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WELDING SIMULATION FOR COMPARATIVE ANALYSIS OF STEELS FOR MAIN PIPELINES

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Abstract

Estimation of the weldability of new linepipe steels, based on the traditional carbon equivalent approach has certain shortcomings especially when considering the very low carbon contents in ultra high strength steels (X-80 and above).

The I.P. Bardin Institute has developed a new method based on analysis of continuous cooling transformation diagrams and the hardness, microstructure and CTOD properties of samples prepared in the dilatometer. Studies of a broad range of steels using the new method have shown that cold cracking resistant microstructures form over a much larger range of cooling rates when carbon contents are reduced from above 0.10 percent to 0.03 percent. This is attributed to the formation of acicular ferrite/bainite microstructures in the CGHAZ in 0.03 percent carbon steels versus ferrite – pearlite microstructures at more conventional carbon levels >0.10 percent. The SSC performance of the low carbon steels also improves at low carbon levels and bodes well for the new generation of X-80 steels in pipeline service.

Introduction

Metallurgists of Russia and the CIS have faced the challenging tasks of developing of a complex product range of pipe steels and linepipe with higher strengths and toughness.

These products are as follows:

- Pipes with diameter of 1420mm (one-seam)
- Pipes with wall thickness up to 40 mm;
- Plates and pipes of Grade X80;
- Pipes for pressures of 100 atmospheres and higher;
- Pipes with increased resistance to stress corrosion cracking.

A further complication concerning construction and maintenance conditions of new pipelines in Siberia, is the seismically active mountain regions of Transbaikalia, and offshore pipelines which result in an increase of requirements to pipes, including requirements for welded joints and strain tolerance. A critical aspect involved in development of steel is the estimation of weldability. The term "weldability" means low susceptibility to formation of weld cracks and operational reliability, i.e. sufficient resistance to brittle and ductile crack propagation at the required strength levels.

Earlier the estimation of impact toughness of welded joints was carried out using U-notch specimens on the fusion line. Now, according to new requirements of "Gazprom" and "Transneft", the main consumers of pipes, the impact toughness is estimated on both the fusion line and in the center of a joint using V-notch Charpy specimens. The impact toughness level is a minimum of 59 J/cm^2 for gas pipes and not less than 35-39 J/cm^2 for oil pipes.

This paper covers only the topic of the welding heat-affected zone (HAZ) properties and the effect of chemical composition on its structure and properties. The welding heat-affected zone includes regions with various cooling conditions. The temperature of the base metal immediately adjacent to melted zone, comes close to the melting temperature of steel, therefore the steel microstructure in this area is severely coarsened. This part of the welded joint is referred to as the grain coarsened heat-affected zone (GCHAZ).

Effect of Base Chemistry

For a description of the effect of base chemical composition of steel on susceptibility to cold cracks a series of regression equations has been developed. Carbon equivalent C_{eq} is applicable for steels, having rather high carbon content, while PCM is more applicable to modern steel grades with carbon less than 0,10%:

$$Ceq = C + Mn/6 + (Cr + Mo + V)/5 + (Cu + Ni)/15$$
$$PCM = C + Si/30 + (Mn + Cu + Cr)/20 + Mo/15 + Ni/60 + V/10 + 5B$$

Previous investigations have demonstrated that such estimation is not always sufficient or satisfactory. In I.P Bardin Institute a technique for estimation of weldability, based on welding thermal cycle simulation of GCHAZ has been developed. Furthermore in this paper the GCHAZ is referred to simply as the HAZ.

The method is based on dependences of structure and properties of the HAZ on cooling rate which is, directly connected with heat input of welding and plate thickness. This method allows one to reach the conclusions about weldability (loss of strength, susceptibility to cold cracking, impact toughness of the simulated heat-affected zone, etc.). In this method the results of investigations of phase transformation during continuous cooling are studied. A CCT-diagram for welding is produced. Microstructure, hardness and impact toughness and determination of crack tip opening displacement – CTOD are used.

