Influence of Long-Term High-Temperature Action on the Impact Toughness of the Base Metal and the Weld Metal of the 22K Steel Welded Joint

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Abstract—One of the applications of construction low-carbon 22K steels (AISI 1022 type) is used as a material for the body of a core catcher (CC) for nuclear power plants with water-cooled reactors (WCRs). In the event of a severe beyond design-basis accident, the CC vessel will be under conditions of prolonged high-temperature impacts, which can significantly change the structural state and lead to degradation of the mechanical properties of the vessel material. The data on the effect of such actions on the mechanical properties and fracture resistance of welds (its properties usually differ from those of the base metal) from low-carbon steels are very limited in the literature, which makes it difficult to guarantee the reliability and safety prediction of CC. The purpose of this work was to carry out comparative Charpy V-notch impact tests of samples of the base metal and the weld metal of the 22K steel welded joint before and after long-term high-temperature heat treatment, simulating the thermal effect in the conditions of a severe accident on the material of the NPP vessel. Welded joints of 22K steel sheets were obtained by the method of automatic argon-arc welding with a consumable electrode (welding wire SV-08G2S was used) in accordance with Rules and norms in nuclear industry PNAE G-7-009–89. Based on the test results, the ductile–brittle transition curves were plotted and the analysis of fracture of the samples was carried out. The influence of structural factors on the KCV impact toughness has been studied. It is shown that prolonged high-temperature exposure leads to an increase in the temperatures of the beginning and end of the ductile-brittle transition by 30–50°C and to an expansion by 15–25°C of the temperature range of the ductile-brittle transition of both the base metal and the weld metal of the welded joint.

Keywords: low-carbon steel, core catcher, weld, impact toughness, ductile–brittle transition curves, microstructure, heat treatment, fracture

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INTRODUCTION

Construction low-carbon steels of the 22K type have good weldability \cite{1–5} and are usually used as a structural material for operation under medium mechanical loads and temperatures no higher than 450°C \cite{6–8}.

The properties of the weld are usually different from those of the base metal \cite{1, 9, 10}. The heating temperature in the weld zone, which is significantly higher than the austenization temperature during heat treatment of the base metal, and the differences in crystallization conditions due to the nature of thermal fields and small melting zones, create non-equilibrium conditions for structural-phase transformations in the weld zone. When using electrodes, welding wire and other materials in the welding process, it is possible to change the chemical composition in the seam zone relative to the base metal.

In emergency situations, the superduty structures made of low-carbon steels—elements of the vessel for core catcher (CC) in Russian VVER nuclear reactors of a new generation—will be subjected to prolonged...
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Table 1. Chemical composition of 22K steel welded joints

| Material    | Fe  | C   | Si  | Mn  | P   | S   | Cr  | Ni  | Cu  | Co  |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Base metal  | Bal.| 0.23| 0.25| 0.74| 0.013| 0.001| 0.04| 0.03| 0.02| 0.01|
| Weld metal  | Bal.| 0.11| 0.61| 1.39| 0.013| 0.006| 0.06| 0.08| 0.12| 0.02|

The duration of thermal exposure was 7 days. The process was carried out in a SNVE 1.3.1/16I4 furnace in a vacuum of $6.5 \times 10^{-3}$ Pa with automatic digital recording of signals from control thermocouples. This temperature regime was obtained from the computer simulation results of the cooling process of the vessel material in a severe accident.

The impact toughness tests were carried out on specimens $10 \times 10 \times 55$ mm in size with a V-notch (type 11 according to GOST 9454-78) at temperatures from 150 to $-80^\circ$C on an INSTRON SI-1M pendulum impact tester with a maximum impact work of 300 J when the speed of the pendulum at the moment of impact is $5 \pm 0.5$ m/s. The cuts were made on the samples by the electrospark method. Impact specimens from the weld metal of the welded joint were made so that the notch was located in the center of the weld. The geometry of the notched samples was controlled using an optical microscope. The impact samples were heated to the test temperature in an electric furnace, and cooling was carried out in a LAUDA Pro-line RP890 climate chamber. The samples were heated/cooled for 15 min, after which they were transferred to a pendulum impact tester for 5 s and tested. For plotting serial curves, 18 samples of each state were tested. The temperature range of ductile-brittle transition was determined from the temperature of the onset of the appearance of a brittle component in a fracture to the formation temperature of a completely brittle fracture for at least one specimen tested at a given temperature.

