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STRUCTURAL-PHASE CHARACTERISTICS OF DAMAGE TO WELDED JOINTS OF TPP STEAM PIPELINES FROM HEAT-RESISTANT STEELS (REVIEW)

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ABSTRACT

The paper considers the peculiarities of damage to welded joints of steam pipelines that have been operated for a long time (more than 280 thou h) under creep and fatigue conditions. It was established that the damage caused by creep and fatigue depends to a large extent on a structural-phase state of the metal of welded joints, which changes considerably during their long-term operation. With longer service life of welded joints, a ferrite-carbide mixture forms in their structure as one of the components. The presence of such a mixture contributes to acceleration of damage to welded joints. The dependence of formation of the ferrite-carbide mixture on the initial structure of welded joints was established, and recommendations were given for producing an initial structure with improved quality characteristics, which is advisable for increasing their reliability and service life.

KEYWORDS: steam pipelines, welded joints, heat-resistant steels, structure, damage, reliability, service life, pores, fatigue cracks

INTRODUCTION

Welded joints of steam pipelines largely determine the level of reliability of power units at thermal power plants (TPP). First of all, these are welded joints of steam pipelines of live steam, hot intermediate superheating, as well as steam pipelines within boilers. The metal of welded joints is characterized by the presence of structural, chemical and mechanical inhomogeneities, which at their long-term operation under creep conditions significantly contributes to appearance of micro- and macrodefects. The presence of such defects is considered as respective damage to welded joints [1–4]. The structural inhomogeneity grows with an increase in the service life of welded joints, which leads to a decrease in the resistance of metal of welded joints to its deformation and damage.

It should be noted that curvilinear and bending sections of steam pipelines (bends) also refer to the most damaging. However, the features of damage to bends and welded joints are different, that determines an individual approach to their study [5]. The impact of the support and suspension system, condition of tees, rebars, as well as operating conditions of welded joints on damage also requires separate study.

It is advisable to use the equipment of TPP (including steam pipelines and their welded joints), whose life is 35–45 years, up to 60–65 years (about 350 thou h). Namely such an operation of aging TPP requires 3.0–3.5 times less costs than replacing them with the new ones. And, therefore, individual testing of metal of welded joints of steam pipelines is required, as one of the most damaging components of TPP power units.

THE AIM OF THE WORK

is to analyze the features of the influence of a structural-phase state on damage to welded joints of steam pipelines, operating for more than 280 thou h under creep and fatigue conditions.

FEATURES OF PROCEDURE AND RESEARCH METHODS

The metal of steam pipelines of 12Kh1MF and 15Kh1M1F steels, in particular their welded joints after operation under creep conditions for more than 280 thou h are exposed to gradual degradation. And therefore, to determine the reliability of operation of steam pipelines, as well as their residual life, it is advisable to carry out appropriate complex studies. Such studies should be conducted in cooperation with experienced specialists from TPP and power systems. To solve the research tasks, specimens for sections from operating steam pipelines should be cut out in places where their damage is the most probable. The study of such sections allows determining to a large extent the real structural-phase state of the metal of welded joints, as well as their operational properties [1–3, 6–9]. For research, methods of microstructural, electron microscopic and micro X-ray spectral analyses, as well as X-ray method, are used. The studies of the mechanisms of creep and fatigue cracks formation are carried out with the use of optical and electron microscopy [4–9]. By using photometry as well as by X-ray patterns, respectively, the quantitative composition and structure of M_3C, M_7C_3, $M_{23}C_6$, Mo_2C and VC carbides are determined, their shape and appearance are summarized, which allows increasing the accuracy of determining the type of carbides. The use of optical microscopy allows determining the size of bainite, ferrite, sorbite, troostite and pearlite grains, as well as austenite grains. Creep and fatigue life tests are required to determine the reliability and life of welded joints.

For the theoretical and practical solution of the mentioned tasks, it is advisable to use the appropriate mathematical apparatus [10, 11] in relation to simulation of the temperature mode of the welding process. It is advisable to optimize the welding mode parameters by taking into account the obtained results, which will allow producing welded joints with increased quality indices of their initial structure [12, 13]. At the same time, simulation allows clarifying the features of the creep and fatigue process in the metal of welded joints by comparing the obtained results with the indices of their properties [8, 9, 13].

