Express evaluation of welded joints cool resistance

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Abstract. Low-temperature instrumented indentation tests of welded joints are carried out. The effect of metal cooling on indentation diagrams and metal hardness is investigated. Impact strength tests with a gradual decrease in temperature with the identification of the cold brittleness threshold and determination of the critical brittleness temperature for several structural steels are performed. For an express evaluation of a metal cold resistance, the parameter $\gamma$ is proposed, which is equal to the ratio of hardness at a given low temperature to hardness at room temperature. The relation between the parameter $\gamma$ and the temperature coefficient of hardness, which is included in the equation describing low-temperature dependence of hardness, is established. For several grades of carbon and alloy steels, the relation between the parameter $\gamma$ and the critical brittleness temperature $T_{0.4}$, determined by the criterion value of impact strength $KCV = 0.4$ MJ/m$^2$, is established. For welded joints obtained by electron beam welding and arc welding, the values of $T_{0.4}$ are determined by the parameter $\gamma$ in various local zones, including parent metal, heat-affected zone and weld metal. The possibility of establishing the acceptable operation temperature of welded joints using the obtained distributions of the critical brittleness temperature $T_{0.4}$ is shown.

1. Introduction

Metal cold resistance characteristics allow establishing the possibility of operating items made of this metal at low temperatures. The evaluation of the metal cold resistance is performed by the critical temperature of brittleness, at which the metal undergoes a transition from a ductile to a brittle state. There are various methods for determining the critical temperature of brittleness [1, 2], which use either values of the mechanical characteristics or fracture analysis data as a criterion of metal brittleness evaluation. To implement these methods, it is necessary to make a test of a series of samples with a gradual decrease in temperature. More often, a series of notched samples is made and tested for impact strength. The temperature dependence of impact strength reveals the cold brittleness threshold of steel, which is used to evaluate the critical temperature of brittleness using the criterion value of impact strength. For typical welded joints, the application of the described methodology is not always possible due to the lack of metal necessary for the manufacture of a standard samples series. Moreover, with the inevitable differences in the structure and mechanical properties of the welded joint local zones (heat-affected zone, fusion zones, weld metal and parent metal), the task of the critical temperature of brittleness evaluation in each zone by the above method is not feasible in practice. Thereby, scientific researches of the cold resistance of welded metal designed for use in the Far North and Siberia are very relevant [3, 4]. The goal of these researches is to develop a method that allows obtaining the distribution of the critical brittleness temperature over the entire welded joint,
which would make it possible to determine the upper value of this temperature and to obtain a more reasonable conclusion about the possibility of using the welded construction at low temperatures.

In the work [5], the method was proposed for determining the zero plasticity temperature \( (T_{ZP}) \) of metal from the low-temperature change in the values of hardness at the yield strength and hardness at the ultimate strength, determined by indentation. With decreasing test temperature, these hardness characteristics monotonically increase and gradually approach each other in their values. The point of the lines intersection of low-temperature variation of these two hardness characteristics corresponds to the temperature of \( T_{ZP} \). An approximate relationship was revealed between \( T_{ZP} \) and the critical brittleness temperature \( T_{K0} \) for several grades of carbon steels and pearlitic alloy steels [6]. The temperature \( T_{K0} \) was chosen as the higher of two critical temperatures: temperature \( T_{0.4} \), obtained by the criterion value of impact strength \( KCV = 0.4 \) MJ/m\(^2\) and temperature \( T_{50} \), determined by fracture microscopic analysis (\( T_{50} \) is the temperature corresponding to a share of ductile fracture of 50% in the fractured surface of the sample). It should be noted that the described method is quite laborious and requires special instruments and devices for determining hardness at the yield strength and hardness at the ultimate strength at low temperatures. This problem can be partly solved by using instrumented indentation with registration of indentation diagrams “load - displacement”.

In this paper, we developed an express method for the rapid evaluation of the critical brittleness temperature of welded joints local zones by instrumented indentation and suggested informative cold resistance parameters by which it is possible to establish the permissible operation temperature of weld structures in low climatic temperatures.

