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Review of modern requirements for welding of pipe high-strength low-alloy steels

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ABSTRACT

For many years, proven arc welding processes have been used to weld large pipes of oil and gas pipelines, the scope of which extends from manual arc welding with stick electrodes to the use of metal orbital welding machines. **Introduction** reflects that the creation of new steel compositions for oil and gas pipelines is an urgent task to ensure its high reliability. **Research Methods.** Low-carbon steels with ferrite-perlite structure are usually used in pipe production, but these steels are unable to meet the increased market demands. New grades of steel with bainitic structure are appearing. **Results.** The failure of welded joints of pipelines made of high-quality steel is becoming a serious problem for the pipeline industry. **Discussion.** This paper analyzes the characteristics of weld microstructure and its relationship with impact toughness. The prediction of impact toughness based on the microstructural characteristics of weld-seam metals is complicated due to a large number of parameters involved. The common practice linking this property to the microstructure of the last roll of a multi-pass weld turned out to be unsatisfactory because the amount of needle ferrite, the most desirable component, may not always be the main factor affecting the impact toughness. The present review reports on the most representative study regarding the microstructural factor in the welded seam of pipe steels. It includes a summary of the most important process variables, material properties, normative rule, as well as microstructure characteristics and mechanical properties of the joints. **Conclusion.** It is intended that this review will help readers with different backgrounds, from non-specialist welders or material scientists to specialists in various industrial applications and researchers.

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Introduction

Due to the growing demand for oil and gas, pipelines made of high-quality steel are widely used in the pipeline industry. The material from which these pipes are made meets strict design requirements to withstand severe operating and environmental conditions [1, 2].

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The most common materials naturally chosen by pipe manufacturers are steel alloys due to its sufficient mechanical reliability and economic feasibility. Specifications concerning the chemical composition, mechanical properties and other important aspects such as welding, cutting, production, etc. of materials for oil and gas pipelines are determined by the *American Petroleum Institute* (*API*) [3], the *International Organization for Standardization* (*ISO*) and other national agencies [3-5]. *API* standards are commonly used by many national agencies as a reference to establish its own specifications for these materials. *API* specifications are accepted and widely used all over the world. In accordance with *API* requirements, pipeline materials are manufactured or supplied with product specification requirements: *PSL 1* and *PSL 2*.

The *PSL 1* document contains only recommendations for the carbon equivalent; there are no restrictions on the impact strength, yield strength and ultimate strength. The *PSL 2* document already prescribes mandatory values in a certain range for carbon equivalent, impact strength, yield strength and ultimate strength. Another significant difference is based on the type of pipe ends [1–3]. Knowledge of the chemical composition and mechanical properties of these pipes is necessary to understand the weldability and other aspects of welding these pipes.

Pipe steels from different manufacturers that meet the requirements for strength and ductility [1–5] may have different microstructures [1–3, 10–34]. The most common steels are those with ferrite-perlite or ferrite-bainite microstructure [10–33]. Pipes can be made in two traditional ways: cold stamping (*UOE: U-pressing, O-pressing, and expanding*) and seamless [3]. The production of pipes by cold stamping (*UOE*) tends to introduce intense deformation gradients into the sheet in different directions relative to a fixed orthogonal coordinate system during forming, with more serious gradients occur in the transverse direction [1, 2]. This affects not only the yield strength, but also the deformation hardening and subsequent instability (neck formation), which, finally, are the driving forces of the initiation and propagation of fracture.

On the other hand, the production process of seamless pipes makes it possible to obtain a product with improved mechanical properties due to heat treatment, which removes residual stresses and reduces the out-of-roundness of the final shape. Consequently, it is expected that the mechanical properties of the final product will be uniform in space and direction [1, 2, 10]. Regardless of the method of pipes production, later during the construction of the pipeline pipes are connected to each other by welding.

In recent decades, many studies of annular welds of onshore and offshore pipelines with cracks under operational load have been carried out [11, 12]. Cracks in the cup welds of pipelines made of high-quality steel are mainly located on the fusion line of the root material and in the heat-affected zone [13]. At the same time, cup welds have zones of material with different properties, such as base metal (*BM*), weld material (*WM*), root material (*RM*) and heat affected zone (*HAZ*). The heterogeneity of welded joints in geometry and material properties leads to a significant concentration of stresses and deformations in defective parts, which significantly reduces the deformation bearing capacity of welded pipe joints [13, 14].

During the welding process, the metal being welded heats is heated, the filler wire melts and a weld with a cast structure is formed, which has a transition zone to the base metal structure (*HAZ*). It is in this zone that the impact strength values decrease [14–20].

Due to the fast-flowing process of heating and melting of metal in the weld zone and the adjacent area of the base metal, *HAZ* structure with different sizes of austenitic grains is formed, with metal sections heated above and below the points A_{c1} and A_{c3}. All this leads to a decrease in the mechanical properties of the metal. Consequently, considerable efforts to study high-strength steels for pipelines have been focused on increasing the impact strength in the heat-affected zone.

The relationship between microstructure and impact strength for metals of multiple passes is very complex, since various factors can have beneficial and adverse effects depending on the material under study and its microstructural state. In addition to microstructural components, the influence of reheating, the presence of microphases and inclusions are recognized as critical factors affecting the microstructure and, consequently, the impact strength. Although little research has been conducted on the microstructure characterization of weld metals due to the aforementioned complexity, knowledge of the microstructure characteristics is critical for predicting impact strength. Thus, a more systematic study is fundamental to uncover this relationship between microstructure and strength.

This review is devoted to the analysis of works related to the evaluation of the influence of the microstructure of the weld on the impact strength, as an indicator of the sensitivity of hot-rolled pipeline steels to brittle fracture.

Steels for the pipes production

The influence of the development of production technology and micro-alloying of pipeline steel on the strength is shown in fig. 1. Low-carbon alloy steels with ferrite-pearlite structure are widely used in pipe production [27].

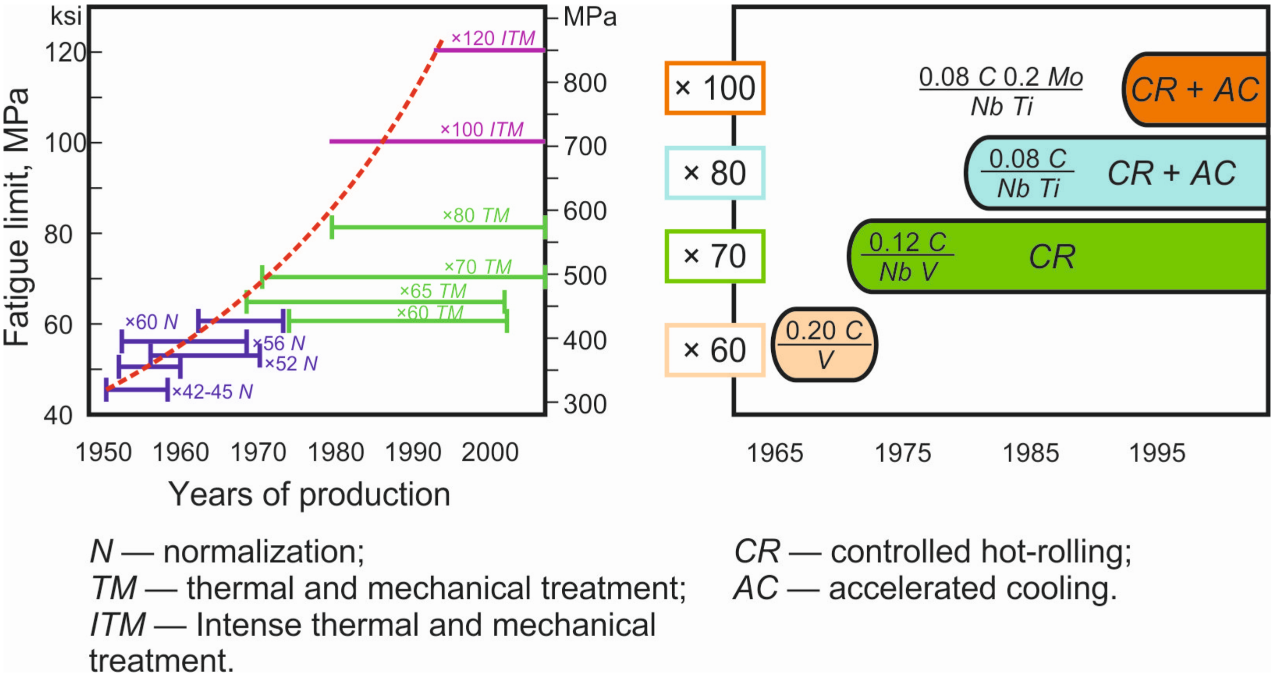


Fig. 1. Effect of development of production technology and microalloying of pipeline steel on strength