The fractures were studied using a Hitachi TM-1000 scanning electron microscope at magnifications of 100–1500. The fraction of the brittle component ($X$) in the fracture of the samples was determined from photographs of the fracture surface at low magnification ($\times 10$) and was calculated as the ratio of the area of the “brittle square” of the fracture, occupied by the brittle component to the entire fracture area.

Electron microscopic studies were performed on thin foils cut from the samples under study. Micro-

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1 According to the report of the National Research Center "Kurchatov Institute" on the topic “Development of a program for heat treatment and mechanical tests for the experimental assessment of the degree of degradation of the mechanical properties of welded joints of the CC vessel material and the guide plate.” No. RPR.0131.10UJA.JKM.BN.DD0001, inv. No. 110.10–49/1–138–118, 2018.

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thermal loads at temperatures up to 1000°C and above [11–13]. Under these conditions, the material of the reactor vessel must maintain the required minimum margin of safety and impact toughness [14]. However, the data on the influence of such actions on the impact toughness of welded joints made of low-carbon steels are very limited in both Russian and foreign sources. A number of works are devoted to the analysis of the mechanical properties of low-carbon unalloyed and low-alloyed steels under extreme thermal actions [15–18]. The negative effect of long-term temperature exposure in the temper brittleness range (slow—for 7 days cooling from a temperature of 650°C) on the characteristics of the impact toughness of steel 22K has been shown [19]. At the same time, a similar effect on the characteristics of the impact toughness of low-carbon steels can be expected after prolonged holding at high temperatures (in the austenitic region) with the formation of a coarse-grained structure.

The impact toughness tests of the samples were carried out in as-received state and after long-term temperature exposure with slow cooling and to assess the degree of embrittlement of the material.

MATERIALS AND RESEARCH METHODS

Hot-rolled sheets with a 60-mm thickness made of 22K steel were used for research in as-received state (after normalization).

Welded joints of 22K steel sheets were obtained by automatic argon-arc welding with a consumable electrode (welding wire SV-08G2S was used) without preheating the materials to be joined in accordance with PNAE G-7-009–89. The chemical composition of the base metal, and the weld metal of the welded joint, determined by the optical emission method, is given in Table 1.

The impact toughness tests of the samples were carried out in as-received state and after long-term high-temperature exposure with slow cooling and to assess the degree of embrittlement of the material.

The fractures were studied using a Hitachi TM-1000 scanning electron microscope at magnifications of 100–1500. The fraction of the brittle component ($X$) in the fracture of the samples was determined from photographs of the fracture surface at low magnification ($\times 10$) and was calculated as the ratio of the area of the “brittle square” of the fracture, occupied by the brittle component to the entire fracture area.

Electron microscopic studies were performed on thin foils cut from the samples under study. Micro-
graphs were obtained using a JEM 2100 (JEOL) transmission electron microscope in bright field mode.

The study of the fractures of the samples by the method of Auger electron spectroscopy was carried out on the PHI-680 installation of the company “Physical Electronics” under the following conditions:

— energy of the primary beam $E = 10$ keV;
— primary beam current $j = 10$ nA;
— diameter of the primary beam is 40 nm;
— depth of analysis $t = 5–50$ Å;
— pressure of residual gases in the research chamber $P = 2 \times 10^{-9}$ Torr;
— sensitivity to elements—all elements except hydrogen and helium;
— limit of sensitivity by elements—0.3–1.5 at %.

