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Dedicated to the 117th anniversary of the birth of K.F. Starodubov

FEATURES OF THE FERRITE-BAINITE STRUCTURE LOW-ALLOY LOW-CARBON STEEL AFTER HEAT HARDENING AND SUBSEQUENT TEMPERING

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Abstract. ***Problem statement.*** In recent decades, there has been a tendency to increase the mechanical properties of low-carbon, low-alloyed steel plate iron by using controlled rolling or hardening heat treatment of finished steel parts. At the same time, for welded parts, the most suitable is a metal having a ferrite-bainite (or bainite) structure. The work investigated the features of the ferrite-bainite structure of low-carbon and low-alloyed steel 15ХСНД for the production of connecting pipeline parts. ***Purpose of the article.*** To establish the laws of formation of a ferritic-bainitic structure in low-carbon low-alloy steels depending on the parameters of heat treatment. Determine the effect of heat treatment parameters on the properties of the connecting parts of pipelines made of these steels. ***Conclusion.*** The regularities of the influence of heat treatment parameters on the structure, mechanical properties and topography of fractures of impact samples of 15ХСНД steel with a ferrite-bainitic structure are established.

Keywords: *stamped-welded connecting parts of man pipelines; heat treatment; microstructure; bainite; mechanical properties; fractography*

ОСОБЛИВОСТІ ФЕРИТНО-БЕЙНІТНОЇ СТРУКТУРИ НИЗЬКОЛЕГОВАНОЇ МАЛОВУГЛЕЦЕВОЇ СТАЛІ ПІСЛЯ ТЕРМІЧНОГО ЗМІЦНЕННЯ ТА НАСТУПНОГО ВІДПУСКУ

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Анотація. ***Постановка проблеми.*** В останні десятиріччя спостерігається тенденція до підвищення комплексу механічних властивостей товстолистового прокату з маловуглецевих низьколегованих сталей за рахунок використання контрольованої прокатки або зміцнювальної термічної обробки готових виробів із нього. При цьому для зварюваних металовиробів найбільш прийнятним визнано метал, що має феритно-бейнітну (або бейнітну) структуру. Досліджувались особливості феритно-бейнітної структури маловуглецевої та низьколегованої сталі 15ХСНД для виробництва з'єднувальних деталей трубопроводів. ***Мета статті*** – встановити закономірності у процесах структуроутворення в маловуглецевих низьколегованих сталях із феритно-бейнітною структурою залежно від параметрів термічної обробки та їх вплив на властивості з'єднувальних деталей трубопроводів. ***Висновки.*** Встановлено закономірності впливу параметрів термічної обробки на структуру, механічні властивості та характер руйнування ударних зразків сталі 15ХСНД з феритно-бейнітною структурою.

Ключові слова: *штампозварні з'єднувальні деталі магістральних трубопроводів; термічна обробка; мікроструктура; бейніт; механічні властивості; фрактографія*

Introduction. In recent decades, in the production of plate steel from low-carbon low-alloy steels in the production of pipes and connecting parts of main pipelines (CPP), there has been a tendency to increase the complex of mechanical properties due to the use of either the technology of controlled rolling of rolled metal, or hardening heat treatment of finished products. Moreover, for welded metal products, the most suitable is a metal that has a ferritic-bainitic (or bainitic) structure.

For the industrial production of competitive connecting parts for main oil and gas pipelines with a diameter of up to 1 420 mm at strength levels X60−X80 and higher, parameters of hardening heat treatment of stamped-welded connecting parts were developed. This developed heat treatment is ensuring the obtaining of a ferrite-bainitic or bainite structure in low-carbon low-alloy steels with a thickness of 14...50 mm.

When developing technology and equipment for bulk heat hardening (HH) of stamped-welded connecting parts of piplines (CPP), the parameters of heating modes for finishing heat treatment (austenitization temperature, cooling intensity, tempering temperature, etc.) were selected, Design and technological parameters of the heating device and cooling environment providing the required level of normalized properties due to the production of parts of ferrite-bainitic or bainitic structure in the metal [1–3].

As a result of comprehensive studies, the regularities of the formation of a ferrite-bainitic (bainitic) structure in low-carbon low-alloy steels during heat hardening and subsequent tempering in various temperature ranges were established [4].

The influence of the processes of formation of a ferrite-bainitic (bainitic) structure on the change in the complex of mechanical properties at all stages of heat treatment of finished parts made of steels of different alloying levels also was established (09Г2С, 10...15ХСНД, 14...16Г2АФ, 15Г2АФЮ, 09...10Г2ФБ, etc.).

Table 1 shows the chemical composition of steel 15ХСНД (in accordance with GOST 19281-89) and the chemical composition of one of several melts of this steel (close to the lower limit in carbon concentration).

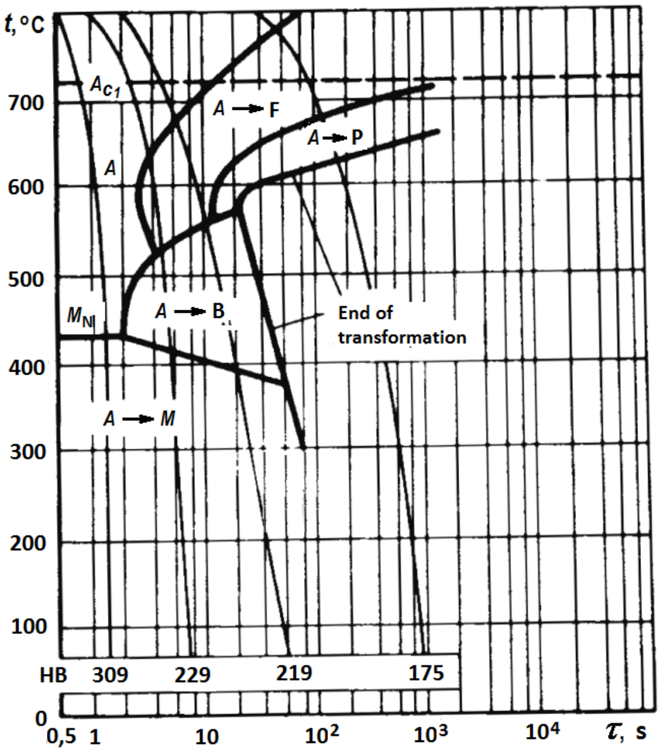
Table 1

The chemical composition of steel 15ХСНД in accordance with GOST 19281-89 and the chemical composition of the melting of this steel, which was investigated in this work

C	Si	Mn	S	P	Cr	Ni	As	Cu	N
0,12...0,18	0,4...0,7	0,4...0,7	≤ 0,040	≤ 0,035	0,6...0,9	0,3...0,6	≤ 0,08	0,20...0,40	≤ 0,012
0,12	0,45	0,56	0,029	0,023	0,73	0,33	0,08	0,24	—

In this case, in products made of steels of the 10...15KhSND type in thicknesses of more than 18...30 mm in the process of bulk heat hardening, a ferrite-bainitic structure with a different number of structural components was formed with unchanged parameters of the austenitization and accelerated cooling regime and the strengthening phase upper bainite. The morphology of the upper bainite is represented by alternating plates of ferrite and cementite [1–5].