RESULTS AND DISCUSSION

To produce operating steam pipelines, mostly 12Kh1MF and 15Kh1M1F steels were used. Steam pipelines, in which accordingly the largest damage

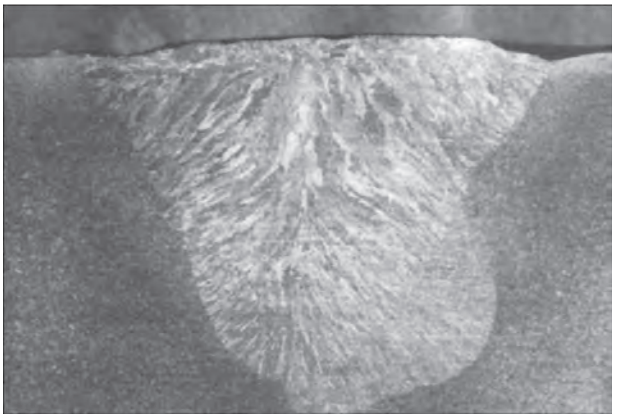

Figure 1. Macrostructure (×2.1) of welded joint of 15Kh1M1F steel

after their operation for more than 280 thou h is observed, operate under normative recommended conditions: at a temperature of 545 °C and a pressure of 25.5 MPa. During operation of steam pipelines, their short-term overheating periods of up to 585 and even up to 600 °C are possible (emergency steam discharge).

The alloying elements like chromium, molybdenum and vanadium, included in the mentioned steels provide them appropriate physical and mechanical properties. The mentioned elements partially alloy

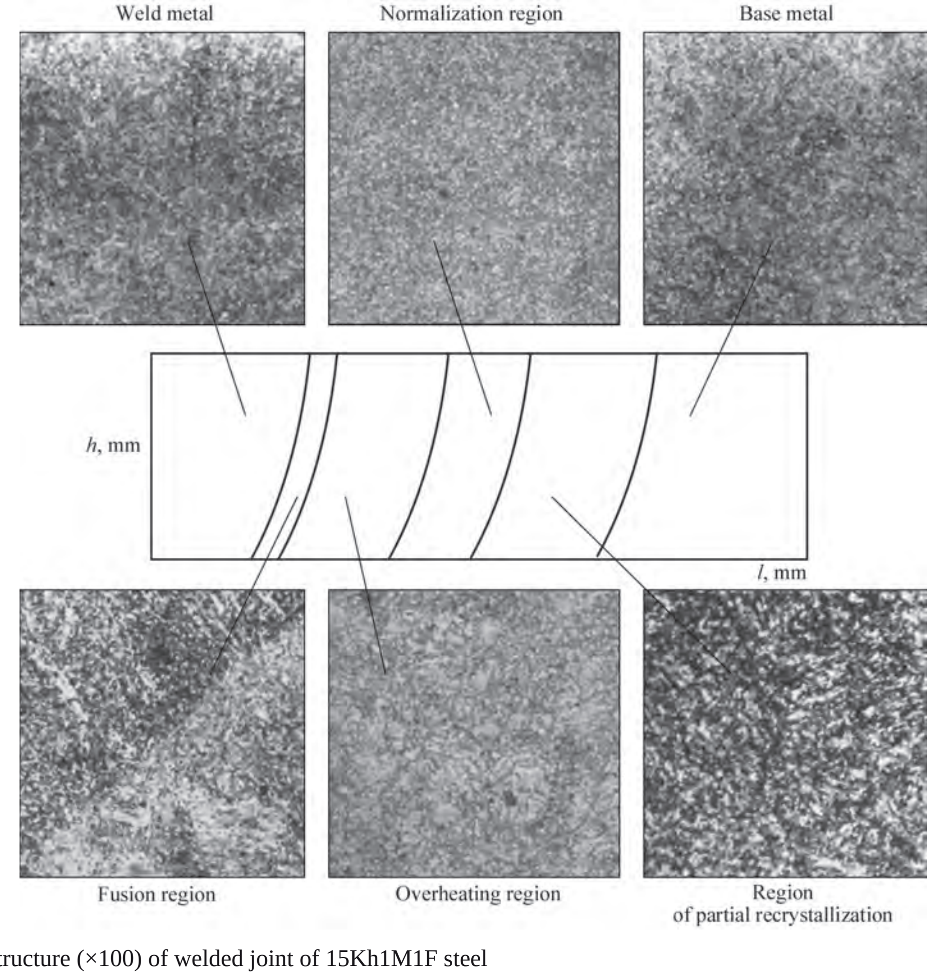

Figure 2. Microstructure (×100) of welded joint of 15Kh1M1F steel

Table 1. Chemical composition of 15Kh1M1F steel, wt.%

C	Si	Mn	Cr	Mo	V	Ni	Cu	S	P
						Not more than			
0.10–0.16	0.17–0.37	0.40–0.70	1.10–1.40	0.90–1.10	0.20–0.35	0.25	0.25	0.025	0.025