Increasing strength is a constant goal of the development of metallurgical alloys; currently more attention is paid to improving other important characteristics, such as toughness and weldability, each of which is negatively affected by the carbon content in steel. High-strength low-alloy (*HSLA*) or micro-alloyed (*MA*) steels, as it was later called [21–25], were already used at the beginning of the 20th century [23, 24]. Low-alloy steels, a much earlier defined class of steels than *MA* steels, are generally considered to contain less than 3.5 wt. % of all alloying elements and include *Cr* (0.5–2.5 %), Mo ≤ 3 % and V ≈ 1 %. High-strength low-alloy (*HSLA*) steels and the paradigm of microalloyed (*MA*) steels suggest that carbon may not be the best alloying element for making good steel [21–25].

In this context, *HSLA* steels show lower carbon content, which improves weldability and formability, but lower mechanical properties resulting from lower *C* content, which can be improved by the addition of alloying elements such as *Nb*, *Mo* and *Ti*, and an appropriate thermal and mechanical treatment. Each of these elements affects different mechanisms. On the one hand, many studies agree that *Nb* is capable of causing the accumulation of deformation in austenite before transformation, providing significant microstructure refining [1–3, 26–28]. *Mo*, in addition to the effect of solute resistance on the static kinetics of recrystallization, enhances the formation of complex non-polygonal transformation products [27, 28]. These strategies pursue finer final microstructures, which will result in a better combination of strength and toughness. On the other hand, *Ti* and *Mo* microalloyed steels have an interesting combination of high strength and good formability due to the wide dispersion of nanometer-sized titanium carbides in a thin matrix [21–23].

HSLA steels usually contain very low carbon content and a small amount of alloying elements [1, 2, 14], and are classified by the *American Petroleum Institute* (*API*) in order of its strength (*X-42*, *X-46*, *X-52*, *X-56*, *X-60*, *X-65*, *X-70*, *X-80*, *X-100* and *X-120*). These properties are achieved by careful selection of *Miroslav's* composition and optimization of thermal and mechanical treatment (*TMT*) and accelerated cooling conditions after *TMT*. Specifications concerning chemical composition, mechanical properties and other important aspects such as welding, cutting, manufacturing, etc. of oil and gas piping materials are determined by the *American Petroleum Institute* (*API*), the *International Organization for Standardization* (*ISO*) and other national agencies [4–9].

Requirements for pipe steel of strength class K55 according to GOST R 53366-2009

The chemical composition (table 1) of steels is limited only by the content of harmful impurities – the content of sulfur and phosphorus should be no more than 0.030 wt. % ($P \le 0.030$, $S \le 0.030$). In addition, when tested in tension, steels should have a yield strength (σ_y) equal to 379–552 MPa and an ultimate strength (σ_u) above or equal to 655 MPa (table 2).

Requirements for pipe steel of strength class K55

According to *API* requirements, piping materials are manufactured or supplied with two levels of product specification, known as *PSL 1* and *PSL 2*. According to *API 5L* specification, *PSL 1* pipes are supplied with grades *A25*, *A25P*, *A*, *B*, *X42*, *X46*, *X52*, *X56*, *X60*, X65 and *X70*, while *PSL 2* pipes are supplied with grades *B*, *X42*, *X46*, *X52*, *X56*, *X60*, *X65*, *X70*, *X80*, *X90*, *X100* and *X120*.

It is also worth noting that there is no carbon equivalent limit for *PSL 1* pipes. Another significant difference is based on the type of pipe ends. *PSL 1* pipes can be manufactured and supplied with smooth ends, threaded ends, sockets and as a special connecting pipe, whereas *PSL 2* pipes are manufactured only with smooth ends. In this document, information on the chemical composition, mechanical properties and the pipe manufacturing technologies used is indicated for pipe steel from *X42* to *X120*. The original grades *A25*, *A25P*, *A* and *B* are excluded from the main discussion, since these grades are considered medium-strength materials. According to the *American Society of Metals* (*ASM*), low-alloy steel with a yield strength of at least 290 MPa is considered a high-strength steel. Knowledge of the chemical composition and mechanical properties of these pipes is necessary to understand the weldability and other aspects of welding these pipes.

Requirements for chemical composition according to *API 5CT* are limited only to the content of harmful impurities – the content of sulfur and phosphorus should be no more than 0.030 wt. % ($P \le 0.030$, $S \le 0.030$). The difference in chemical composition requirements between *PSL 1* and *PSL 2* is shown in table 3.

Table 1

Chemical composition of pipelines steel according to *GOST R 53366-2009* (p. 71, Table 5)

Class	Strength Group	type	Mass content of element, %													
			C		Mn		Mo		Cr		Ni	Cu	P	S	Si
			min	max	min	max	min	max	min	max	min	max	min	max	min
1	*H40*	–	–	–	–	–	–	–	–	–	–	–	0.030	0.030	–
	J55	–	–	–	–	–	–	–	–	–	–	–	0.030	0.030	–
	K55	–	–	–	–	–	–	–	–	–	–	–	0.030	0.030	–
	K72	–	–	–	–	–	–	–	–	–	–	–	0.030	0.030	–
	N80	1	–	–	–	–	–	–	–	–	–	–	0.030	0.030	–
	N80	*Q*	–	–	–	–	–	–	–	–	–	–	0.030	0.030	–

Table 2

Requirements for mechanical properties of steel for pipelines according to *GOST R 53366-2009* (p. 72, Table 6)

Class	Strength Group	Type	Total elongation under load, %	Yield strength R_t, MPa		Strength R_n, MPa, min.	Maximum hardness		Back wall t hickness *t*, mm	Permissible hardness variation *HRC*
				min	max		*HRC*	*HBW*		
1	*H40*	–	0.5	276	552	414	–	–	–	–
	J55	–	0.5	379	552	517	–	–	–	–
	K55	–	0.5	379	552	655	–	–	–	–
	K72	–	0.5	491	–	687	–	–	–	–
	N80	1	0.5	552	758	689	–	–	–	–
	N80	*Q*	0.5	552	758	689	–	–	–	–
2	*M65*	–	0.5	448	586	586	22	235	–	–
	L80	1	0.5	552	655	655	23	241	–	–
	L80	9*Cr*	0.5	552	655	655	23	241	–	–
	L80	13*Cr*	0.5	552	655	655	23	241	–	–

Table 3

Differences between *PSL 1* and *PSL 2* pipe materials depending on its chemical composition

Chemistry	*PSL 1* (wt. %)	*PSL 2* (wt. %)
Maximum Carbon content for seamless pipes	0.28 % for ratings ≥ *B*	0.24 %
Maximum Carbon content welded pipes	Maximum	0.22 %
Maximum Manganese content for seamless pipes	1.40 % for classes ≥ *X46*	1.40 % for classes ≥ *X46*
Maximum Manganese content welded pipes	1.40 % for stamps ≥ *X46* and ≤ *X60*; 1.45 % for *X65*; and 1.65 % for *X70*	1.40 % for stamps ≥ *X46* and ≤ *X60*; 1.45 % for *X65*; 1.65 % for *X70*; и 1.85 % for *X80*
Maximum Phosphorus	0.030 % for ratings ≥ A	0.025 %
Maximum Sulfur	0.03 %	0.02 %

Weldability of pipe steels

An additional criterion for pipe steels is the quantitative value of the carbon equivalent. The term "*carbon equivalent*" (*CE*) is used to refer to the hardenability or tendency to crack of a steel weld. *CE* helps to evaluate the cumulative effect of all important alloying elements on the microstructure (formation of the martensitic structure) during welding of steel, since it is the change in the microstructure of steel that determines its properties and behavior after welding. Therefore, a lower *CE* value is always preferable, which indicates good weldability. The *American Petroleum Institute* has adopted two equations (CE_{IIW} and $CE\ P_{cm}$) to determine the carbon equivalent limit for *API PSL 2* grade pipe steel. The CE_{IIW} equation is provided by the *International Welding Institute* and is commonly used for simple carbon and carbon-manganese steels.