Figure 1 shows the thermokinetic diagram of 15ХСНД steel, in which there are clearly identified temperature-structural zones. The diagram allows you to calculate critical cooling rates and select quenching media to obtain the desired structural state of the metal during heat treatment..



Chemical composition of steel smelting, which was investigated to construct a thermokinetic diagram (TKD):
C = 0,17 %; Si = 0,44 %; Cr = 0,73 %;
Ni = 0,35 %; Cu = 0,28 %.
A_{C1} = 720 °C/c;
A_{C3} = 840 °C;
t_{aust} = 930 °C.
To calculate the critical cooling rate in order to obtain the structure of martensite, bainite or ferrite-pearlite structure, the following data were used in accordance with this diagram A_{r1} = 680 °C.
V_M ~ 120 °C/s;
V_B ~ 33 °C/s;
V_{F+P} ~ 12 °C/s.

Fig. 1. Thermokinetic diagram of the decomposition of austenite steel 15ХСНД [6]: t − the temperature of the metal, C; τ – the time during which the process of structure formation in the metal, seconds; HB – metal hardness according to the Brinell method (GOST 9012); structural components: A – austenite, P – perlite; F – ferrite, M – martensite; B – bainite; A_{C1} – temperature of the first critical point when heating steel, C; A_{C3} – temperature of the third critical point when steel is heated, C; Ar_1 – temperature of the first critical point during steel cooling, C; M_N − the temperature of the critical point corresponding to the beginning of the martensitic transformation of supercooled austenite, C; t_{aust} – the temperature of austenitization, °C; V_M − the critical cooling rate for obtaining a martensitic structure in steel, °C/s; $V_Б$ − the critical cooling rate for obtaining a bainitic structure in steel, C/s; $V_{(F+P)}$ − the critical cooling rate for obtaining a ferrite-pearlite structure in steel, C/s

To obtain the desired structural state in the metal (according to the set of mechanical properties), it was necessary to ensure a stable and uniform process of forced cooling of the metal with a given intensity.

Methodology. When choosing the parameters of the process of thermal hardening of CPP, water with a temperature of more than 90 °C was selected as the cooling medium, which ensured the temperature stability of the process of heating by heating by evaporative cooling and obtaining the desired structural state in the metal of products with different wall thicknesses. It is known that for each quenching medium (including liquid), which changes its state of aggregation, there is a cooling curve (in the coordinates “cooling rate – surface temperature of the cooled metal” or “heat transfer coefficient, which is characteristic only for a specific composition and state-surface temperature of the cooled metal”). In Figure 2 shows the characteristic cooling curves for water at various temperatures [7]. From figure 2 it is clearly seen that for water at temperatures above 90 C the film boiling stage continues from the moment the metal is immersed in such a cooling medium and to the surface temperature of the treated metal, approximately 200…180 °C (at this temperature the metal is already in an elastic state). The choice of the cooling medium and the cooling method should provide the required cooling rate in the subcritical region, at which partial decomposition of austenite will take place in the ferritic and bainitic regions of the state diagram of this steel in accordance with the developed method [5] and the state diagram. A feature of the cooling medium that was used for the thermal hardening of CPP was the presence in it of a low-temperature region of the crisis of boiling in the temperature range 160…200 °C. Those, the transition from film to bubble boiling took place in a very short time (actually thermal shock) in the temperature range when the mobility of dislocations is very small in the metal. The resulting thermal stresses are not able to quickly relax, which leads to the appearance in the metal with the ferrite-bainitic or bainitic structure of an additionally portion of defects in the crystal lattice – vacancies, dislocations and stresses.

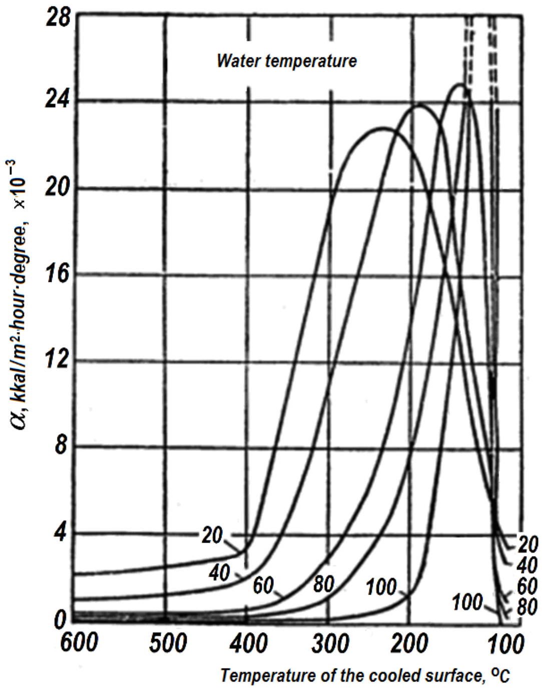


Fig. 2. Curves of changes in the heat transfer coefficient (α) depending on the surface temperature of the hardened metal obtained by cooling silver balls in water with different temperatures [7]

Moreover, the character of the dependence of the metal heat transfer coefficient on temperature largely determines the behavior of metal products during the hardening process – cold buckling or even partial or complete cracking of parts of various sections. These processes are the result of thermal impact, i.e. the emergence of large temperature gradients over the cross section of the part in a short time. Such an effect of quenching on a heat-treated metal is similar to a cold deformation process.

The researchers were faced with the task of developing a technology for heat treatment of parts, which should provide not only a normalized level of strength characteristics, but also toughness, for which the level of values is normalized depending on the pressure and diameter of the pipeline (Table 2).