Table 2. Chemical composition of electrode wire of Sv-09KhMFA grade, wt.%

C	Si	Mn	Cr	Ni	Mo	V	S	P
0.09	0.20	0.45	1.0	0.15	0.60	0.25	0.020	0.020

Table 3. Chemical composition of weld metal, wt.%

C	Si	Mn	Cr	Mo	V	S	P
0.09	0.15	0.30	1.0	0.60	0.21	0.019	0.019

α-phase grains (ferrite, tempering bainite, sorbite, troostite) and partially form the part of M_3C, M_7C_3, $M_{23}C_6$, VC and Mo_2C carbides, providing dispersion strengthening of steels. Welded joints of 12Kh1MF and 15Kh1M1F steels are subjected to mandatory postweld tempering, which provides: strengthening of metal by precipitation of dispersed VC and Mo_2C carbides in sufficient quantity; relief of welding stresses; substructural strengthening; thermal stability of the strengthened state; necessary service properties.

Macrostructure of welded joints is characterized by the presence of three characteristic regions, Figure 1: base metal, which did not undergo the effect of welding heating; weld metal; heat-affected zone.

Weld metal (Figure 2) represents a mixture of deposited electrode metal and partially molten base metal of a joint being produced.

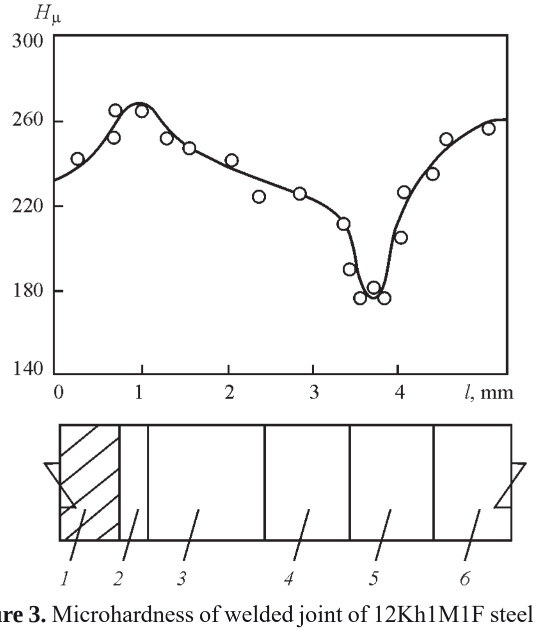

Figure 3. Microhardness of welded joint of 12Kh1M1F steel after operation of 290 thou h: *1* — weld metal; *2* — fusion region; *3* — overheating region; *4* — normalization region; *5* — region of partial recrystallization; *6* — base metal

The process of the molten metal crystallization begins from partially molten α-phase grains. The direction of crystal growth in the weld metal structure is coordinated with the heat removal. Welding on the optimized parameters of the mode of thick-walled steam pipes prevents the formation of relatively coarse ferrite grains in the regions of fusion and HAZ overheating (Figure 2) [10–12]. The formation of locally grouped liquation precipitations on side surfaces of crystals is also not admitted. At the same time, the formation of fine-grained, disoriented structure occurs (see Figure 2). On the macrosections (see Figure 1), the relief of each layer is clearly observed. Welding without preheating does not ensure the formation of the required amount of VC and Mo_2C carbides in the weld metal, which promotes the reduction of its properties and leads to the acceleration of damage [1–4]. The chemical composition of the weld metal is different from the chemical composition of the base metal, for example, in mechanized welding in the CO_2 + Ar environment (respectively, 50 and 50 %) of steam pipelines of 15Kh1M1F steel (Table 1) with the use of the electrode wire of Sv-09KhMFA grade (Table 2), chemical composition of the weld metal (Table 3).