Cylindrical samples of $3 \times 15$ mm with a cone-shaped thinning to 1 mm in the middle of the sample were used. Fractures were obtained after the destruction of the samples in the vacuum chamber of the installation. The element concentrations were calculated by analyzing the Auger lines of elements excited by an electron beam. The energy resolution of the spectrometer $\Delta E/E$ was 0.5%. Auger spectra were recorded with a step of 1 eV at an accumulation time of 20 ms/eV in the $E\,N(E)$ pulse counting mode. Determination of the position of the peaks of the elements on the PHI-680 electronic Auger spectroscopy unit of the Physical Electronics company was carried out with an energy measurement uncertainty of 0.03 in the range 0–2500 eV.

### RESEARCH RESULTS

**Notch-impact strength of the base metal.** According to the test results (Table 2, Fig. 1a) in the temperature range from 200 to 50°C, the Charpy V-notch impact energy $K_{CV}$ of 22K steel in as-received state is on aver-

| Temperature, °C | $K$, J before | $K$, J after | $K_{CV}$, J/cm² before | $K_{CV}$, J/cm² after | $X$, % before | $X$, % after |
|-----------------|----------------|-------------|------------------------|------------------------|--------------|--------------|
| 200             | 151.3 ± 11.9 | 147.3 ± 5.4 | 192 ± 17              | 181 ± 8               | 0            | 0            |
| 150             | 149.2 ± 6.1 | –           | 190 ± 8               | –                      | 0            | –            |
| 125             | 161.9 ± 4.9 | 153.2 ± 3.1 | 205 ± 6              | 192 ± 4               | 0            | 0            |
| 100             | 161.9 ± 1.0 | 165.5 ± 8.8 | 204 ± 2              | 205 ± 11              | 0            | 0            |
| 75              | –            | 137.1 ± 19.1| –                     | 169 ± 23              | –            | 15–40        |
| 50              | 163.7 ± 1.3 | 100.8 ± 9.0 | 207 ± 1              | 125 ± 12              | 0            | 95           |
| 23              | 139.5 ± 5.2 | 62.5 ± 13.1 | 177 ± 4              | 78 ± 16               | 15–30        | 95–100       |
| 0               | 110.9 ± 11.9| 27.0 ± 4.2  | 141 ± 14              | 33 ± 5                | 80           | 100          |
| −20             | 42.2 ± 4.2  | 15.7 ± 1.5  | 54 ± 5               | 19 ± 2                | 100          | 100          |
| −30             | 13.9 ± 1.8 | 9.8 ± 22    | 17 ± 2               | 12 ± 3                | 100          | 100          |
| −50             | 11.4 ± 0.1 | –           | 14 ± 1               | –                     | 100          | –            |

**Table 2.** Results of impact bending tests of specimens of 22K steel base metal in as-received state and after high-temperature exposure

![Fig. 1. Serial impact toughness curves of specimens of 22K steel base metal in as-received state (a) and after high-temperature exposure (b) (% $X$ is the fraction of brittle constituent in the fracture).](image-url)
After prolonged high-temperature exposure, the impact toughness of the steel during testing in the temperature range from 200 to 100°C does not noticeably change and averages 181–205 J/cm² (Table 2, Fig. 1b). However, with a decrease in the test temperature to 75°C, a brittle constituent appears in the fractures in the amount of 15–40%, while in the fractures of steel in as-received state, the brittle constituent appears only when the test temperature drops to room temperature (Figs. 2a, 2b).

A completely brittle fracture in steel samples in as-received state and after prolonged high-temperature exposure is formed at test temperatures of minus 20°C and room temperature, respectively, while the impact toughness decreases on average to 54 and 78 J/cm².

Thus, a long-term high-temperature exposure on the base metal of steel 22K leads to expansion by 15–20°C and a shift in the temperature range of the ductile–brittle transition towards higher temperatures—the temperatures of the beginning and end of the ductile–brittle transition increase by 40–50°C.

Impact strength of the weld metal. According to the test results (Table 3, Fig. 3a), in the temperature range from 125 to 50°C, the Charpy V-notch impact energy KCV of the weld metal of the welded joint of 22K steel in as-received state is slightly lower than the impact toughness of the base metal and averages 168–188 J/cm² with completely ductile fractures.