Equipment and Testing

The equipment: high-speed induction heating, rapid-operating dilatometer, and cooling in an inert gases (Ar, He) stream. The reheating temperature (1300°C) corresponds to the maximum temperature in the heat-affected zone. Cooling rate is measured in the temperatures range 800-700 °C and varies from 0.6 to 350°C/s.

The type of specimens for the dilatometer hollow cylinders with an outside diameter of 6 mm and wall thickness of 1mm are used, for ductility testing and resistance to SCC 5x10x55 mm with V-notch are used.. Testing of samples with a simulated HAZ is more difficult, than testing of real welded joints since properties of the HAZ only are evaluated, without participation of other zones (or regions) of the metal less affected by welding heat input, as routinely occurs during testing of actual welded joints. For the evaluation of weldability the correspondence between simulated cooling conditions and conditions of cooling in the actual HAZ of different types of welds is used. Additionally the results of investigations of steels with different chemical composition are presented.

Results

Austenite transformation in the HAZ during welding of 0,19C-Mn-Si steel is characterized by a large region of pearlite-type transformations up to cooling rates slightly above 50^{o}C/s. The region of ferritic transformations is limited to cooling rates below 15 ^{o}C/s. The ferrite and pearlite prior austenite constituents have a coarse morphology with an unfavorable distribution of ferrite on grain boundaries. Bainitic transformation occurs in the cooling rate range of 5 - 150 $^oC/s$. Martensite appears in the structure beginning with a cooling rate of 50 $^oC/s$. The steel has a heterogeneous structure through all ranges of cooling rates, typical of all types of welding procedures, Figure 1a.

Austenite transformation in the HAZ metal during welding of a 0,1C-Mn-Nb steel is characterized by a developed pearlite region up to cooling rate of 75$^oC/s$. The region of ferritic transformations is limited to cooling rate of <20 $^oC/s$. Ferrite and pearlite also have coarse morphology with distribution of ferrite on grain boundaries. Bainitic transformation occurs in the range of cooling rates from 3 to 300$^oC/s$. Martensite appears in the structure at cooling rates higher than 85$^oC/s$. The steel has a heterogeneous structure throughout all cooling ranges, except for the narrow corridor between 70 and 90 $^oC/s$, Figure 1b.