In Europe, P_{cm}, the critical parameter of the metal, denoted by P_{cm}, is calculated. *CE* P_{cm} is taken from the documents of the *Japanese Society of Welding Engineers*. *CE* P_{cm} was proposed specifically to test the weldability of high-strength steels.

$$P_{cm} = \%C + \frac{\%Si}{30} + \frac{\%Mn + \%Cu + \%Cr}{20} + \frac{\%Ni}{60} + \frac{\%Mo}{15} + \frac{\%V}{10} + 5B;$$

$$CE_{IIW} = \%C + \frac{\%Mn}{6} + \left(\frac{\%Cr + \%Mo + \%V}{5}\right) + \left(\frac{\%Cu + \%Ni}{15}\right).$$

The *API* piping specification states that CE_{IIW} restrictions will be taken into account if the mass fraction of carbon exceeds 0.12 %. *CE* P_{cm} is used when the mass fraction of carbon in steel is less than or equal to 0.12 % (*American Petroleum Institute*, 2012). In addition to metal alloying, thermal cycles play an important role in changing the microstructure, as well as cooling rates during welding. Before predicting the behavior of steel during and after welding, it is also necessary to take into account the welding materials used and the conditions for preparing and conducting the welding process.

The requirements of *API 5CT* for pipe steels for mechanical properties during tensile testing are shown in table 4.

API 5CT requirements for pipe steels of a strength group *K55* for mechanical properties during tensile testing are as follows:

σ_y = 379–552 MPa, $\sigma_u \geq$ 655 MPa, minimum elongation, *e*, expressed as a percentage, should be determined by the following equation:

$$e = k\frac{A^{0,2}}{U^{0,9}},$$

Table 4

API 5CT requirements for pipe steels for mechanical properties in tensile tests

Pipe grade	Minimum yield strength, MPa	Maximum yield strength, MPa	Minimum ultimate tensile strength, MPa	Maximum ultimate tensile strength, MPa
X42	290	496	414	758
X46	317	524	434	758
X52	359	531	455	758
X56	386	544	490	758
X60	414	565	517	758
X65	448	600	531	758
X70	483	621	565	758
X80	552	690	621	827
X90	625	775	695	915
X100	690	840	760	990
X120	830	1,050	915	1,145

where e is the minimum elongation within the estimated length of 50.8 mm (2 in) as a percentage, rounded up to 0.5 percent when it is less than 10 % and up to one percent when it is 10 % or higher; k is a constant equal to 1942.57 (625,000 when calculated in inches); A is the cross-sectional area of the tensile test specimen in mm^2 (in^2), based on the specified outer diameter or nominal width of the specimen and the specified wall thickness, rounded to an accuracy of 10 mm^2 (0.01 in^2) or 490 mm^2 (0.75 in^2) (whichever is less); U is the minimum specified tensile strength in MPa (psi).

Impact strength requirements

In accordance with *API 5CT* [3], the impact test is carried out using the *Charpy* method for V-notched specimens. The requirements for the absorbed impact energy of the tested specimens (at least 3 pieces) should be:

– for transverse specimens $KV^{+21} \geq 20$ J;
– for longitudinal specimens $KV^{+21} \geq 27$ J.

The result less than the required absorbed energy can be obtained on no more than one specimen, and the absorbed energy value should be less than two-thirds of the required. The permissible dimensions of the impact test specimens and the reduction coefficients of the absorbed impact energy are presented in the standards (table 6).

Requirements for heat treatment

The *API 5CT* standard does not contain specific requirements for the heat treatment of pipes of strength class *K55*, it is allowed to be supplied in a state after normalization, normalization with subsequent tempering or after quenching and tempering along the entire length and throughout the pipe body at the manufacturer's choice or in accordance with the requirements of the supply contract. However, the weld of electric-welded pipes should be heat-treated after welding at a temperature not lower than 540 °C (1,000 °F) or treated in such a way that there is no untempered martensite. This is due to the requirements for testing pipes for crumpling.

Production of pipes for oil and gas pipelines

Currently, two main technologies are used for the production of rolled products for large diameter pipes: controlled rolling followed by air cooling and controlled rolling followed by accelerated cooling. The basic concept of thermal and mechanical treatment (*TMT*) or thermal and mechanical controlled treatment (*TMCT*) underlies the development of many advanced steel grades with improved mechanical properties over the past 50 years.

At *TMCT*, cooling rates and deformation models affect the heterogeneity of the microstructure and crystallographic texture of thick-walled rolled plates. It led to heterogeneity of the mechanical behavior in thickness and affected the properties of the plate. An increase in the thickness of the steel plate leads to significant differences in the plastic ability of the material to deform in the direction of thickness at different stages of forming [1–3]. Tests of the mechanical properties of thick-walled pipeline steel *K60* at *TMCT* demonstrated these differences in thickness [1, 2]. Thick-walled steel plate *K60* undergoes a longer holding time in thickness near the center during rapid cooling; cooling occurs at a lower rate and promotes grain growth [8–13]. On the other hand, changes in the deformation mode also affect the microstructure along the thickness of the rolled metal. In the process of hot rolling, the surface layer undergoes severe shear deformation due to friction between the surface and the rolls, which leads to the appearance of many dislocations in the ferrite [10, 11]. Moving dislocations weave, forming new grain boundaries, as a result of which the initial ferrite grains break up into many subcrystals [13, 25, 26]. Crystal fragmentation leads to more significant deformation and an increase in the internal stored energy of the grain, contributing to the rapid formation of ferrite in the surface layer [25, 26]. This combination (rapid cooling and shear deformation) leads to a decrease in the grain size in the surface layer. Hardening during grain refining often improves mechanical properties. Reducing the grain size increases the plasticity of the surface layer, so that the finer ferrite provides better coordination of deformation, effectively preventing stress concentration. At the same time, grain refining effectively restricts the movement space of dislocations inside the ferrite along the surface layer, enhancing the interaction between dislocations and increasing strength [9, 11].

However, the mechanical properties manifested by the microstructure can affect the degree of deformation hardening and the behavior of plastic damage during further forming of the pipe, which, in turn, affects the final pipes' properties [1–4]. After the pipes are formed, the outer and inner layers of the pipes in the walls experience repeated tensile and compressive deformations, respectively [1–3]. Because of these different deformation histories, the flattened segment of pipe walls often exhibits unexpectedly much lower or higher yield strength than the sheet metal from which it is made.

Many studies have shown that the yield strength of the material increases and the ductility decreases during production and that the deformation behavior varies depending on the microstructure [8, 31]. Therefore, when it is necessary to obtain a strength class of steel below *K60*, *TMT* is used, and if it is required to obtain rolled products with a strength above *K60*, *TMCT* is used. Many researchers recognize that with an increase in the pipe thickness over 27 mm, there are many unresolved issues in the pipe production process to obtain a homogeneous structure across the rolled section, and in the future during the subsequent production of the pipe by wall thickness during the forming process.

API class pipes can be made both seamless and welded. The seamless process is a hot-working process used to form a pipe product without a weld. Welding processes used for the manufacture of *API* class pipes can be divided into welding processes without the use of filler metal (contact welding, electric welding and laser welding) and with the use of filler metal (submerged-melt welding and arc welding with a metal electrode). The manufacturing technology of steel pipes and pipes by conventional electric resistance welding (ERW) is shown in fig. 2.