2. Research methods
A technique of determining hardness using instrumented indentation by a ball indenter, developed at MPEI [7] was applied. According to this technique, using a “\( F - \alpha \)” diagram containing loading and unloading curves, it is possible to determine hardness at yield strength and hardness at ultimate without measuring the indent dimensions using optical means. The loading curve of the instrumented indentation diagram “\( F - \alpha \)” can be transformed into the diagram “Brinell hardness \( HB \) - indent depth \( t/R \)” [7]. For many structural materials, the \( HB \), hardness determined in accordance with ISO 6506 is equal to or close to the maximum hardness \( (HB)_{20} \). Therefore, it is advisable to study the low-temperature change in \( HB \), hardness at a constant defined indentation load for the corresponding indenter diameter.

The studies were performed on carbon steels 10 (0.1% C) and 45 (0.45% C) with a change in the test temperature from 293K (20°C) to 193K (-80°C) in increments of 10...20°C. Indentation was carried out using an Instron 5982 universal machine equipped with a chamber where the test metal was cooled by nitrogen vapor. The accuracy of maintaining the low temperature was ± 1°C, the strain rate in compression mode was 0.5 mm/min. A steel ball with a radius of \( R = 1.25 \) mm was used as an indenter. According to ISO 6506, the indentation load was 1839 N (187.5 kg).

It is known that in the studied temperature range, the change in \( HB \), hardness can be quite accurately described by the power equation:

\[
HB = AT^{-b}, \quad (1)
\]

where \( A \) and \( b \) are constant for a given material.

With deeper cooling of the metal, for example, to a temperature of liquid nitrogen of 77 K (-196°C), it is advisable to describe the temperature dependence of hardness with the equation (2) [8]:

\[
HB = HB_{20} + B \cdot \exp(-\beta T). \quad (2)
\]

where \( HB_{20} \) - Brinell hardness at room temperature; \( B \) and \( \beta \) are constant for a given material.

Parameters \( b \) and \( \beta \) included in equations (1) and (2) are the temperature hardness coefficients that characterize the metal cold resistance. Moreover, as was shown in [8], the temperature hardness coefficient \( \beta \) correlates with the critical brittleness temperature of low-carbon steels. At the same time,
the type of the impact specimen and the criterion value of the impact strength, by which the critical
temperature of brittleness were estimated, were not indicated. Thereby, in this research the
experimental studies were carried out to establish the relationship between the cold resistance
characteristics determined during impact strength tests and the characteristics determined by
instrumented indentation. For this, a series of specimens with a sharp notch (Charpy specimens) were
prepared to determine the KCV impact strength at lower temperatures for several carbon and alloy
steels. The tests were carried out on an Instron MPX-450 pendulum equipped with a cooling chamber.
The test temperature decreased in increments of 10 degrees from room temperature \( T_R = 293 \text{ K} \) (20°C)
to \( T = 223 \text{ K} \) (-70°C). This test temperature range was chosen based on real climatic temperature range
in Siberia and the Far North. According to the test results, the temperature dependences of the impact
strength KCV were obtained with the identification of the cold brittleness threshold and determination
of the critical brittleness temperature \( T_{0.4} \) by the criterion value of the impact strength \( KCV = 0.4 \)
MJ/m².

Indentation diagrams “F - \( \alpha \)” were obtained at \( T_R = 293 \text{ K} \) (20°C) and \( T = 223 \text{ K} \) (-70°C) on the
microsections made of these steels, and hardness values at these temperatures \( (HB)_T \) and \( (HB)_R \) as
well as temperature hardness coefficient \( b \) were calculated. The equation for calculating the coefficient
\( b \) is obtained from equation (1)

\[
b = \frac{\ln[(HB)_T / (HB)_R]}{\ln(T/R)}.
\]  \( \text{(3)} \)

In a given temperature range \( T_R - T \), the coefficient \( b \) is related to the ratio \( (HB)_T / (HB)_R \). If this
relation is denoted by \( \gamma \), then, taking into account equation (3), we obtain

\[
b = \frac{\ln \gamma}{\ln(T/R)} \quad \text{(4)}
\]

\[
\gamma = \exp[b \cdot \ln(T_R/T)] \quad \text{(5)}
\]

3. Results and discussion

In order to study the effect of cooling on the instrumented indentation diagrams “F - \( \alpha \)” and “\( HB \) -
t/R”, carbon steels “10” and “45” were tested by indentation in the temperature range from \( T = 293 \text{ K} \)
(20°C) to 193 K (-80°C). Figure 1a shows the instrumented indentation diagrams “F - \( \alpha \)”, and in figure
1b shows the “\( HB \) - t/R” diagrams for the “45” steel at two temperatures: 293 K (20°C) and 193 K
(-80°C).