It is known that the impact toughness and the type of fracture of impuct samples are most sensitive to changes in macro-, micro- and fine structure, as well as to changes in the stress state of metal samples. There is an established opinion in the literature about the low toughness of a metal, which has upper bainite in the structure. The developed technology of heat hardening of CPP from 17ГС, 10...15ХСНД steels and a number of other steels ensures the presence of just such a structural component in the structure (ferrite + bainite or only bainite), and needle ferrite is stably present in the structure of 09...10Г2ФБ steels. Therefore, a series of studies was conducted aimed at studying the influence of the parameters of the developed technology on the macro-, micro-, fine metal structure and the type of fracture of impact samples.

Such important parameters of the volumetric heat hardening regime include, first of all, the austenitization temperature, which determines the size of the austenitic grain, the degree of homogeneity of austenite and its resistance to $\gamma \rightarrow \alpha$ transformation, as well as the temperature of cooling water. The water temperature should be $\geq 90\ ^oC$ to ensure the stability of obtaining a given structural state and the required level of residual stresses in the metal of the product.

Table 2

The value of toughness (KCV) for pipes of difference large diameters in accordance with the requirements of SNiP 2.05.06-85 depending on the working pressure (7.5/10 MPa)

Diametr of pipe, mm	1 000	1 200	1 400
KCV, J/cm^2	58,8/78,4	78,4/107,8	39,2/58,8

Based on the analysis of literature and experimental data, it was established that for steels of the type 10...15ХСНД, the temperature of critical growth of austenitic grain (TCGAG) during heating of the metal is approximately 1 000…1 050 ^oC. The choice of austenitization temperature at the level of 980…990 ^oC (i. e., at 80…90 ^oC higher than A_{C3}, but not higher than TCGAG) is due to the need to obtain a homogeneous and sufficiently fine austenite grain with increased resistance to subsequent decomposition upon cooling. Stabilization of the necessary parameters of austenitization makes it easier to implement the intermediate mechanism of decomposition of austenite during quenching of metal products.

Results and discussion. Thus, after the heat hardening of CPP from steels of the type 15ХСНД, 17ГС, 09Г2С and others, we obtain a ferrite-bainitic or bainitic structural state depending on the wall thickness, on which the metal cooling rate depends).

In figures 3–6 shows the microstructures of 15ХСНД steel at various magnifications (chemical composition corresponds approximately to the lower grade, wall thickness 30 mm) after different modes of heat treatment.

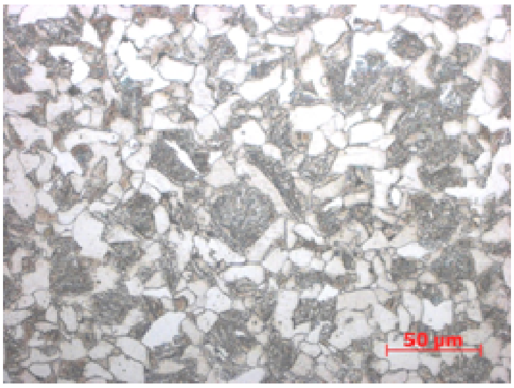
To describe the features of the structural state of the steels under study, the basic principles of classification by G. Krauss [8], which are often used by researchers from the CIS countries [9], were used.

Using the terminology of the authors of [9], after heat hardening of steel of the 15ХСНД type, a ferrite-bainitic structure was obtained, the ferrite component of which was quasi-polygonal (massive) ferrite (QPF), which differs from polyhedral ferrite (PF) by curved boundaries, high density of dislocations that form substructural constructions.

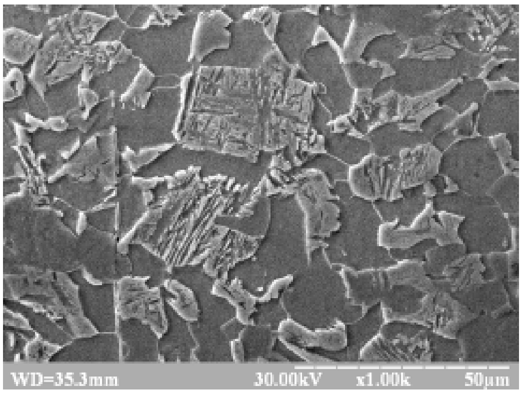
The bainite component of the metal structure was defined as upper bainite in accordance with the classical works of G.V. Kurdyumov, Tavadze et al. or rack bainite [9], as in the classification system of the Bainite Committee of the Japanese Institute of Steel and Alloys (ISIJ) [10−12]. In general, this structural component, investigated by various methods, represents alternating long thin laths of bainitic ferrite and cementite, combined into large packets of relatively equiaxial shape with an insignificant amount (up to 3 %) of retained austenite along the lath boundaries. This article examines the microstructures of 15ХСНД steel after heat hardening in water with a temperature above 90 ^oC by the mode of complete cooling to the ambient temperature.

Under a light microscope, bainite colonies look like translucent glass (light yellow or light gray) in which streaky discharge of a darker color is visible. Subsequent tempering (up to ~500 ^oC) does not significantly change the structure of bainite colonies visible under an optical microscope. And only after higher tempering temperatures (Fig. 4, 5), visible acicular components of dark color begin to appear inside the bainite colonies – cementite slats along their entire length, which begin to break up with an increase in the tempering temperature or holding time.

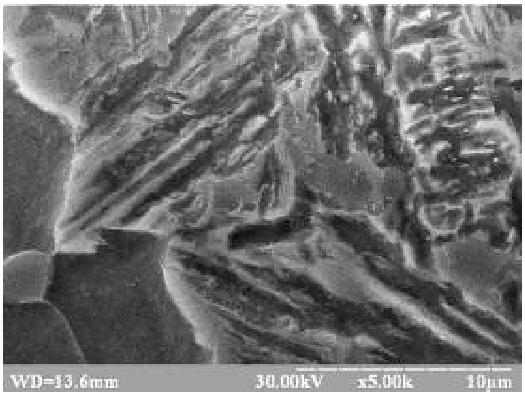
In Figure 7 shows generalized graphs of the effect of heat treatment parameters on the change in the complex of mechanical properties of 15ХСНД steel with a melting chemical composition close to the lower and average grade composition.