Heat-affected zone representes the area of the base metal (see Figure 2), in which under the effect of welding heating, the structure was formed, which is different from the structures of the base and weld metal. Accordingly, mechanical properties are also characterized by the presence of differences (Figure 3).

The width of HAZ of welded joints of steam pipelines amounts to about 4.3–5.4 mm and is clearly observed on the macro- and microsections. Such observation makes it possible to determine the presence of normatively not recommended structures in HAZ [1, 2], as well as the presence of structures of, for example, pearlite, in which at the service life of more than 280 thou h, accelerated damage is admitted.

The metal of the region of the HAZ fusion (see Figure 2) is heated in the temperature range T_L–T_S, its width in welded joints, produced using regulatory-recommended and optimal mode parameters, is 0.1–0.2 mm. In this region, diffusion processes actively occur, which at increased parameters of the mode promotes the possible formation of coarse austenitic and ferritic grains [3, 13].

The structure of the overheating region (see Figure 2) is formed under the effect of welding heating in the temperature range T_L — 1150 °C (approximate). The width of the region amounts to 1.2–1.8 mm. At long-term exposure higher than A_{c3}, coarse austenitic grains (grain size number is 3–5, DSTU 8972:2019) can be formed in this region, which is observed in welded joints of thick-walled steam line pipes, for example, in steam pipelines of live steam (diameter is 630 mm, wall thickness is 60 mm).

The normalization region is subjected to welding heating in the temperature range of 1150 °C (approximate) — A_{c3}. Its width amounts to 0.9–1.1 mm. The structure of the region is fine-grained. The mechanical properties of the region are higher than similar properties of other HAZ regions, and damage is respectively lower.

The structure of the partial HAZ crystallization region (Figure 4) is formed under the influence of welding heating in the temperature range A_{c1}–A_{c3}. The width of the region is about 2.1–2.3 mm. Welding heating provides a partial formation of austenitic grains. A complete transformation $\alpha \rightarrow \gamma$ does not occur. And respective to the cooling rate after welding, as a result of $\gamma \rightarrow \alpha$ transformation, pearlite, sorbite or troostite can be formed, which generally enhances structural inhomogeneity. Pearlite component is especially undesirable, the presence of which contributes to the acceleration of the process of reforming the initial structure into a ferrite-carbide mixture. Such a process takes place at a long-term operation of welded joints under creep conditions.

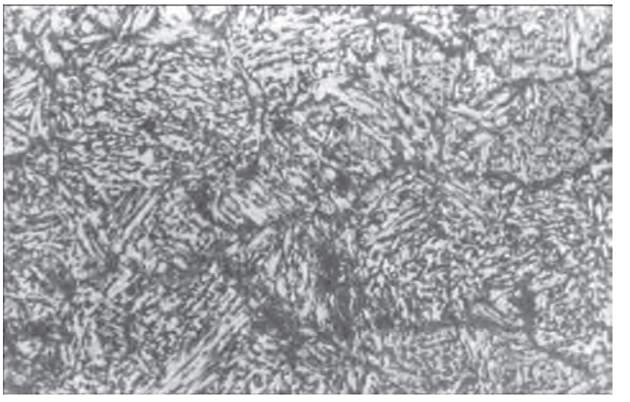

Figure 4. Microstructure (×300) of region of partial recrystallization of HAZ of welded joint of 15Kh1M1F steel [6]

Structural-phase transformations in the metal of welded joints, as a result of which a ferrite-carbide mixture is formed, depend to a large extent on their initial structure. The presence of such a mixture promotes the reduction in mechanical properties and an increase in damage to welded joints. For example, strength indices are reduced by 10–15 % and impact toughness by 15–20 % [8, 13]. Fatigue life and creep indices also depend on a structural-phase state of steels of steam pipelines. Thus, 12Kh1MF and 15X1M1F steels, having ferrite-bainite, ferrite-sorbite, ferrite-carbide and sorbite-troostite structures, are characterized by a spread of fatigue life of up to 37 % [1, 4, 8].

At a long-term operation of welded joints under creep and fatigue conditions, their damage, depending on a structural-phase state, grows significantly.