ERW steel pipe manufacturing procedures begin with a rolled steel sheet of the appropriate thickness and a certain width to form a pipe that meets certain specifications. The steel strip is stretched through a series of rollers, which gradually form a cylindrical tube. When the edges of the cylindrical plate meet, an electric charge is applied at the right points to heat the edges so that to be welded together. However, it is difficult to get good performance when using a conventional *ERW* process.

The reason is that *ERW* steel pipes are made by cold rolling steel strap, and the ductility of steel pipes is inevitably inferior to the ductility of steel strap due to deformation hardening during cold rolling. In addition, the hardening caused by rapid cooling after welding has the same effect on the mechanical properties of the steel pipe in the welded joint.

The processes used to produce two levels of product specification (*PSL 1* and *PSL 2*) for *HSLA* pipe steels are presented in documents [4–9].

From the information presented above, we see that the production of pipes is a complex high-tech process, which at the output gives us an innovative high-quality product, which in the future should be welded in the field into a gas or oil pipeline.

The analysis of works [21–28] shows that when forming a weld in steels of strength class *K60* with a predominant structure of ferrite and perlite, it is impossible to obtain high values of strength and toughness at the same time. One of the promising directions for the development of high-strength pipe steels is the production of a crystalline ordered bainite structure [1, 2, 21–25], instead of ferrite-pearlite.

It is shown in [26] that two generations of low-alloy steels (ferrite/perlite, and then bainite/martensite) have been developed over the past thirty years and have been widely used in structural applications. The third generation of low-alloy steels is expected to provide high strength, improved ductility and toughness, as well as meet new requirements for weight reduction, environmental friendliness and safety. This paper examines the recent progress in the development of low-alloy steels of the third generation with M^3 microstructure, namely microstructures with multiphase, metastable austenite and multiscale separations. The review summarizes alloy designs and processing methods for microstructure control, as well as the mechanical properties of alloys. Special attention is paid to the stabilization of residual austenite in low-alloy steels. Then, multiscale nanowires are added, including carbides of microalloying elements and copper-enriched precipitates obtained in low-alloy steels of the third generation. The structure-properties

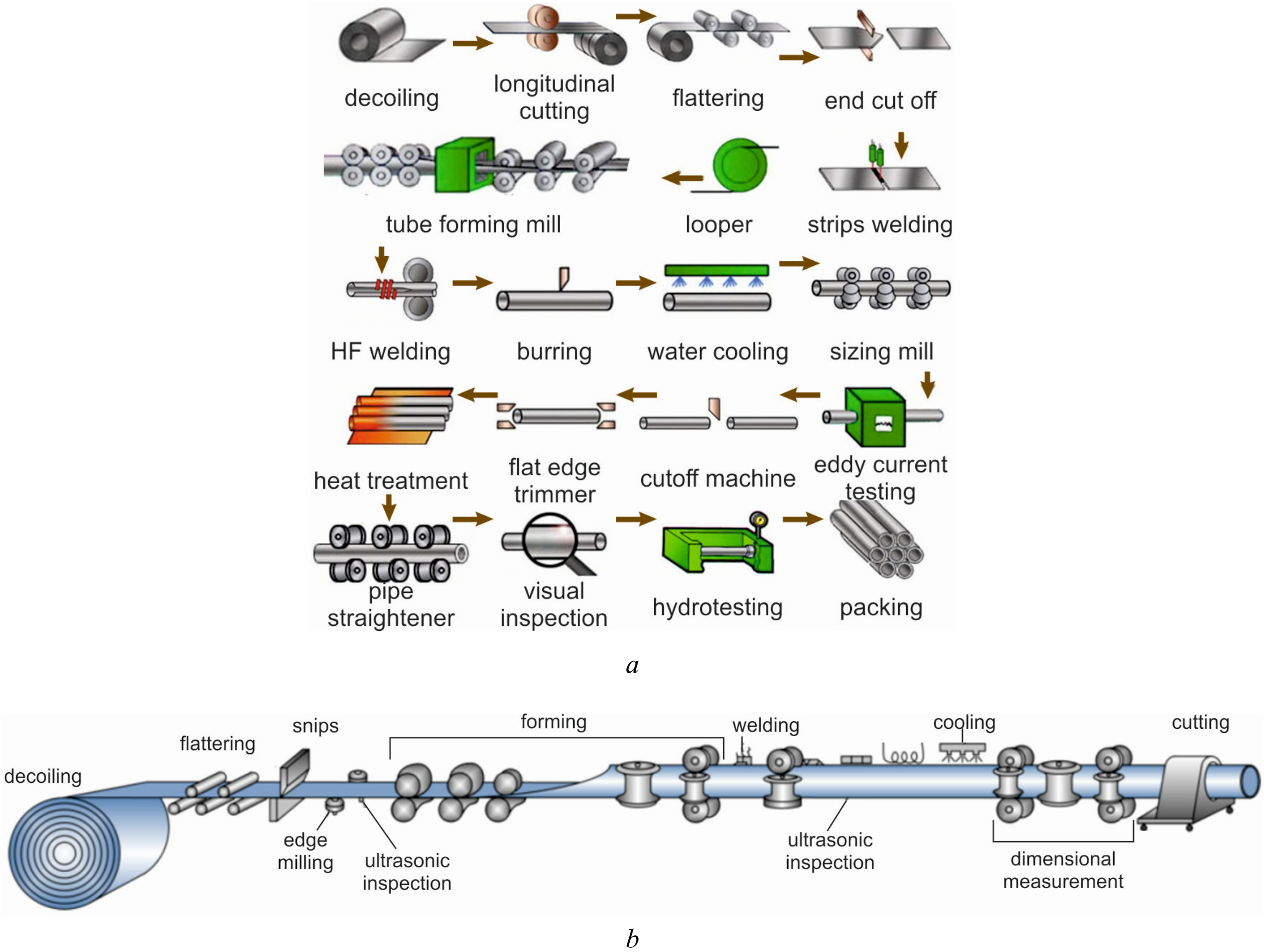


Fig. 2. Technologies for manufacturing welded steel pipes (*a*) and conventional electric resistance welded (*ERW*) pipes (*b*)

relationships of third-generation alloys are also discussed. Finally, the prospects and problems of future applications are studied.

It is noted in [27] that the most important phenomena in this context are the martensitic phase transformation and the associated effects of accommodation plasticity (*TRIP*) and twinning-induced plasticity (*TWIP*) that can occur, both of which are possible due to the presence of thermodynamically metastable austenite.

The paper [28] provides an overview of the technology for manufacturing high-strength pipeline steels. The microstructure and mechanical properties of sheets and pipes made of steel grades *X80*, *X100* and *X120* are analyzed and discussed. The microstructure of steel *X80* consists of needle ferrite containing the *M*/*A* phase (martensite/austenite component). The *X80* steel sheets and pipes tested were found to exhibit superior performance in the Drop Weight Tensile Test (*DWTT*). The *DWTT* of 85 % *SATT* of *X80* steel in the pipe was about –40 °C. The deformation capacity of the *X80* pipeline was evaluated on a large-sized deforming machine operating under the load of bending and axial compression forces. The developed *X80* pipeline was found to meet *DNV* and *API* bending resistance requirements. In the case of *X100* steel, the main phase was bainitic ferrite, which has a lath and granular morphology, and *M*/*A* existed as the second phase. It was shown that the developed steel *X100* can be implemented with the appropriate properties for *UOE* pipes. *DWT* 85 % *SAT* of steel pipe *X00* was shown at temperatures below –40 °C. The development of pipeline steel of the *X120* grade was also tested. The microstructure of steel *X120* consists of bainitic ferrite and needle ferrite. The tensile strength of the developed steel sheets and pipes *X120* fully meets the target properties required in the current study. The *DWTT* of 75 % *SATT* of the developed *X120* sheet steel and pipe was below –30 °C. Bainitic ferrite, exhibiting a lath and granular morphology, was the main phase, and *M*/*A* existed as the second phase.