a – ferrite-bainite structure at ×500 magnification under a light microscope

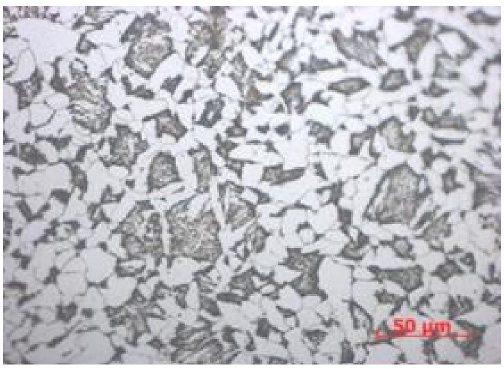


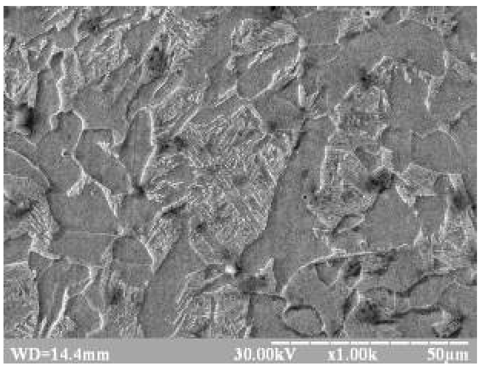
b – ferrite-bainitic structure under a scanning microscope



c – ferrite-bainitic structure under a scanning microscope

Fig. 3. Microstructure of 15KhSND steel after heat hardening in water with a temperature of ≥90 °C according to the complete cooling mode at different magnifications





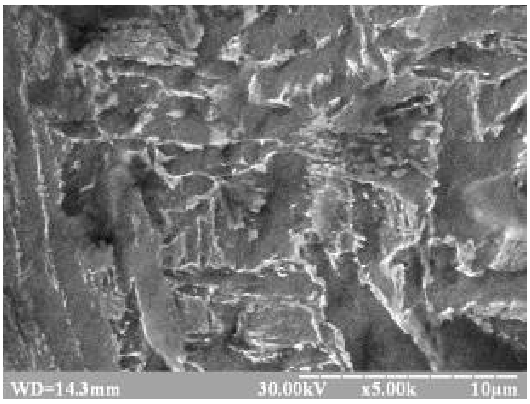
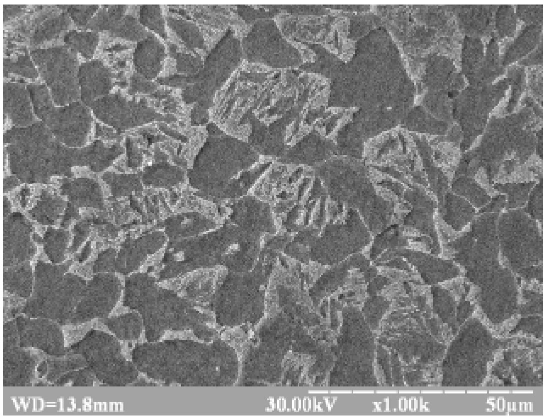


Fig. 4. Microstructure of 15ХСНД steel after heat hardening in water with a temperature of ≥90 °C according to the mode of complete cooling and subsequent tempering 500 °C (30 min) at different magnifications



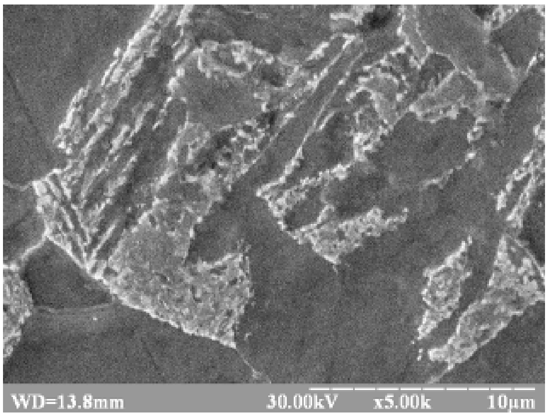


Fig. 5. Microstructure of 15ХСНД steel after heat hardening in water with a temperature of ≥90 °C according to the mode of complete cooling and subsequent tempering 500 °C (30 min) at different magnifications