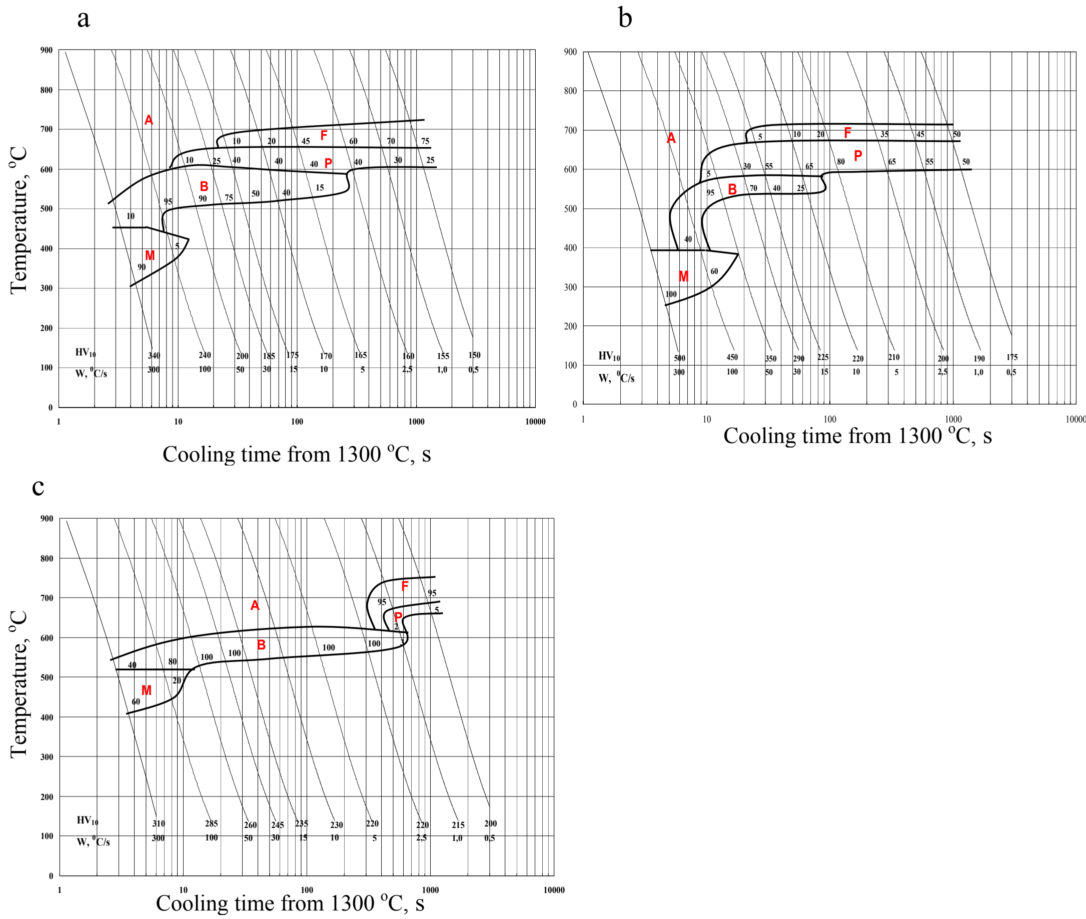

Figure 1. Welding CCT diagrams for pipe steels: (a) 0.19C-Mn-Si, (b) 0.10C-Mn-Nb, (c) 0.03C-Mn-Cr-Ni-Cu-Nb

Austenite transformation in the HAZ metal during welding of 0,03C-Mn-Cr-Ni-Cu-Nb steel differs from other tested steels due to a shifting of the ferritic transformation region to cooling rate lower than 1.5 $^oC/s$. The perlitic transformation has a very narrow temperature range and is limited to a cooling rate of 1 $^oC/s$. In this steel diffusional transformation to polygonal ferrite is almost completely suppressed for normal post-welding cooling rates. Bainitic transformation takes place in the temperature range 620 - 550 ^oC for cooling rates from 0.7 $^oC/s$ to all practically achievable cooling rates. High temperature martensitic transformation in the temperature range of 520 - 400 ^oC is observed for cooling rates above 70 $^oC/s$, Figure1c.