Works [2, 11–18] note that when welding pipes made of steel *X80*, *X100* and *X120* grades in field conditions, difficulties arise in ensuring an optimal structure in the *HAZ* and a decrease in the mechanical properties of the weld metal.

Welding technologies

In the standard *GOST 29273-92*, a definition of weldability is given for all metal materials, taking into account all processes, various types of structures and whatever properties it should satisfy: *"Definition of weldability. A metal material is considered to be weldable to a certain extent in these processes and for this purpose, when metal integrity is achieved by welding with an appropriate technological process so that the parts to be welded meet technical requirements, both in terms of its own qualities and in terms of its influence on the structure it forms."*

According to *AWS* (*American Welding Society*), weldability is defined *"the capacity of a material to be welded under the imposed fabrication conditions into a specific suitably designed structure and to perform satisfactorily in the intended service."* This concept, although unique, can be divided into three: operation weldability, metallurgical weldability and weldability during operation.

Operation weldability is related to the operational conditions of welding, such as: the combination of the process and the nature of the base metal; welding position; welder skills; co-assembly methods, etc.

Metallurgical weldability is associated with thermal and chemical conditions that can create defects or undesirable mechanical properties in the welded joint associated with metallurgical phenomena such as phase transformation, microsegregation, etc.

Weldability during operation is more related to the service life of the component being welded.

At this point, the main focus will be on metallurgical weldability.

Metallurgical issues of steel pipe production are widely covered in the literature; however, the subsequent welding of pipes in the field makes its own adjustments to the operational efficiency of the entire pipeline. The main methods of pipe welding are: arc welding with a low hydrogen electrode, submerged metal automatic welding (*SMAW*), gas metal arc welding (*GMAW*), flux-cored arc welding (*FCAW-S*). The technological features of these methods and equipment are well covered in the literature. Let's consider promising technologies [29–39].

Laser-arc hybrid welding (*LAHW*) and automatic welding equipment have been in the research, development and design stages since 2,000 [29–33]. In the laser-arc hybrid welding (*LAHW*) process, the laser beam and the electric arc interact in the welding bath, and its synergetic effect is used to perform deeper and narrower welds (fig. 3), increasing productivity [30–33].

This method has been successfully implemented in the laboratory when welding the root in all positions of linear pipes with a tip diameter of 8 mm, and the laser source and cooling system are under investigation for its in-situ applicability [29, 30].

In the review paper [32], data on the thickness of the materials being welded are given in table 5. The paper [33] presents industrial options for welding pipelines (fig. 4).

In [30], the influence of the parameters of hybrid laser-arc welding: heat input and preheating on the cooling rate, microstructure and mechanical properties of the welded joint is investigated. Specimens made

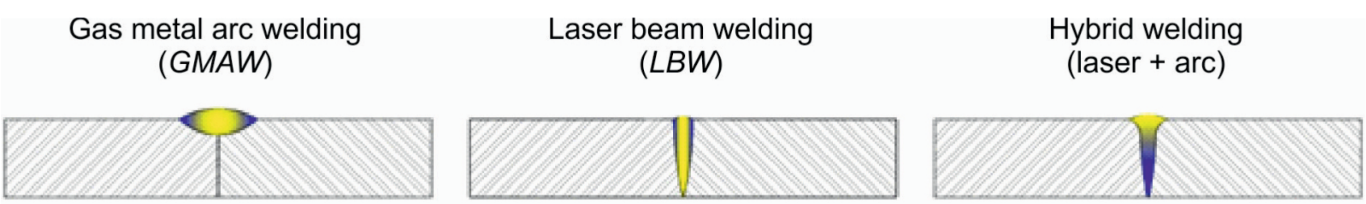
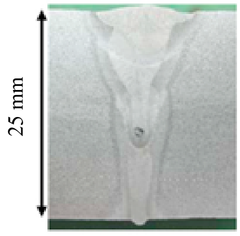
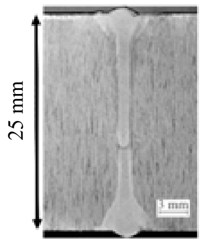
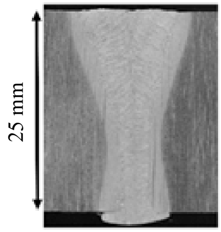
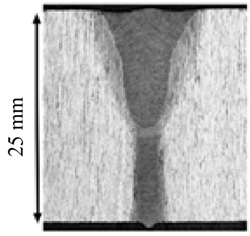
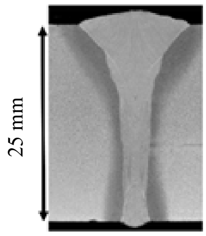
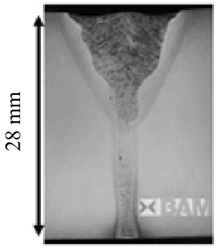
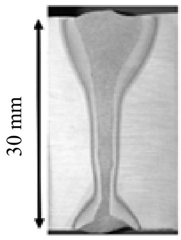
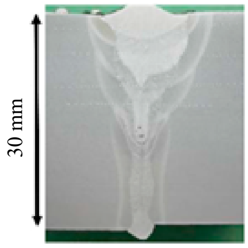
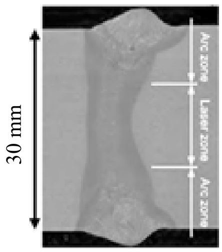
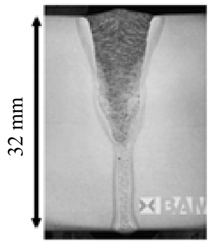
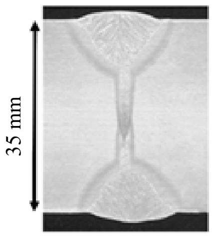
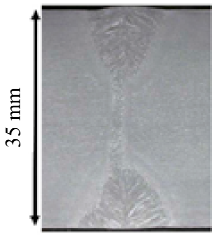
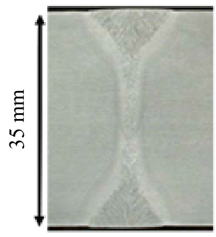
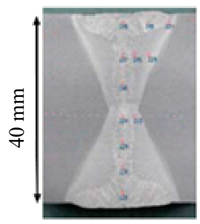
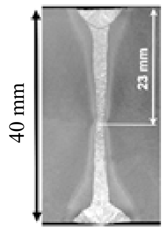
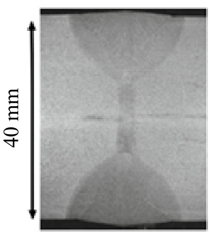
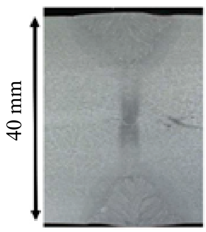
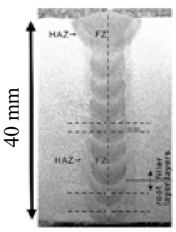
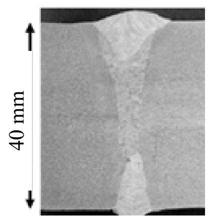
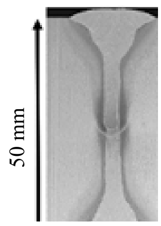
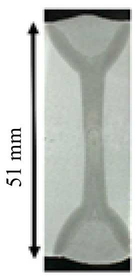
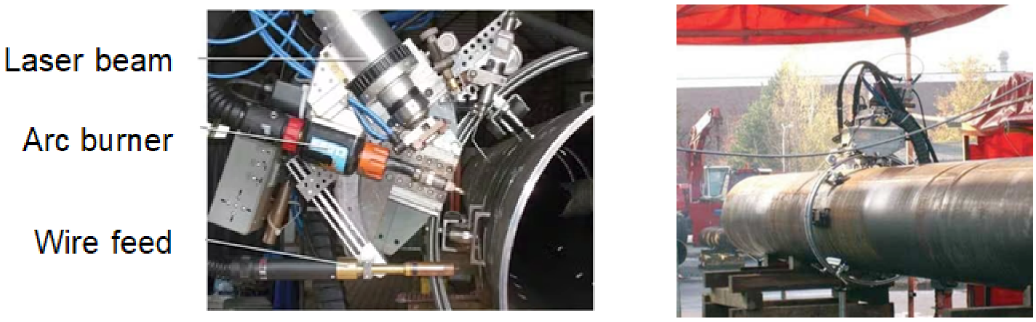