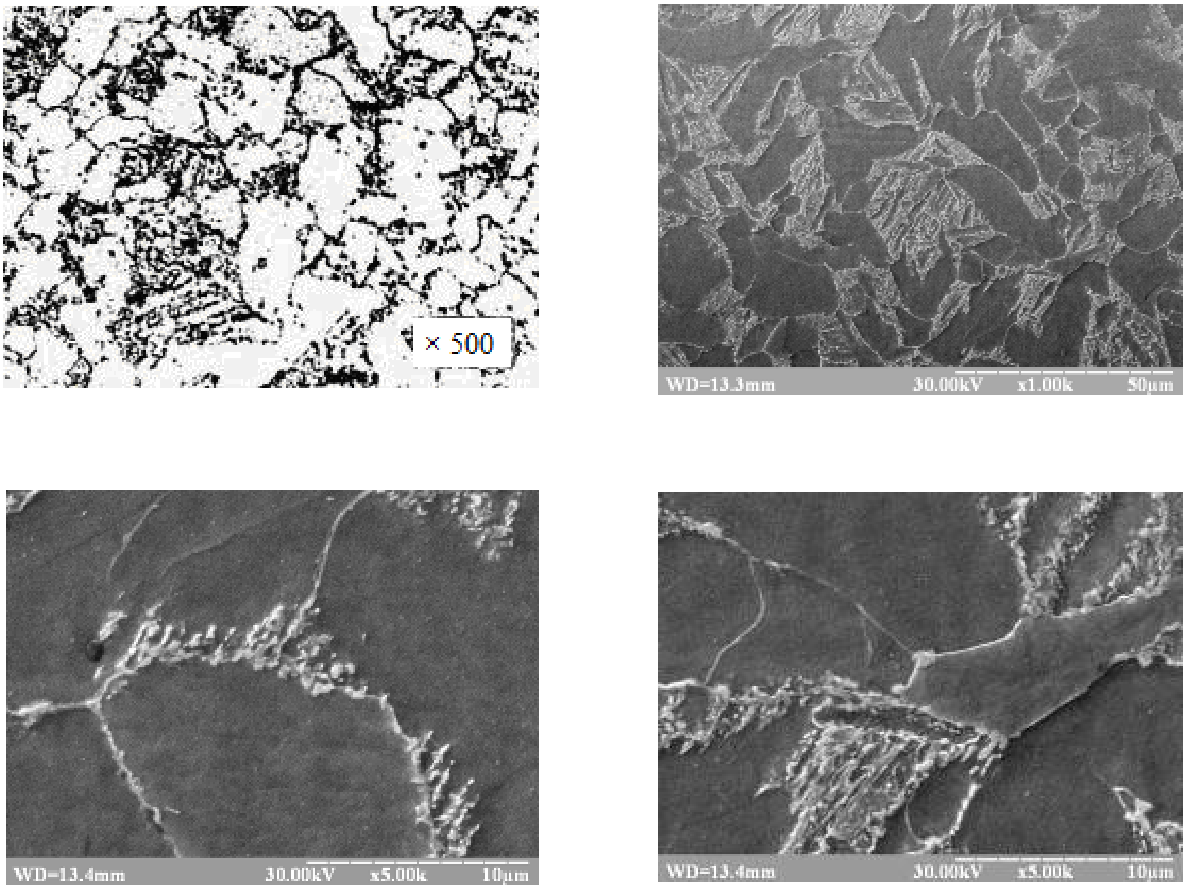
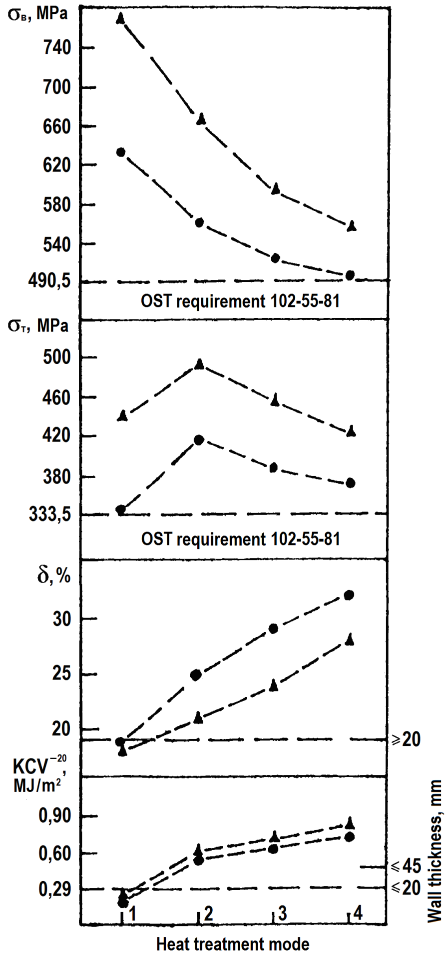


Fig. 6. Microstructure of 15ХСНД steel after heat hardening in water with a temperature of ≥90 °C according to the mode of complete cooling and subsequent tempering 700 °C (30 min) at different magnifications

Studies have shown that after heat hardening according to the developed technology, the degree of saturation of the ferritic structural component of steels with ferritic-bainitic structure with carbon and defects in the crystal structure is sufficient to ensure structure formation processes during subsequent tempering that can provide a required yield strength level in the metal (Fig. 3). The results of studies of the processes of structure formation, which were obtained in the process of developing the technology of heat hardening CPP, are confirmed by a number of studies, for example [8]. In these works, a new regularity of the change in the concentration of carbon in the ferrite component was established at the used cooling rates of the metal of the parts. In the process of heat hardening in the temperature range of 480…550 °C in the solid solution of ferrite can be up to 0,06 % carbon. This concentration of carbon in the ferrite component of the structure is sufficient for the formation of cementite particles during the next tempering. Considering that in such a cooling method, a sufficiently high density of crystal lattice defects occurs in the metal (Table 3), which will delay the redistribution of carbon atoms in the metal during subsequent tempering, the temperature of formation of cementite particles is expected to will be displaced towards tempering temperatures of 300…320 °C.

The level of impact toughness of a heat hardening metal is determined by the tempering temperature, which affects the degree of decomposition of structural components, the level of microstrains, the size of the particles of the secondary phase, their number, location, etc.

İn Figure 8 shows the results of a study of the type of destruction of Charpy impact specimens made of 15ХСНД steel after different heat treatment modes, performed using instrumental and scanning microscopes at different magnifications and tested at a temperature of minus 20 °C. At magnifications of ×3 and ×25, the topography of the fractures of impact specimens after various heat treatments showed the presence of a viscous and brittle component. After the HH regime, brittle fracture occurs, and after further tempering >400 °C at different temperatures of the heat hardening metal, areas of the brittle component, metal striping (in the form of parallel lines, ridges and troughs) and structural rolling striping caused by dendritic structure deformation are formed on the surface of ductile fractures of the samples.

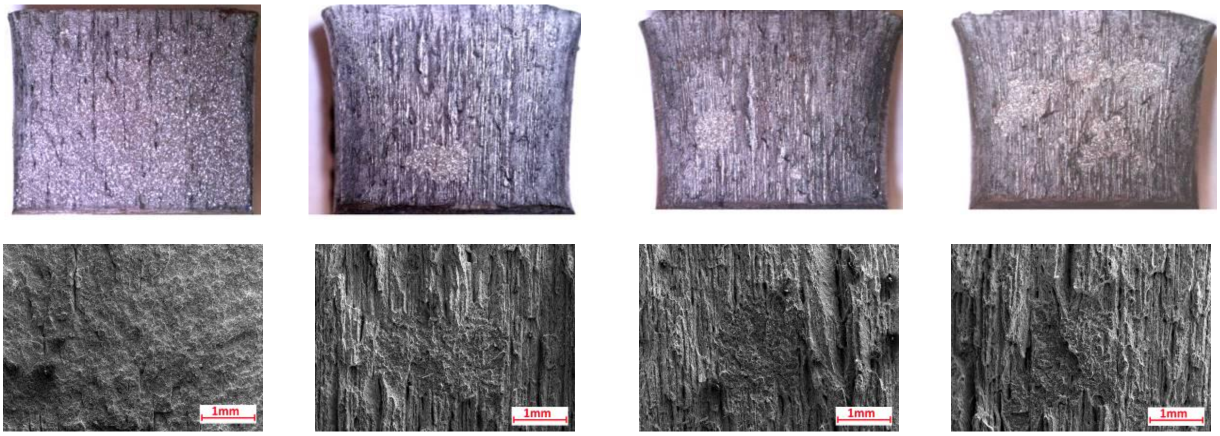


Mode 1 – water heat hardening (WHH) from 980 °C in water (t_W = 94...98 °C) until the metal cools completely.
Modes 2, 3, 4 – WHH + Tempering 500, 600, 700 °C, 30 min.
● – *melting 1, corresponds to approximately the lower grade composition by carbon concentration;*
▲ – *melting 2, corresponds approximately to the average grade composition.*
Fig. 7. The dependence of the mechanical properties of steel 15ХСНД on the heat treatment mode and grade chemical composition : $\sigma_в$ *– tensile strength, MPa;* $\sigma_т$ *– yield strength, MPa;* δ *– relative extension, %;* KCV^{-20} *– impact ductility, determined on a sample with a concentrator of type V at a temperature of minus 20 °C, MJ/m²*