After prolonged thermal exposure, the impact toughness of steel when tested in the temperature range from 125 to 75°C is on average 194–217 J/cm² (Table 3, Fig. 3b). A slight increase in the impact toughness values of the weld metal of the welded joint after prolonged thermal exposure in comparison with in as-received state may be associated with a decrease in thermal stresses from welding and an increase in the uniformity of metal deformation [20]. However, in the fractures of specimens at a test temperature of 75°C, a brittle constituent appears in the amount of 50%, while in fractures of specimens in as-received state, the brittle constituent appears only when the test temperature is reduced to room temperature (Figs. 2c, 2d).
Thus, a long-term thermal exposure on the welded joint of 22K steel, as in the case of the base metal, leads to expansion by 20–25°C and to a shift in the temperature range of the ductile–brittle transition of the weld metal of the welded joint towards higher temperatures—the temperature of the beginning and the end of the ductile-brittle transition increase by 50 and 30°C, respectively. Thus, the temperatures of the beginning of the ductile-brittle transition of the base metal and the weld metal of the welded joint of steel 22K after the same treatment (normalization or prolonged high-temperature exposure) practically coincide, and the temperatures of the end of the ductile-brittle transition differ by no more than 10–20°C.

**Microstructure of base metal and weld metal of the welded joint.** The structure of the base metal and the weld metal of the welded joint of 22K steel in as-received state and after prolonged high-temperature exposure was studied earlier [15]. In the structure of the weld metal in as-received state, the grain size of the ferrite is significantly smaller than that of the base metal. After prolonged high-temperature exposure, a finer ferrite grain is retained in the weld metal than in the base metal. The austenite grain in the structure of the welded joint is less prone to growth during high-temperature heating compared to the base metal.

The features of the structural state of 22K steel after prolonged high-temperature exposure were revealed in the study of the microstructure by transmission electron microscopy (TEM) and fractures by Auger spectroscopy. Figure 4 shows the images of the microstructure of the base metal and the weld metal of the welded joint in various structural states obtained by the TEM method.

| Temperature, °C | K, J | KCV, J/cm² | X, % |
|----------------|------|------------|------|
|                | before | after | before | after | before | after |
| 150            | 158.5 ± 12.0 | 195 ± 15 | –      | 0     |
| 125            | 169.5 ± 9.8 | 209 ± 12 | 168 ± 9 | 0     | 0     |
| 100            | 156.1 ± 16.2 | 194 ± 20 | 168 ± 4 | 0     | 0     |
| 75             | 174.6 ± 4.0 | 217 ± 5 | 176 ± 4 | 0     | 50    |
| 50             | 132.0 ± 6.1 | 163 ± 8 | 188 ± 12 | 0    | 85    |
| 23             | 89.1 ± 0.2 | 110 ± 1 | 166 ± 9 | 0–15  | 95    |
| 0              | 67.9 ± 1.2 | 84 ± 1 | 142 ± 1 | 65–80 | 100   |
| −20            | 47.7 ± 3.9 | 59 ± 5 | 103 ± 2 | 95    | 100   |
| −30            | 42.2 ± 8.3 | 52 ± 10 | 121 ± 32 | 100  | 100   |
| −50            | 23.1 ± 8.4 | 28 ± 10 | 65 ± 47 | 100   | 100   |
| −80            | 4.7 ± 0.9 | 5.8 ± 1 | 33 ± 15 | 100   | 100   |

**Table 3.** Results of impact bending tests of specimens of 22K steel weld metal in the as-received state and after high-temperature exposure

![Fig. 3. Serial impact toughness curves of samples from the weld metal of 22K steel in as-received state (a) and after high-temperature exposure (b) (% X is the fraction of the brittle constituent in the fracture).](image-url)
It can be seen that the structure of the base metal of steel 22K in as-received state contains numerous precipitates of square-shaped carbide particles 50–250 nm in size (Fig. 4a). Carbides are located mainly in the body of ferrite grains and do not embrittle steel; therefore, the samples are characterized by high values of impact toughness.

Prolonged high-temperature exposure leads to a twofold grain growth [15], as well as to the dissolution of carbide particles (Fig. 4b) and, consequently, to the enrichment of the solid solution with carbon. These factors increase the tendency of steel to brittle fracture.