Fig. 3. Cross-section of welds joined by different welding methods: *GMAW*, *LBW* and *LAHW* [31]

Table 5

Cross-sections of hybrid laser joints made of heavy gauge steel [32]

A	B	C	D	E
				
AH36 *H1, T3*	*S355J2* *H3, T3*	*S355J2* *H3, T1*	*S355J2* *H3, T2*	*SM490A* *H2+CW, T2*
F	**G**	**H**	**I**	**J**
				
API 5L X65 *H2, T2*	*RQT701* *H1, T3*	*AH36* *H1, T2*	High-strength *H2,+ T4*	*API 5L X65* *H2, T2*
K	**L**	**M**	**N**	**O**
				
API X65 *H5, T3*	*API X65* *H4, T3*	*API X65* *H4, T3*	*S355 J2+N* *H0, T3*	*HSLA* *H2+CW, T3*
P	**Q**	**R**	**S**	**T**
				
S355J2+N *H6, T4*	*P265GH* *H4, T3*	*Q235* *H2, T2*	*S355 J2+N* *H0, T4*	*SM490A* *H2+CW, T3*
U				
 *S460* *H5, T3*	*H0* – arc *GMAW* + laser *H1* – arc *GMAW* + laser CO_2 *H2* – arc *GMAW* + fiber laser *H3* – arc *GMAW* + disk laser		*H4* – arc *SAW* + disk laser *H5* – arc *SAW* + laser CO_2 *H6* – *GMAW* + *SAW*	*T1* – OS_SP *T2* – OS_MP *T3* – DS_SP *T4* – DS_MP



a *b*

Fig. 4. Laboratory version of laser-arc hybrid technology (*a*) and field version for pipe welding (*b*) [33]

of *API 5L X80* steel with a root thickness of 14 mm were welded with *MF 940 M* welding wire. It is shown that a decrease in the cooling rate of welds from 588 °C/s to 152 °C/s reduces the hardness of the weld metal from 343 ± 12 HV to 276 ± 6 HV and the tensile strength from 1,019.5 ± 14 MPa to 828 ± 10 MPa, as well as an increase in the bainitic phase of the weld metal is revealed when increasing the preheating temperature to 180 °C and the maximum running energy.

The work [31] notes that to develop oil and gas resources in deep-sea areas, it is necessary to lay a large number of underwater pipelines. *J*-lay is the primary method for laying deep undersea pipelines. Welding the circumferential seam in a horizontal-vertical position is a mandatory part of the *J*-lay method. Currently, the following sequence is usually used: hot pass welding of the root, filling and facing layers of the welded joints [31]. Due to problems with welding efficiency and quality, traditional welding methods could not meet the requirements of industrial pipelines with thicker pipe wall and larger pipe diameter, so there was an urgent need to develop a welding method with high efficiency and productivity, as well as a high degree of automation. The heat source characteristics of laser-*MAG* hybrid welding, which combines deep laser penetration and wide arc adaptability, make it very suitable for welding pipes with thicker walls [29–34]. Compared to conventional welding in a horizontal-vertical position, it has the following advantages: deep penetration, high welding speed and high welding quality. The level of penetration with single-sided welding is the same as with other root welding methods + one fill pass. At the same time, it reduces spatter and welding distortion, reduces the need for back gouging, and improves production efficiency [29–32].

A lot of work has been carried out in the country and abroad to study the technology of hybrid laser-*MAG* welding in the field of pipeline laying (for welding in a horizontal-vertical position) [34, 35]. The use of hybrid laser-*MAG* welding not only increases the speed and quality of welding, but also gives great advantages in reducing the sensitivity of butt joints and welding defects [34, 35].

Despite the significant progress of *LAHW* in technical implementation, research work on the structure and properties of metals, and taking into account the indisputable fact that this technology has a high penetrating power and efficiency; at this stage of development it is considered an industrial innovation. The technology and equipment need constant improvement in the process to meet the requirements of field welding.

The *transfer controlled MAG* (*TC*) welding process is a derivative of the *MAG* process for root pass welding in pipelines. There are various patents for short circuit switching control [35]. Among them there is a control developed and patented by *The Lincoln Electric Company* under the trade name “*STT*® (*Surface Tension Transfer*) [35]. One of the variants of the *MAG-TC* welding process is to control the current without changing the electrode feed rate, using a special welding source for this, which ensures low welding energy, smoke and spatter. Reducing the spatter rate reduces the time required for cleaning both the burner and the welded joint [35].

The metal transfer obtained by this process is carried out by short-circuiting using pure CO_2 or Ar/CO_2 mixtures as a protective gas [35]. Fig. 5 shows the waveform used in the *MAG-TC* process.

Unlike *MAG* process sources, *MAG-TC* process sources operate on a constant current curve rather than a constant voltage curve. Thus, the source is capable of changing the electric current of the arc in a short period of time. Arc stability is maintained even with changes in electrode length and welding angle due to precise control of the welding current. Thus, as in the *MAG* process, the change in current to adjust the electrode elongation is eliminated, ensuring that there is no point reduction in the heat transferred [35].

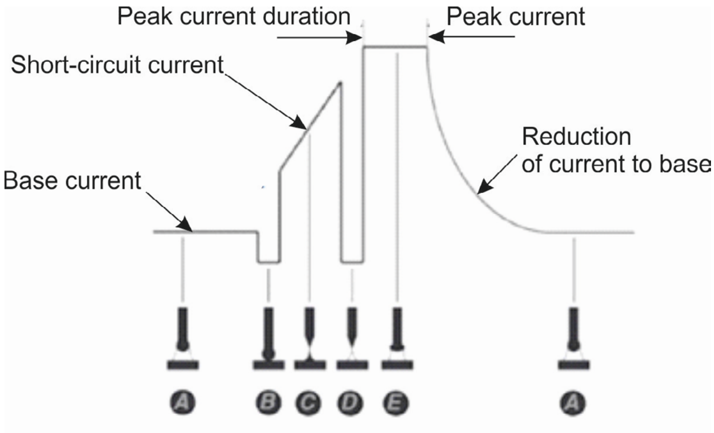


Fig. 5. Welding pulse shape with controlled transfer (*TC*)

Point ***A*** in fig. 5, corresponds to the base current (from 50 to 100 A), which has the function of maintaining the arc open and transferring heat to the weld pool. When a drop formed at the tip of the electrode touches the molten pool, creating a short circuit (point ***B***), a current drop occurs. At point ***C***, the current of the pinch effect of the drop is applied, which has the function of separating the drop from the tip of the electrode and placing it in the melt pool. At point ***D***, the electronic control device of the welding current source monitors the electrical parameters of the arc and determines when the liquid bridge between the molten drop and the tip of the wire is about to break, in order to then reduce the current to values from 45 to 50, ensuring the restoration of the electric arc. After restoration of the arc (point ***E***), the peak current, the function of which is to press down on the molten pool to prevent short circuit and heat the connection. The function of the tail is to control the rate at which the peak current decreases to the base current, acting as a rough control of the welding energy.

The advantages of using the *MAG-TC* process for pipe root welding compared to *MAG* welding are that short-circuit control prevents lack of fusion, heavy smoke and spatter even when using CO_2 as a shielding gas, which ensures good surface finish and weld strength [35]. Compared with the *TIG* process, the *MAG-TC* process has a welding speed 4 times higher [35].

Compared to the *ER* process, the *MAG-TC* process has advantages mainly in terms of increased productivity, since there is no need to stop welding to change consumables and grind after finishing the root pass, since, unlike the *ER* process, the weld profile is flat. The finishing profile of the root pass with cellulose wires is convex, which leads to large losses of time during the roller grinding operation [35].