Table 3

The results of x-ray structural studies of steel 15ХСНД after various heat treatment modes

Mode of heat treatment	Level of microdeformations, L, $\times 10^{-3}$	Density of dislocations, ρ, $\times 10^{10}$, см$^{-2}$
Water heat hardening (WHH) ($t_W \geq 90$ °C)	0,27	1,94
WHH + Tempering 300 °C	0,60	4,98
WHH + Tempering 400 °C	0,37	1,89
WHH + Tempering 500 °C	0,29	1,21
WHH + Tempering 600 °C	—	0,90
WHH + Tempering 700 °C	—	0,65



Mode of heat treatment of metal

after water heat hardening (WHH) | *after WHH + Tempering 500 °C, 30 min* | *after WHH + Tempering 600 °C, 30 min* | *after WHH + Tempering 700 °C, 30 min*

Fig. 8. View of the fracture of impact samples (10 × 10 mm) made of 15ХСНД steel after various heat treatment modes and after testing at – 20 °C, performed using a scanning microscope at various magnifications (photo of the top row – ×3, bottom – ×25)

Table 4 shows the impact toughness of the studied metal depending on the test temperature and processing mode, and in figures 6 and 7 are the results of the study of fractures of metal samples: a brittle fracture after WHH (Fig. 6) and a ductile fracture (Fig. 7) after the WHH mode + tempering 600 °C.

The figure 9 (on the top photos) shows a general view of the fracture at magnifications (×100 and ×500), which allows us to evaluate the fracture of the metal as brittle (flat facets) and consider the joint of two layers of metal formed during rolling. Figure 6 (on the bottom photos) shows enlarged sections of a brittle fracture (×500 and ×2 000), it can be assumed that the size of each facet corresponds to the size of the austenitic grain, and the limiting sections between these facets were destroyed by a ductile mechanism. This is evidenced by a comb with a large number of facets in the form of holes.

Figure 10 shows the fracture sections of impact specimens at various magnifications. Impact specimens were tempered at 600 °C after heat hardening. Figure 10 *a* (×100) shows a section of a metal fracture with a ductile component and with clearly defined metal streakiness in thickness (in the form of parallel sections of ridges and depressions between them). In Figure 10 *c* the ductile component of the surface of the fracture of the metal is shown at a magnification of ×500. Figures 10 *b* and *d* show a photo of the portion of the fracture of the sample that corresponds to the top of the ridge (the ductile component at magnification ×2000 – Figure 10 *b*) and to the depression (brittle or quasi-brittle component of a metal fracture at magnification ×2 000 – Figure 10 *d*).

Table 4

Change in toughness (KCV) of steel 15ХСНД depending on the heat treatment mode and test temperature

Test temperature of samples	Mode of heat treatment of metal					
	WHH ($t_W \geq 90$ °C)	WHH + + Tempering 300 °C, 60 min	WHH + + Tempering 400 °C, 60 min	WHH + + Tempering 500 °C, 60 min	WHH + + Tempering 600 °C, 60 min	WHH + + Tempering 700 °C, 60 min
	Toughness (KCV), J/cm^2					
–20 °C	13	28	41	59	81	79
–40 °C	12	21	36	39	56	57
–60 °C	10	17	23	29	39	39

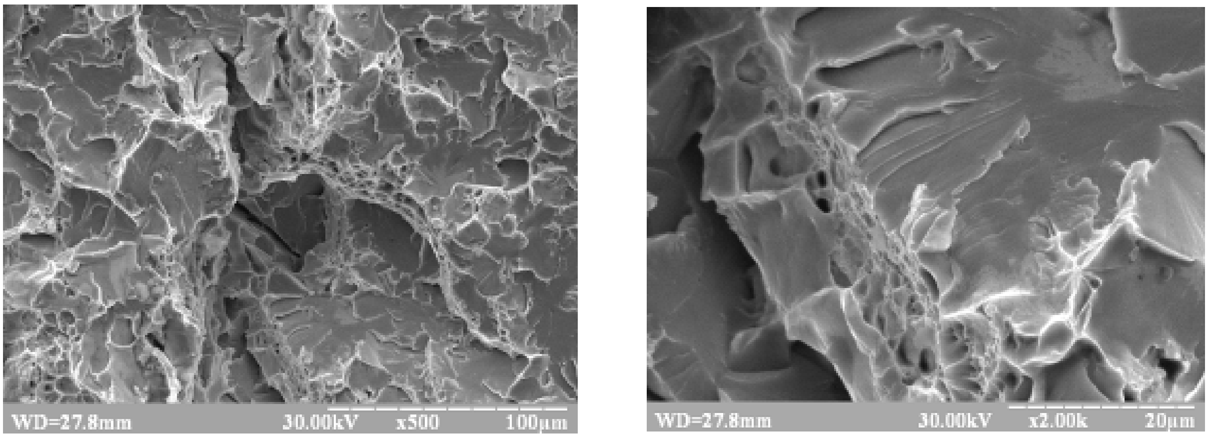


Fig. 9. Fractography of fractures of metal samples after heat hardening at various magnifications

In the production of plate metal in a metal, structural changes occur at various hierarchical levels at all stages of the production technology (ingot crystallization, hot rolling (normalized or controlled) and finishing heat treatment). These structure formation processes have their own characteristics. For example, for sheet metal produced by the controlled rolling method, the characteristic features of the macro- and microstructure of the metal are the stratification of the metal along planes parallel to the surface of the sheet, inside which there is a pronounced structural streakiness (for example, ferrite-perlite) [9]. The fractures of high-strength pipe steels after controlled rolling have sections in the form of ridges. These ridges in microphotographs look like lines located in the rolling plane (parallel to the surface of the sheet) and are referred to in the European Standards (EN 10274) as the "dimensional arrow". For sheet metal obtained by the normalization rolling method, the phenomenon of metal stratification along planes manifests itself to a lesser extent, and structural streakiness remains quite pronounced. In this article, we used 15ХСНД plate steel, produced by the normalization rolling method, which, after hot stamping and welding, was subjected to hardening heat treatment with thermal impact in the low-temperature region already in the product. There is reason to believe that heat treatment with thermal impact in the low-temperature region together with bainitic decomposition enhanced the effect of metal layering in the structure of fracture of impact samples. It should be noted that fragments in the form of a “dimensional arrow” are present in the fracture surface of the samples not only in the heat hardened state, but also after the next tempering at various temperatures.