Table 4. Classification of damage to welded joints of 12Kh1MF and 15Kh1M1F steels with regard to their long-term operation under creep and fatigue conditions

Metallographic feature	Damage area	Service life, thou h	Damage cause
Damage by creep and fatigue			
Stage I Presence of pores along the grain boundaries, in places of grains contact with coagulating carbides, as well as on the body of grains	HAZ	> 250000	Structural-phase, operational, technological, design
Stage II Presence of pore chains along the grain boundaries, and pores on the body of grains	HAZ Weld metal	> 280000	Structural-phase, technological
Damage by fatigue			
Presence of fatigue-corrosion cracks having a grid and filamentous appearance	HAZ Weld metal	> 270000	Operational, structural-phase, technological
Fatigue transcrystalline cracks caused by cyclic mechanical loads under creep conditions	HAZ Weld metal	> 280000	Structural-phase, technological, operational

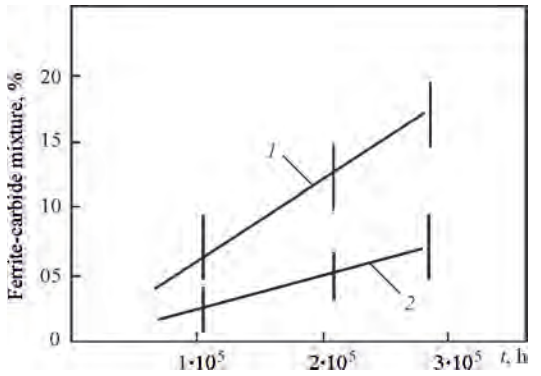

Figure 5. Dependence of ferrite-carbide mixture formation in the region of partial recrystallization of HAZ on the presence of structural components: *1* — recrystallized pearlite; *2* — sorbite. Welded joint of 15Kh1M1F steel

Therefore, it is advisable to classify the dependence of the growing damage on the features characterizing its formation (Table 4). The impact on the damage of design, technological and operational factors deserves a separate study [1–2, 4, 14–21].

Damage to welded joints by creep is featured by the predominant formation of pores on the grain boundaries in the places of the coagulating carbides contact with the α-phase grains. The mentioned damage mostly occurs in welded joints in the region of partial recrystallization of their HAZ, which is facilitated by the presence of pearlite components in its structure (see Figure 4). Namely this region is characterized by the largest softening among other regions, and its impact toughness is respectively lower.

Figure 6. Embryonic creep micropores (arrows) in the metal of welded joint of 12Kh1MF steel. Service life is 280 thou h

Also, in the region of partial HAZ recrystallization, transformation of the initial structure into a ferrite-carbide mixture occurs at a higher rate (Figure 5).

In the metal of welded joints, which operate for a long time under conditions of creep transformation of the initial structure into a ferrite-carbide mixture, the following physicochemical processes are provided:

1. Self-diffusion of alloying elements and formation of segregations along the grain boundaries.
2. Coagulation of carbides, mostly $M_{23}C_6$.
3. Carbide reactions $M_3C \rightarrow M_7C_3 \rightarrow M_{23}C_6$.
4. Travel of dislocations by sliding and climbing, as well as accumulation and annihilation of dislocations.
5. Formation of vacancies, which by fusion are transformed into microdiscontinuities and further into embryonic pores (Figure 6). Pores grow in sizes, their quantity increases, and pores are transformed into creep cracks.

The mentioned processes depend largely on the initial structure of welded joints and, therefore, take place in the HAZ regions at different rates. For example, their rate in the region of partial recrystallization, due to the presence of recrystallized pearlite grains, is higher than in other HAZ regions (see Figure 4). The deformation of this region significantly exceeds the deformation of other HAZ regions, as well as weld and base metal [3, 8]. Accordingly, the damage to the metal of this region is greater (Figure 6). In the regions of fusion and overheating, in relation to the operation of welded joints for more than 280 thou h, the rate of these processes is also accelerated, which is associated with the presence of coarse austenitic grains and requires a separate study. In general, occurrence of the considered processes in the HAZ regions is more intensive than in the weld and base metal.