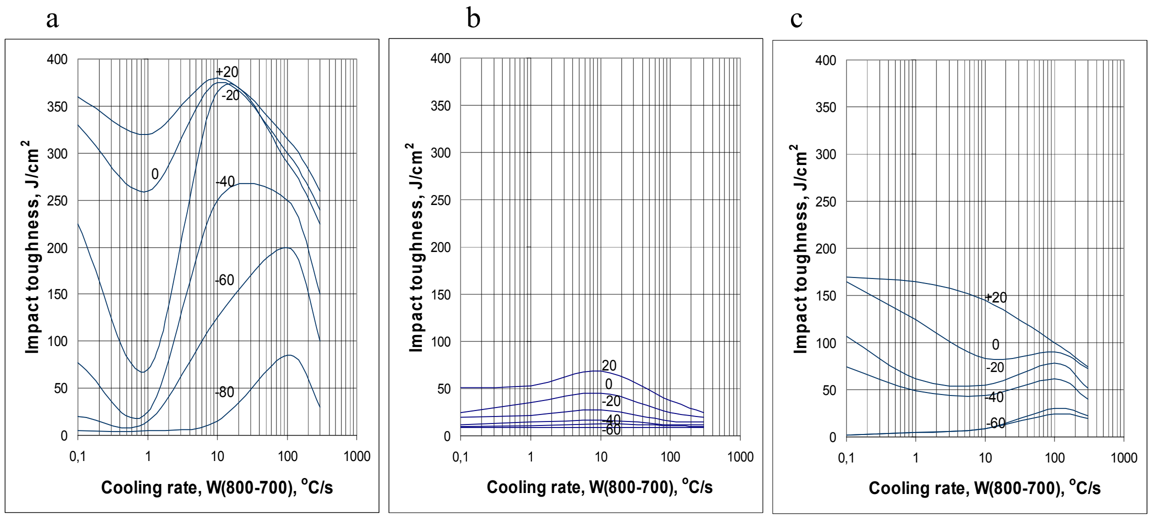

Figure. 2. HAZ toughness results of pipe steels: (a) –0.19C-Mn-Si, (b) 0.10C-Mn-Nb, (c) 0.03C-Mn-Cr-Ni-Cu-Nb

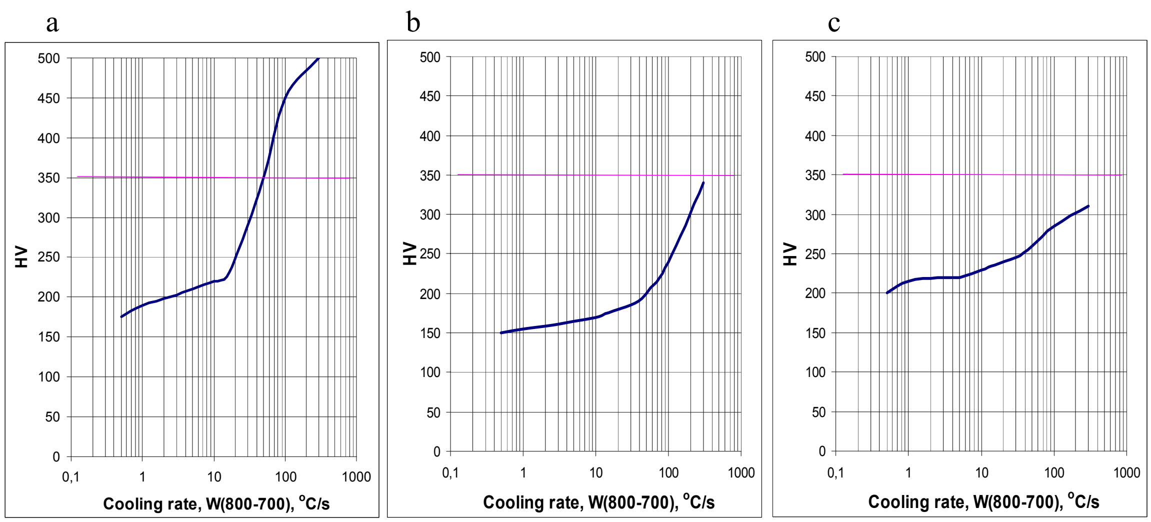

Figure. 3. HAZ hardness results of pipe steels: (a) –0.19C-Mn-Si, (b) 0.10C-Mn-Nb, (c) 0.03C-Mn-Cr-Ni-Cu-Nb

As a consequence of the high carbon content and unfavorable heterogeneous structure the HAZ of 0.19C-Mn-Si steel has insufficient Charpy impact toughness at temperatures below 0°C. Slight improvement of Charpy toughness at -20°C is achieved at cooling rates, corresponding to the automatic submerged arc welding process. The impact toughness of the HAZ of 0.10C-Mn-Nb steel is slightly higher, but still the level is rather low. The HAZ of 0.03C-Mn-Cr-Ni-Cu-Nb steel, as a consequence of favorable morphology of austenite transformation products (lath bainite, acicular ferrite), exhibits high Charpy toughness values at temperatures as low as -60 °C under all automatic submerged arc welding conditions, Figure 2.

For 0.19C-Mn-Si steel the required level of critical hardness 350 H_v10 that guarantees absence of cold cracks (hydrogen induced embrittlement) corresponds to a cooling rate of 50°C/s. The critical hardness 350HV for 0.03C-Mn-Cr-Ni-Cu-Nb steel has not been achieved at the highest cooling rates after welding even with low heat input values, Figure 3.