In this case, the ductile constituent in the fractures of the samples appears after heat hardening followed by tempering at 450 °C and higher, and the maximum amount of the ductile constituent (as well as the level of impact strength (look Table 4 and Fig. 3)) in the fractures of Charpy samples is observed after tempering, 600 ^{o}C (look Fig. 5). In the fracture of such samples (after tempering at 600 ^{o}C), there are virtually no sections of the classic brittle failure, but sections with fragments in the form of a “dimensional arrow” are clearly visible along the entire plane of the fracture. Standards of the CIS countries (GOST 30456) and the USA (API RP 5L3) classify such a break as ductile fracture. After tempering at 700 ^{o}C (even at a test temperature of minus 20 ^{o}C), sections of the brittle component reappear in the fracture of impact specimens, which is mainly due to coagulation and growth of carbide particles. The energy values of the impact strength of the metal after tempering at 700 ^{o}C can be such that they are equal to or even higher than for metal after tempering at 600 ^{o}C. In fractures of samples after tempering at 700 ^{o}C, sections with fragments in the form of a “dimensional arrow” and individual depressions (visually visible stratifications of metal along planes) are also observed

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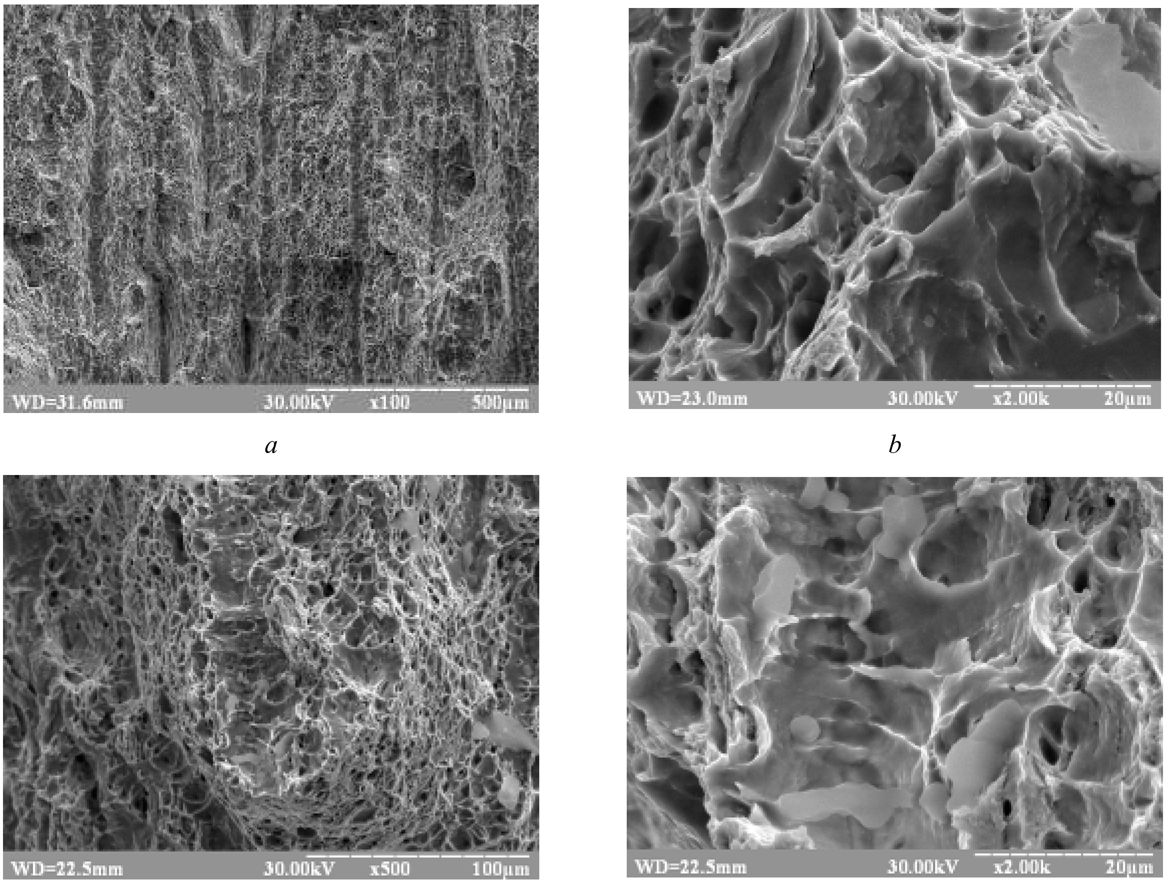

a *b* *c* *d*

Fig. 10. Fractography of fractures of metal of impact samples after heat treatment according to the WHH regime + Tempering 600 °C

Lowering the test temperature to minus 40 and 60 °C reduces the level of toughness and the amount of the ductile component in the fractures of impact samples, including after tempering at 600 °C. Studies have shown that for steels with ferrite-pearlite or ferrite-bainitic structure, heat hardening in water (or aqueous chloride solutions) with a temperature >80 °C has a number of negative factors. Studies of toughness in terms of components (fracture energy of samples and the amount of ductile component in fractures of impact samples) showed that the cold-shortness threshold of a metal heat-strengthened with complete cooling (i. e. to the temperature of the quenching medium) is significantly higher compared to the same metal subjected to similar heat treatment but with interruption of the cooling process at >200…250 °C, that is, above the boiling crisis temperature (Table 5, Fig. 11).

