Effect of Nb on the Kinetics of Austenite Transformations

The changes in impact toughness shown above reflect changes in microstructure resulting from the transformation of coarse-grained austenite in the HAZ for a specific thermal cycle. Investigations of phase transformations resulting in the building of continuous cooling transformation diagrams (CCT) were performed after the high-speed heating of dilatometer samples to a temperature of 1300°–1320°C.

As shown in Fig. 8A, B, the kinetics of austenite transformation in both steels that were investigated is featured by bainite transformations in a wide range of cooling rates. The fact that Nb promotes the formation of lower temperature transformation banite-like products at a relatively high cooling rate is noted also at comparative investigation of effects of Nb and V (Ref. 15). Martensitic transformation is observed at high enough cooling rates, but they do occur in pipeline butt joints. Niobium slightly increases the stability of austenite, so that the formation of martensite in steel containing 0.094% Nb is observed at a cooling rate of 50°C/s, compared with 70°C/s at 0.056% Nb content. This effect is small and it is necessary to note that the actual cooling, which accompanies the root welding without preheating the weld, even with a cooling rate of 90°C/s, results in the volume fraction of martensite being not more than 25% and 10%, respectively, for the 0.094% and 0.056% Nb. As can be seen from the CCT, the formation of a significant amount of (low-carbon and therefore not very hard) martensite in these steels is impossible.

Diffusion-controlled ferrite transformation is shifted, under the influence of niobium, to the slow cooling rates — up to 2.5°C/s at 0.094% Nb, and up to 4.2°/s at 0.056% Nb, i.e., toward significantly lower than the usual cooling rates during welding of thick-walled tubes under a layer of flux.

Evaluation of Tendency to Cold Cracking

During multipass welding, the HAZ cooling rate depends on the heat input and the temperature of the weld before the welding, beside the effect of the wall thickness. Processing of multipass butt-joint welding of pipelines varies depending on type of weld and heat input values as the following:

- Root weld with heat input up to 0.55 kJ/mm;
- Hot pass with heat input up to 1.2 kJ/mm;
- Facing joint with GMA (CO_2) welding with heat input up to 2.0 kJ/mm.

The diagram of cooling rates vs. heat inputs for these types of butt-joint welding is shown in Fig. 9.

Measurements of microhardness of dilatometric samples used at constructing CCT diagrams to characterize products of austenite transformations allow the evalu-

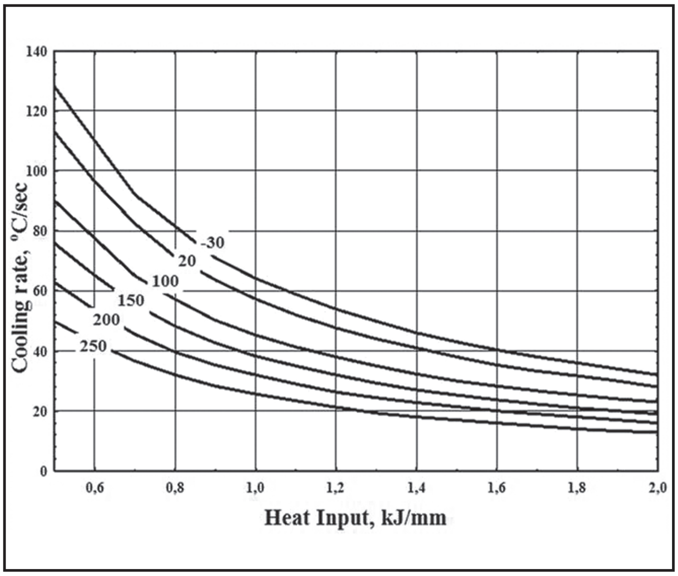

Fig. 9 — The cooling rate, depending on the heat input at multipass welding of butt joints (figures show the temperature before the next weld pass, °C), independent of pipe wall thickness.

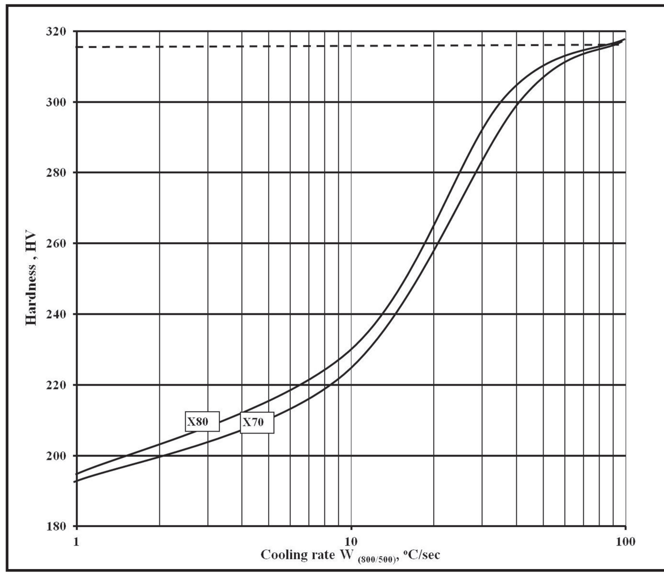

Fig. 10 — Determination of the critical cooling rate, preventing cold cracking in the HAZ, based on the maximum permissible hardness of 315 HV.

ation of the tendency to cold cracking in the HAZ during welding.

The permissible level of hardness is 315 HV, which reflects a certain amount of bainitic-martensitic mixture in the HAZ structure, is established by norms of Det Norske Veritas (DNV-OS-F101) and is applicable for welding pipes with a wall thickness of 20 mm or more. (This criterion applies to the evaluation of field joints of pipelines welded with high cooling rates, when partial quenching of HAZ site is possible in the case of increased stability of the austenite).

As shown in Fig. 10, neither steel exceeds the 315-HV limit up to cooling rate of 70°C/s. It should be noted that the increase in Nb content up to ~0.10% at medium level of Mn and small amounts of Cr did not affect the propensity to quenching of HAZ metal and thus the compositions studied are not at risk of cold cracking during welding, even with very low heat input.

Conclusions

1. Weldability assessment was performed based on careful investigations of two Nb-containing industrial steel grades of X70 and X80, respectively, with 0.056 and 0.094% Nb.

2. The resistance of the two steels to brittle fracture in the HAZ was evaluated on samples of the steels after high-temperature heating and cooling to simulate the weld thermal cycle of welded joints at different heat inputs.

3. Use of different criteria of resistance to brittle fracture including the temperature of 50% shelf impact toughness and temperature of minimum specified impact toughness (here 70 J/cm^2), have shown that the HAZ of both investigated steels ensure performance of pipelines down to 30°C in SAW of thick-walled pipes using high heat input.

4. CCT diagrams developed and measurements of microhardness of microstructures, formed by the transformation of austenite at different cooling rates from 1300°C, have shown that the investigated steels with Nb content up to ~0.1% do not have a tendency to cold cracking in the HAZ, even at very low heat input.

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