An important trend is development of steels with increased strength (X80 and higher). Furthermore the results of investigation of weldability of 0.05C-Mn-Mo-Ni-Cu-Nb steel are presented. At a cooling rate of 2,5˚C/s the structure, consisting of 100 percent low-carbon upper bainite.. The temperature of the bainitic transformation start is around 600˚C, and the martensitic point close to 450˚C. For the 0.05C-Mn-Mo-Ni-Cu-Nb steel the structure consisting of 100 percent of low-carbon bainite up to cooling rates of ~ 70˚C/s, at a cooling rate of 100˚C/s 85 percent of martensite and 15 percent of a bainite are observed in the structure, Figure 4.

Investigation of the structure of simulated HAZ is has shown, that at a cooling rate of 0.1˚C/s the structure is poligonal ferrite with small amounts (10-15 %) of upper bainite. At a cooling rate of 1˚C/s the structure of the steel investigated is mainly bainitic (not more than 10 % of ferrite), for further increases in cooling rate the structure consists only of bainite.

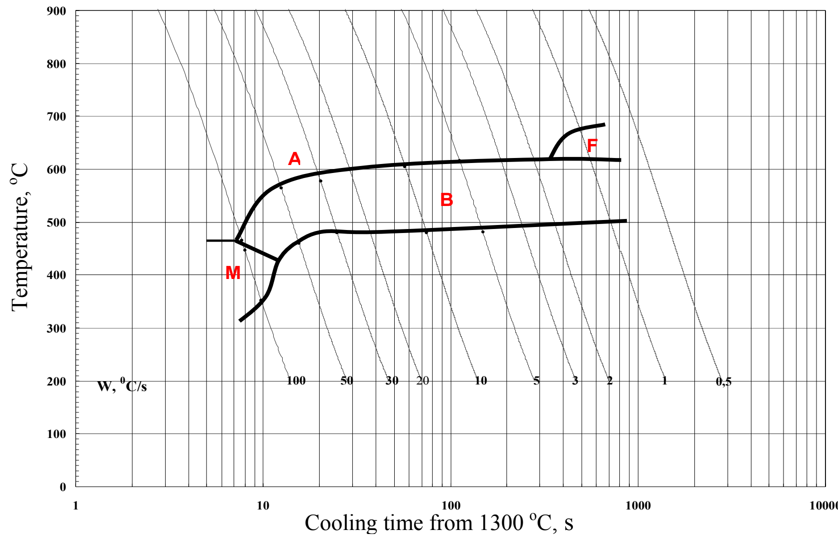

Figure 4 Welding CCT diagrams of pipe steel: 0.05C-Mn-Mo-Ni-Cu-Nb

From the results obtained it is evident, that at low cooling rates some loss of strength of the HAZ in comparison to the base metal is observed, thus at all investigated cooling rates (welding conditions) the steel is not susceptible to cold cracking in the HAZ. For all investigated cooling rates HAZ is characterized by a high level of impact toughness. The hardness of the HAZ of 0.05C-Mn-Mo-Ni-Cu-Nb steel at a maximum cooling rate of 300˚C/s is 340 Hv10 even for a 100 percent martensitic microstructure. The 0.05C-Mn-Mo-Ni-Cu-Nb steel demonstrated excellent weldability characteristics, due to the low carbon content and an optimum steel composition with the additions of molybdenum, which increased the stability of austenite in the heat affected zone, Figure 5.