Another promising option, from the point of view of reducing the cost of welding works and increasing productivity, is butt resistance welding of pipes (*BRW*), which significantly increases work productivity. However, the disadvantage of the technology is the non-standard cutting of edges. To solve this issue, a hybrid technology of combining resistance welding and flux-cored welding (*FCW*) methods is possible. With *BRW*, it is difficult to obtain high impact strength of the joint on specimens with a sharp notch (*Charpy*). To obtain the required impact strength indicators for welded joints of *BRW* pipes, it is recommended to perform an additional technological operation – local heat treatment of the welded joint.

Friction stir welding (*FSW*) is in the research stage, being introduction into traditional pipeline welding technologies. *X80* pipeline steel plates were friction stir welded (*FSW*) under cooling conditions of air, water, liquid CO_2 + water and liquid CO_2, resulting in defect-free welded seams [26]. The microstructural evolution and mechanical properties of these *FSW* joints were studied. It has been shown that the impact toughness of the metal in the *HAZ* is 20–60 % higher compared to traditional welding methods [26].

Welding features

The weld is formed by crystallization of the melt of the weld pool, containing both the main and filler (when introduced) materials. Welding thermal cycles cause significant changes in the mechanical properties of the base material. It is well known that the weld metals of steel differ from most parent steels in that it has a cast structure that cools quickly and have a large number of oxide inclusions. These characteristics cause high levels of segregation and constant changes in solidification behavior even within the same columnar region [11–16], which makes understanding the microstructure and mechanical properties challenging.

The effect of the cooling rate on pipe welding

The higher the cooling rate, the higher the mechanical strength. The cooling rate depends on several factors such as: physical properties of the material, preheating, interpass temperature, pipe thickness, welding energy and joint geometry [1, 24].

Preheating is used to reduce the cooling rate. The preheat temperature can be determined based on the carbon equivalent calculation. Fig. 6 shows a graph of preheat temperature versus carbon equivalent for *API 5L X100* steels.

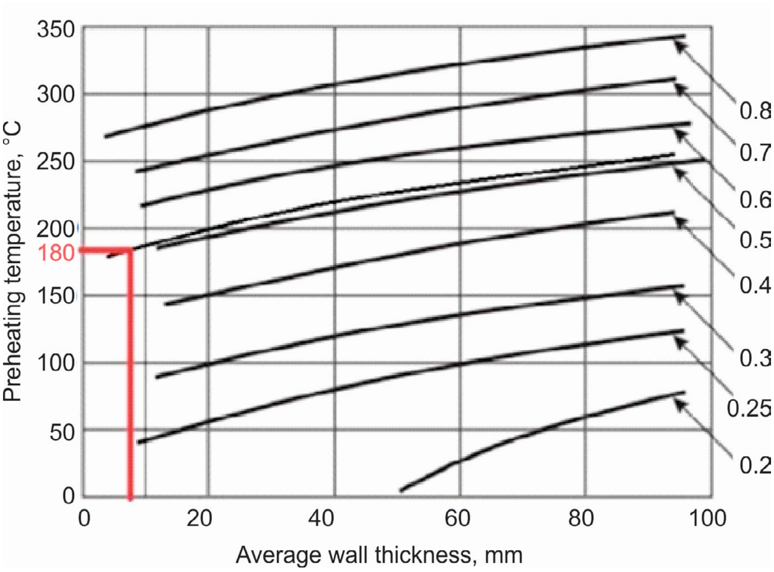


Fig. 6. The dependences of the preheating temperature on the carbon equivalent for steels and *Seferian* metal thickness [24]

When welding *API 5L X80* steel, the preheating values used range from 100 to 150. The author [24] considers the risk of cracking as a function of the preheating temperature and carbon equivalent when using cellulose-coated electrodes.

In pipes with thicker walls, the heat transfer to the rest of the base metal is higher, which increases the cooling rate. Consequently, the greater the thickness of the pipe, the higher the cooling rate and, consequently, the hardening obtained in the *HAZ*. Pipes with thicker walls are also subjected to greater compression during welding, which leads to higher residual stresses [24].

The diameter of the pipe also affects weldability, since large diameter pipes tend to increase the time between passes, causing the weld to cool faster, which can lead to cracking [1].

The influence of structural parameters on the micromechanism of the fracture of a welded joint made of traditional low-carbon low-alloy pipe steels has been the subject of significant work [11–23]. It is shown that the destruction of the metal of the *HAZ* section of the welded joint of steels of this class occurs by two mechanisms: brittle transcrystalline and viscous.

In [36, 37], the influence of bainite structure parameters on the micromechanism of fracture during welding of low-carbon low-alloy high-strength steels (strength categories *K65* and *K70*) was investigated. It is shown that a predominantly bainite structure is formed, which differs from the morphology of traditional pipe steels (as a bainite structure with a granular microstructure, i.e. globular bainite ferrite (*GBF*), as well as lath bainite ferrite (*LBF*), consisting of thin long rails combined into large packages of relatively equiaxed shape).

In [38], microstructural mechanisms for reducing the impact strength values of the coarse-grained heat-affected zone of two microalloyed *K60* steels were studied. It is shown that the greatest influence on the impact toughness of the heat-affected zone is exerted by titanium nitride inclusions, the spalling of which within large bainite packets can lead to macrobrittle fracture of the specimens.

When evaluating the effect of welding on changes in the properties of pipe steel, it is necessary to understand that the ultimate strength and yield strength of pipes has a wide range. For example, fig. 7 shows an example of the permissible ranges of change in yield strength and ultimate strength of pipes of the *X* series according to *API 5L*.

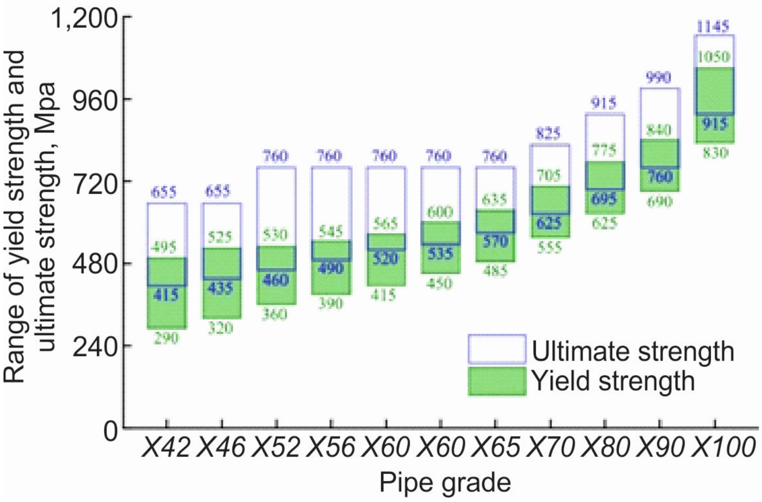


Fig. 7. Permissible variation of pipe strength according to *API 5L* [39]

The upper ultimate tensile strength limit of grades *X80* and higher increases as the grade of pipe increases. Even for the same class, the permissible strength range is in a large range of variations. Nevertheless, studies have shown that the critical strength matching factor satisfying the deformation requirements does not depend on the strength of the pipe [39–50]. Thus, the requirements for the ultimate tensile strength of the weld metal should be very high if the upper strength limit of the pipe is used to set the strength requirements for the weld metal, especially if the misalignment of the pipes from high to low and the apparent fracture toughness are conservatively set [39, 40, 45–50].

The strength requirement remains difficult to satisfy in practice when designing pipelines, taking into account the currently available welding methods and other limitations [39–50].

Since most of the parameters affecting the deformability are uncertain, the ultimate tensile strength requirements obtained by deterministic design methods may not be realistic enough. Therefore, when considering the probabilistic distribution of parameters, a reliability-based approach should be applied. In addition, the appropriate requirements for the strength matching coefficient of circumferential weld metals can be scientifically determined by adopting the theory of structural reliability [38, 39].