From the data of the right graph (see Fig. 8) it is clearly seen that for Charpy samples, after heat hardening with complete cooling of the metal to the temperature of the quenching medium, the cold-shortness threshold, according to the T_{50} criterion (50 % of the ductile component in the fracture of the samples) is at a temperature of minus 10 °C. In case for Menager test piece, after the same heat hardening regime, the cold-shortness threshold lies at the temperature of minus 30 °C. At the same time, for Charpy samples, the metal of which was heat hardened by the interrupted cooling regime at a metal temperature of 300 °C (that is, a self-tempering mode was implemented at 300…250 °C), the cold-shortness threshold (T_{50}) is at a temperature of minus 60 °C.

Table 5

The effect of the heat hardening mode of low-carbon low-alloy steel (for example, steel 09Г2С with a wall thickness of 8 mm) on the level of defect of the crystal lattice and microstrains in the metal

Mode of metal treatment	Level of microstrain, L, $\times 10^{-4}$	Dislocation density, ρ, $\times 10^{10}$, cm^{-2}
Heat hardening (HH) in hot water until the metal is completely cooled	5,6/5,1	3,4/3,0
HH in hot water with interruption of cooling at a metal temperature at ≈250 °C	1,1/4,3	2,6/2,1
HH in hot water with interruption of cooling at a metal temperature at ≈250 °C	0,8/3,6	1,9/1,2
oil quenching (+40 C)	6,1/–	5,04/–
Water quenching (+20 °C)	24,6/–	1,01×10^{11}/–

Note: the numerator shows the values for heat-hardened metal in water with a temperature >90 °C, in the denominator – after heat-hardening and subsequent tempering at 500 °C

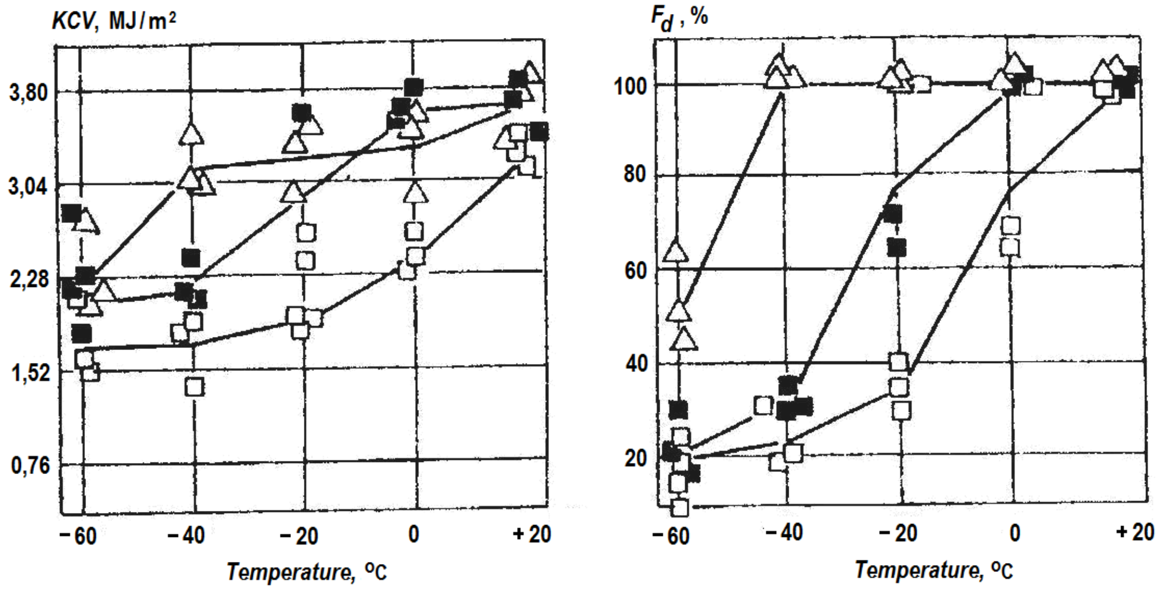

Fig. 11. The dependence of the toughness (KCV) of steel 09Г2С (made in Japan) and the amount of the ductile component (F_d, %) in fractures of impact specimens on the regime of thermal hardening (□ or Δ) and test temperature (from +20 °C to 60 °C) :
■ – values of toughness (KCU) of the metal of the Mesnager test piece after heat hardening in water with $t_B \geq 90$ °C with cooling to the temperature of the quenching medium;
□ – values of toughness (KCV) of Charpy specimen metal after thermal hardening in water with $t_B \geq 90$ °C with cooling to the temperature of the quenching medium;
Δ – the same (values of toughness (KCV) of Charpy specimen), but with interrupted cooling at a metal temperature of 300 °C

The research results showed that during the implementation of interrupted cooling during the heat hardening, the level of toughness for all the studied steel grades was higher in comparison with the regime in which the cooling of metal wasn't interrupted. And the level of strength characteristics for metal subjected to interrupted cooling is lower compared to heat-hardened until the metal is completely cooled in quenching medium. But at the same time, the strength characteristics of the metal (steel type 15ХСНД and even with a lower carbon), heat-hardened by the interrupted cooling mode, satisfy the regulatory requirements for the mechanical properties of products with X60 strength level. For the manufacture of products with a strength level above X60, it is necessary to use steel of another alloying level (for example, 10Г2ФБ).

During the work, technologies were developed for the heat hardening of CPP in water or aqueous solutions of chlorides with a temperature above 80 °C with automatic interruption of the cooling process at optimal temperatures of the metal being treated (US Pat. 2277593 C1; 2265066 C2; 2256705 C1 and others). And also equipment was developed for these technologies implementation (US Pat. 2255985 C1 and others), which allows the industry to produce CPP with a strength level of up to X80 and more.

Conclusions

1. As a result of comprehensive research, the technology parameters for volumetric heat hardening of products from low-carbon low-alloy steels with the formation of a ferrite-bainitic structure, which decomposes in the course of subsequent tempering, were developed.

2. The laws of changes in the complex of mechanical properties of heat hardened steel with a ferritic-bainitic structure depending on the tempering temperature are established.

3. Studies have shown the features of changes in the fine structure of steel (the density of defects in the crystal lattice and the level of microstrains) depending on the heat treatment mode of low-carbon low-alloy steels with ferrite-bainitic structure.

4. The laws of changes in the topographic features of fractures of impact specimens from steels with ferritic-bainitic (upper bainite) structure are revealed depending on the regimes of thermal hardening and subsequent tempering

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