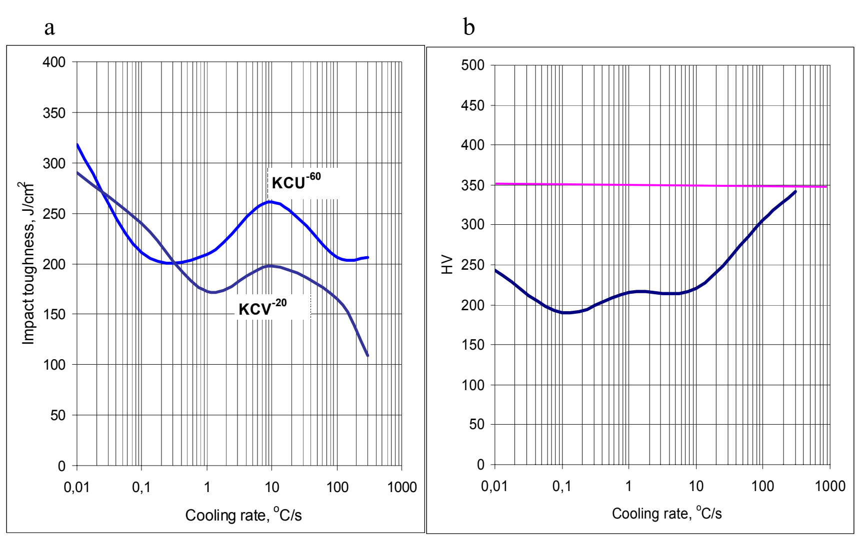

Figure5. HAZ toughness (a) and hardness (b) of steel 0.05C-Mn-Mo-Ni-Cu-Nb

If one re-draws the CCT diagrams in coordinates: "percent of structural constituent – versus cooling rate" it is possible to see clearly, that in the steels investigated the character of the phase transformation in the HAZ differs significantly. In the first steel (0.19C-Mn-Si) for all intervals of cooling rates a heterogeneous structure is observed, and in the second steel (0.05C-Mn-Mo-Ni-Cu-Nb) there is a wide range of cooling rates (from 3 to 90 ˚C/s), where a structure of low-carbon bainite is formed.

In a comparison of several steels with similar Pcm, the advantage of low carbon content both for toughness and resistance to crack formation and propagation is evident, Figure 6.

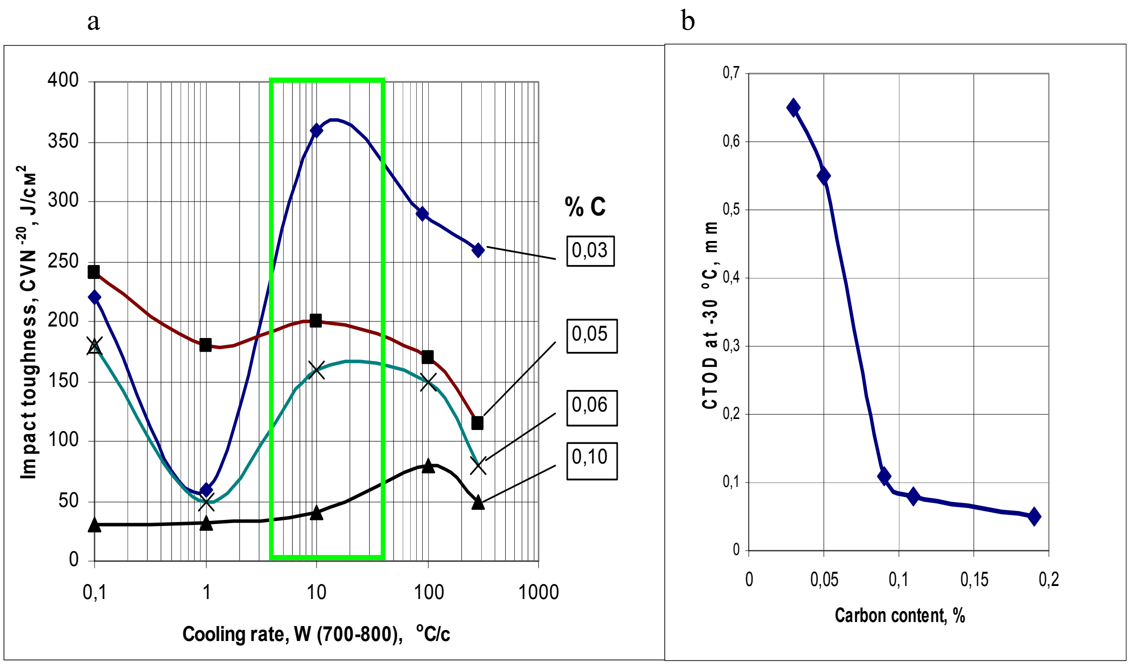

Figure 6 Effect of carbon content on toughness (a) and CTOD (b) of HAZ of pipe steels