Modern requirements for the strength and other mechanical properties of circumferentially welded pipe joints are mainly reflected in the qualification requirements for welders. Anomalies in the form of skewed joints of pipes and pipelines in general, microcracks are inevitable for large-diameter pipelines made of high-strength steel [40]. In recent decades, many studies have been carried out on circumferential welds of onshore and offshore pipelines with cracks under operational load [38–41].

Table 6 presents generalized requirements of regulatory documents adopted in different countries for the ultimate tensile strength of circumferential welds. Almost all standards indicate that fractured specimens at the welding site can be accepted if the ultimate tensile strength of the weld is higher than the established minimum ultimate tensile strength σ_u of the main pipe.

Table 6

Tensile strength requirements for weld metal in various specifications and standards

Documents	Ultimate tensile strength requirement
ISO 13847; API 1104; AS/NZS 2885.2:2020; DEP 31.40.20.37-GEN	If the specimen is destroyed in the welding or fusion zone, then the observed strength should be above or equal to σ_u of the pipe material, and also meet the strength requirements. If the specimen is destroyed outside of both the weld and the heat affected zone (*HAZ*), the strength should be at least 95 % of the strength σ_u of the pipe material.
CSA Z662	The ultimate tensile strength of the test specimen should be above or equal to σ_u of the base metal or 95 % σ_u of the base metal, if the fracture occurs outside the weld and *HAZ*.
GB/T 31032	If the specimen is destroyed in the welding or fusion zone, and the observed strength should be above or equal to σ_u of the pipe material and meet the strength requirements. When the specimen is destroyed outside the weld and the *HAZ*, the strength should be at least σ_u of the pipe material.
RD 26-11-08-86 Welded joints. Mechanical tests.	The overall test result is considered unsatisfactory if at least one of the specimens showed a result that differs from the established standards (downward): in terms of ultimate tensile strength – by more than 10 %; in terms of impact strength – by more than 0.5 kgf×m/cm^2 (0.05 MJ/m^2). These provisions remain valid even if the arithmetic mean of the test results corresponds to the standard indicators.
GOST 31447-2012 Steel welded pipes for trunk gas pipelines, oil pipelines and oil products pipelines. Specifications.	The ultimate tensile strength of the pipes welds of all types when testing a flat specimen with removed excess weld metal or flash should be at least equal to the value of σ_u for the base metal. The maximum actual values of the ultimate tensile strength σ_u should not exceed the established standards by more than 108 MPa for strength classes up to *K55* and more than 98 MPa for strength classes *K55* and more.
SNiP III-42-80: Main pipelines.	The ultimate tensile strength of the welded joint, determined on discontinuous specimens with removed excess weld metal, should not be less than the standard value of the ultimate tensile strength of the metal of the pipes.
GOST 32569-2013 Industrial steel pipe-lines. Requirements for design and operation in explosive and chemically dangerous industries.	The minimum standards of mechanical properties of welded joints should not be lower than the lower value of the ultimate tensile strength of the base metal according to the standard or technical specifications for this steel grade.

However, the analysis shows that the current standard requirements for the ultimate tensile strength of the weld are usually based on the lower ultimate tensile strength of the pipe. Please note that this requirement is aimed at achieving high strength of the butt circumferential welds of the pipeline. In this case, the fracture of test specimens at the welding site will lead to the welding of circumferential welds in conditions of insufficient strength. Under such circumstances, the lower ultimate tensile strength of the base material will be unreasonably used as a requirement for evaluating the ultimate tensile strength of circumferential welds [40], confirming that the current requirements for the ultimate tensile strength of circumferential welds cannot fully ensure the necessary safety of pipeline systems.

In addition, the requirements for the ultimate tensile strength of the weld found in the current specifications and standards are not proposed to meet certain requirements for deformation of circumferential welds. The requirements for deformation of pipelines crossing different landscapes and geological hazards can be completely different. Therefore, the ultimate tensile strength requirements of circumferential welds should be developed and determined in accordance with various situations of deformation requirements [42–50].

The current principle of matching the strength and toughness of welded joints due to increasing the strength and a wide range of the actual strength of the base metal of the steel pipe is not entirely correct because it reduces the safety of pipeline operation [40, 41].

Due to the nature of the welding process, it is more difficult to balance the strength and toughness in the weld metal than in the pipe steel that has passed the *TMCT*, since the metal is a casting structure formed during heating, melting and solidification. The higher the strength class of pipe steel, the more difficult it is to achieve equilibrium in the weld metal. On the other hand, the wide range of the actual strength of the steel pipe makes it difficult to implement a standard compliance of above or equal strength fig. 8 [41].

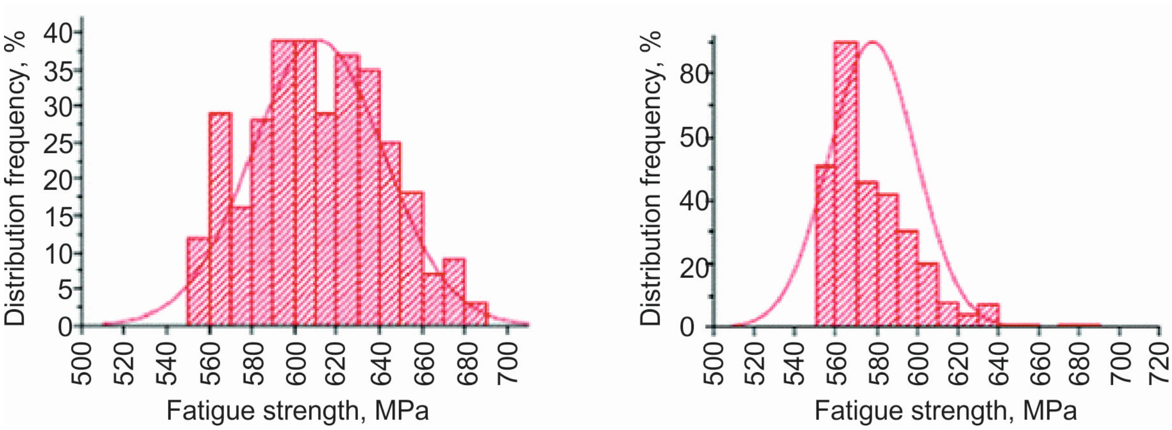


Fig. 8. Distribution of pipes strength from different sources in the *X80* pipeline project [41]

Conclusion

In the course of the analysis of literature sources related to the pipe production technologies and subsequent welding, two ways to increase the tension of a linear pipe are revealed. One of it is the careful design of the metallurgical chemical composition and precise control of the alloy composition during melting. Another is the precise control of the cooling rate during rolling. It perfectly protects the high-strength pipeline steel from cold cracks and *HAZ* brittleness. However, when welding new technical difficulties arise.

Adopting the method of thermal and mechanical sheet rolling for pipes, domestic steel requires a differentiated alloying elements system and better control over the parameters of sheet rolling. Domestic steel type *Cr80* requires special care when welding, especially when assembling pipelines in the field. Regardless of the *API* classification class, welding is the main process in the manufacture and assembly of pipelines. Welding processes require a lot of time in the production and assembly of these structures. This fact should be taken into account in the approach to studying the issues of increasing the efficiency of the welding processes used or the introduction of new processes in order to improve the cost-benefit ratio when implementing of these structures.

Even compared to high-performance welding processes such as hybrid laser and electron-beam welding, the most commonly used process in pipe production is still submerged arc, applied using tandem technology. Among the welding processes used in the assembly of pipelines in the field, the coated electrode continues to be widely used. However, *transfer controlled MAG* (*TC*) welding process combined with the flux-cored welding process provide an excellent alternative to a conventional covered electrode.

Although the ultimate tensile strength of circumferential welded joints is not lower than the minimum specified ultimate tensile strength of the pipe, the circumferential welded joint corresponds to a strength less or equal to the actual strength of the steel pipe, which requires careful selection of welding materials and process.

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Conflicts of Interest

The authors declare no conflict of interest.