Formation of fatigue cracks under creep conditions in the metal of welded joints of steam pipelines and elements of their systems is caused by the action of variable stresses. Such cracks at operation of welded joints for more than 280 thou h are formed in the regions of design and technological stress concentrators, and namely near the backing rings of butt welded joints, in the places of contact of pipe elements of different thicknesses, from undercuts, lacks of fusion, crystallization cracks and other defects (Figure 7). During operation of welded joints for more than 280 thou h, the spectrum of their formation expands. For example, cracks start forming in the region of HAZ fusion of butt and fillet welded joints. In general, the propagation of fatigue cracks is caused by thermal fatigue, which is facilitated by thermal and corrosion components of this mechanism. The propagation of fatigue cracks is also contributed by physicochemical processes occurring under creep conditions. Thermal

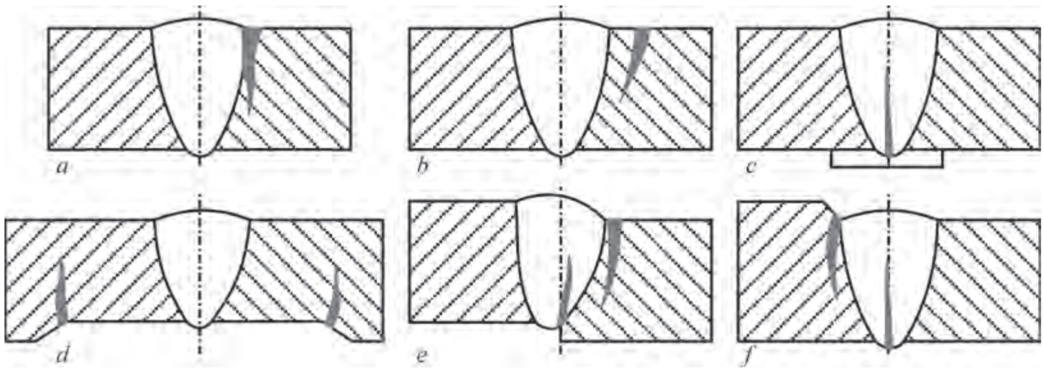

Figure 7. Typical damages of welded joints of steam pipelines: *a* — creep crack in the region of HAZ fusion; *b* — creep crack in the region of partial HAZ recrystallization; *c* — fatigue crack at the weld root near the backing ring; *d* — fatigue crack in the places of contact of pipe elements of different thicknesses; *e* — fatigue crack at displacement of steam pipeline pipes welded abutt; *f* — fatigue crack in welded joints of different thicknesses

fatigue leads to the formation of elongated cracks with probable branching. Depending on the structural state and thermal stresses, cracks may be single, as well as have the appearance of local grid cracking. Corrosion-fatigue cracks are mainly initiated on the inner surface of steam pipelines. Their propagation is facilitated by the presence of welding defects as well as defects of technological origin.

Fatigue cracks caused by cyclic mechanical loads are formed and start propagating from the outer surface of welded joints (see Figure 7). Such cracks are also formed in the contact places of pipe elements of different thicknesses.

According to the results of static analysis on the array of 50 welded joints, operated under creep conditions for more than 280 thou h, a total dependence of damage to their metal on the manifestation of the following factors was established: at a temperature rise to over 545 °C (e.g., emergency steam discharge), the damage is rapidly growing; the damage depends on a structural-phase state and the presence of initial defects. About 75–89 % of damages from its total amount occurs in the region of partial HAZ recrystallization (soft layer), as well as in the overheating region, where austenitic grains are coarse (size number is 3–5). The damage caused by the manifestation of initial defects, is about 20–25 % of its total amount.

To determine the reliability and residual life of welded joints of steam pipelines at their operation for more than 280 thou h, it is advisable to know the dynamics of the dependence of damage of their metal on the considered peculiarities.

CONCLUSIONS

1. It was established that during operation of welded joints of steam pipelines for more than 280 thou h under creep conditions, their structural-phase state is mainly the main factor that leads to the damage of welded joints by creep.

2. It was determined, that producing welded joints of steam pipelines on the optimized mode parameters allows obtaining sorbite or troostite as recrystallization components in the region of partial HAZ recrystallization, and preventing the formation of pearlite.

3. Systematization of physico-chemical processes occuring in the metal of welded joints, operating for a long time under creep and fatigue conditions was proposed. The presence of such systematization is necessary for the study of features of individual processes, which is appropriate for the development of new steels.

4. It was found that the rate of formation of ferrite-carbide mixture in the structure of long-term operating welded joints depends on the presence of a pearlite component in their structure. The rate of formation of such a mixture can be reduced by producing welded joints with improved indices of their initial structure.

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