From the observed results the following conclusions can be drawn::

1.) A decrease of carbon content from 0.19 up to 0,03 percent in high-strength low-alloyed pipe steels widens the range of favorable cooling rates (from 15 °C/s up to 300 ˚C/s) after cooling with these rates the HAZ hardness does not exceed the critical value of 350Hv10, above which the formation of cold cracks is observed.

2.) For the steels investigated a large increase in impact toughness of the HAZ is observed explained as follows :

(a) a decrease in carbon content

(b) a modification of the CCT diagram: resulting in widening of the bainite transformation region ensuring formation of a bainitic structure over a wide range of cooling rates corresponding to (different welding thermal cycles).

3.) A toughness increase in steels with structures of low-carbon acicular bainite is observed owing to the refined bainitic microstructure. The average bainite "grain" size is several times less, than the size of ferrite grains. The width of bainite laths is even less, all of this is important for the heating temperatures during welding. In contrast when ferrite-pearlite microstructures are avoided in high carbon steels and high carbon "grainular" bainite is formed the toughness practically does not improve.

4.) The correct alloy design is important for control of the shape of the CCT diagram.

5. HAZ toughness also can be improved by addition of titanium and niobium, which refine the austenite grain size. Another major factor is the ability of niobium to reduce the temperature of $\gamma+\alpha$ transformation and to increase the amount of acicular products when it remains in solid solution.

Using this simulation method our colleagues G. Filippov and O.Chevskaja also investigated the susceptibility to stress corrosion cracking (SCC) of a range of pipeline steel. Samples tested using the I.P.Bardin Institute developed technique for susceptibility to SCC for static bending in air and in low-acid (pH=5,1) corrosion media and slow strain rate. The integral fracture energy for testing in medium - $A\Sigma^{SCC}$ media is the parameter for evaluation of susceptibility of steel to SCC.

It is evident, that the heat-affected zone is a dangerous (susceptible) site from the point of view of possibility of crack nucleation under influence of stresses and corrosion medium. The fracture energy in the corrosion medium for the heat-affected zone as a whole is lower, than the base metal.

Owing to the various structural conditions of the heat-affected zone of the different steels investigated, they possess different susceptibility to SCC. The highest resistance to SCC was observed for the steel with carbon content of 0.055 percent (mainly acicular ferrite microstructure), microalloyed with niobium and having small additions of nickel and copper. The steel most susceptible to SCC appeared to be the steel with total carbon content of 0.1 percent HAZ structure consists of ferrite and coarse upper bainite.

Investigations of the phase transformation of hot-deformed austenite (reheating to 1150˚C , ε=20% at 1000˚C and ε =50 % at 850-800˚C) have shown that offered steels, having optimum shape of transformation diagram for the HAZ, are also having the favorable diagram of transformation under TMCP conditions, providing the formation a ferrite-bainite or bainite microstructures over a wide interval of cooling rates which thereby increases the stability of the production process .

Industrial Trials

Further examples of industrial trials for production of modern low-carbon niobium microalloyed steels are presented.

1.) On wide-strip mills of "Severstal" and the "MMK" steel works the trial production of low-carbon strip steels (0.04-0.06C-Mn-Mo-Nb-V and 0.04-0.06C-Mn-(Cr-Ni-Cu)-Nb-V) with strength grade X70 , with thicknesses up to 16 mm has been carried out. Spiral-welded pipes with diameter of 1220 mm have been manufactured on the Volzhsky tube plant. Thorough testing demonstrated high values of properties for base metal and the welded joints, Figure 7.