The structure of the weld metal of the welded joint contains numerous oval-shaped manganese sulfide particles 50–500 nm in size (Fig. 4c). These particles are located both in the body of the ferrite grain and at the boundaries. Separate carbide particles with a size of about 50 nm were also revealed (Fig. 4d). Manganese sulfide particles, on the one hand, negatively affect the impact toughness, weakening the strength of the grain boundaries, and on the other hand, they restrain grain growth during high-temperature heating, thereby providing a finer-grained structure of the welded joint compared to the base metal.

Analysis of fracture surfaces of 22K steel samples after prolonged high-temperature exposure in the zone of large cleavage facets by Auger spectroscopy did not reveal the presence of segregations of chemical elements (Fig. 5). On the obtained spectrograms for 22K steel, only iron is reliably present. At the same time, in the fractures of the base metal, a few non-metallic inclusions enriched with calcium, oxygen, sulfur and nitrogen, formed at the deoxidation stage, were revealed, and in the fractures of the weld metal of the welded joint, inclusions enriched in nitrogen and chlorine were found.

**Microstructure of fractures.** At test temperatures above the ductile-brittle transition interval, the fractures of all 22K steel specimens are characterized by a ductile dimple structure. When the test temperature
Fig. 5. Surfaces of fractures and Auger spectrograms of the base metal (a, b) and weld metal (c) of steel 22K: (a, c) as-received; (b) after high-temperature exposure.
decreases to the beginning of the ductile-brittle transition, a mixed ductile-brittle fracture is observed in the fractures of the samples. At the same time, in the area under the notch for the base metal samples in as-received state and after prolonged high-temperature exposure, a ductile dimple fracture is observed, alternating with quasi-cleavage regions (Figs. 6a, 6b). For samples of the weld metal of the welded joint in as-received state and after prolonged high-temperature exposure in the zone under the notch, a ductile micro-dimple formation mechanism of destruction is also observed (Figs. 7a, 7b). In the central fracture zone of all specimens, there are large cleavage facets with a transverse size of up to 150 μm for base metal specimens after prolonged high-temperature exposure, and up to 50 μm for the remaining specimens with ductile dimple fracture bridges along the boundaries of the facets (Figs. 6c, 6d, 7c, 7d). In the fractures of the weld metal, separate areas of secondary cracking along the grain boundaries are revealed (Fig. 7d).

At temperatures of the end of the ductile-brittle transition and below, all samples are destroyed brittle mainly by the mechanism of transcrystalline cleavage with the presence of separate areas of secondary cracking along grain boundaries (Figs. 6e, 6f, 7e, 7f). A small proportion of the ductile component (less than 5%) in the fracture is represented by small dimples.

**CONCLUSIONS**

Long-term high-temperature exposure (holding at a temperature of 1000°C and cooling in a complex mode for 7 days) on samples of both the base metal and the weld metal of the welded joint (argon-arc welding with a consumable electrode) of 22K steel leads to an expansion of the temperature range of the ductile-brittle transition by 15–25°C and an increase in the temperatures of the beginning and end of the ductile-brittle transition by 30–50°C.

The temperatures of the beginning of the ductile-brittle transition of the base metal and the weld metal of the welded joint after the same treatment (normalization or prolonged high-temperature exposure) are the same, and the temperatures of the end of the ductile-brittle transition differ by no more than 10–20°C.

With a decrease in the test temperature in the range of the ductile-brittle transition, the fracture mechanisms of the base metal and weld metal change from a ductile dimple (at temperatures above the transition onset temperature) to a mixed one. Fracture occurs according to the mechanisms of cleavage, quasi-cleavage (with the presence of areas of secondary cracking along the grain boundaries), and ductile dimple fracture (at temperatures below the transition onset temperature) until completely brittle fracture by cleavage at temperatures of the end of the ductile-brittle transition and below.
Fig. 7. Microstructure of samples fractures after impact bending test of the welded joint of steel 22K in as-received state (a, c, e) and after prolonged high-temperature exposure (b, d, f): (a, b, e, f) area under the notch; (c, d) area of a “brittle square” (SEM).

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