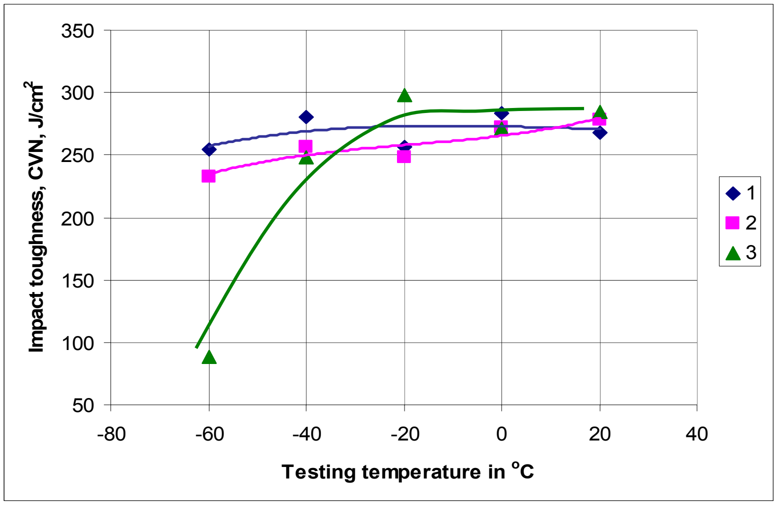

Figure 7 Impact toughness of spiral welds on fusion line (pipes with diameter of 1220mm). 1) 0.05C–Mn–0.20Ni–V – Nb , 2) 0.04C–Mn–0.30(Cr+Ni+Cu)–V–Nb , 3) 0.06C–Mn–Cr–Ni–Nb–V (Pcm = 0.17) "Severstal"

2.) Plates with thicknesses of 31-40 mm from steel 0.07C-Mn-Mo-Ni-Cu-Nb-V (Ceq=0.37) were produced on the Severstal 5000 mill using TMCP. Mechanical properties obtained corresponded to grades X65-X70, with excellent level of impact toughness. Vyksa metallurgical plant manufactured 1020 mm dia. pipes with good results for toughness of welded joints for pipes with wall thickness of 31 mm.

A comparison of results for simulated and real welded joints has been made. It has been shown, that the hardness of the base metal matches the hardness of samples subjected to deformation in the dilatometer, using a simulating controlled rolling schedule. Hardnesses of the HAZ of a real joint matches the hardness of simulated HAZ's at corresponding cooling rates. Results obtained have shown the value of using the simulation technique for weld thermal cycles.

Various alternatives for production of pipe steels with yield strength of more than 570 MPa (grade X80) have been investigated. It has been shown, that the required strengths can be achieved in various ways (e.g. TMCP in γ or $\gamma+\alpha$ area with or without accelerated cooling), for various chemical compositions of steel and with various properties of structural components (the matrix of strained ferrite with sub-grain microstructure and 10-15 % of a bainite or 50 % of ferrite and 50% of a bainite or mainly acicular ferrite). However different structures exhibit different results for impact toughness and cold resistance. The best combination of strength, toughness and cold resistance is obtained in low carbon acicular ferrite which is formed during thermomechanical rolling with subsequent accelerated cooling of 0.05C-Mn-Mo-Ni-Cu-Nb steel. Also, for this steel excellent results for weldability were obtained.

Conclusions

The method of simulation of weld thermal cycles of the heat affected zone, developed by I.P. Bardin Institute allows one to evaluate weldability of steels, by considering the phase transformations in the HAZ, estimation of strength loss and susceptibility to cold cracking plus, impact toughness and CTOD behavior.

The best properties in the HAZ are obtained in steels with structures of low-carbon bainite. The optimum shape of CCT diagram for the HAZ is one with a maximum region bainitic transformation. Such a shape is provided utilizing low carbon contents, balanced with the alloy design for the steel.

Advantages of these low-carbon steels, with correctly developed system of alloying are shown from the point of view of weldability of different steels with similar carbon equivalents but higher carbon contents.

The same steels exhibited the best resistance to stress corrosion cracking (SCC) in the HAZ.

Steel with improved weldability have been developed and tested under production conditions resulting in high values of Charpy impact toughness of the welded joint.