![Figure 1](image)

**Figure 1.** Instrumented indentation diagrams “F - \( \alpha \)” (a) and “\( HB \) - t/R” (b) for steel “45”,
obtained by a ball indenter \( D = 2.5 \text{ mm} \), at 293 K (20°C) (1) and 193 K (-80°C) (2).
As it can be seen from figure 1a, the loading curve of the “$F - \alpha$” diagram rises more abruptly at low temperature, while the full elastoplastic displacement at the maximum indentation load and the residual displacement decrease. These changes are also reflected in the “$H_B - t/R$” diagram (figure 1b). At low temperature the curve is located much higher and the maximum value ($H_B$) is reached at a smaller relative depth ($t/R$). Moreover, the value ($H_B$) increases significantly.

These experiments made it possible to obtain low-temperature dependences for carbon steels “10” and “45” (figure 2) and to verify the validity of equations (1) - (3).

Figure 2. Change in $H_B$ hardness of steel “10” (a) and steel “45” (b) during cooling.

Impact strength tests with a decrease in temperature were carried out with the same carbon steels, as well as with several alloy steels. According to the results of impact tests of a series of specimens (at least 10 specimens for each steel), low-temperature dependences of impact strength were obtained with the identification of the cold brittleness threshold and determination of the critical brittleness temperature $T_{0.4}$. Figure 3 shows such dependences for carbon steel “10” and alloy steel 12Kh2MFA (0.12% C, 1.5% Cr, 0.4% Mo, 0.2% V). The intersection points of the dashed horizontal line at the level of the criterion value of 0.4 MJ/m$^2$ correspond to the critical brittleness temperature $T_{0.4}$.

Figure 3. Impact strength $KCV$ of carbon steel “10” and 12Kh2MFA alloy steel at low temperatures.
Then, for all tested steels “F - α” diagrams were obtained at 293 K (20°C) and 203 K (-70°C) and the γ parameter was determined at these temperatures. A correlation relationship was revealed between the critical brittleness temperature \( T_{0.4} \) and the cold resistance parameter γ (figure 4).

![Figure 4. Relationship between the critical brittleness temperature \( T_{0.4} \) and the cold resistance parameter γ for steels: ● – carbon steel St0 (\( \leq 0.23\% \) C, \( \leq 0.06\% \) S, \( \leq 0.07\% \) P); ○ – carbon steel VSt3sp (0.18\% C, \( \leq 0.05\% \) S, \( \leq 0.04\% \) P); × – steel 10; □ – 12Kh2MFA; ◊ – 15Kh1M1F (0.15\% C, 1.2\% Cr, 1\% Mo, 0.2\% V); ♦ - 09G2S (0.09\% C, 1.5\% Mn, 0.7\% Si).](image)

Thus, the easily determined parameter γ also allows quantifying the critical temperature of brittleness during cooling to a given temperature. However, it should be noted that in order to clarify the established relationship between \( T_{0.4} \) and γ when cooling the material to -70°C, additional experiments on steels of other grades are required. However, at the same time, the γ parameter already allows lining up several controlled materials by cold resistance.

After establishing the relationship between the cold resistance characteristics determined by instrumented indentation and impact strength tests, experiments were carried out to determine the cold brittleness characteristics of the local zones of welded joints according to the technique proposed in the paper. The experiments to determine the hardness \( HB_t \), the cold resistance parameter γ, and the critical brittleness temperature \( T_{0.4} \) were carried out on microsections of welded joints obtained by electron beam welding (EBW) and manual arc welding (MMA welding). On each section, at the designated points along the line covering the parent metal, the heat-affected zone and the weld metal, 7-8 instrumented indentation diagrams “F - α” were registered at \( T = 293 \) K (20°C), and then at \( T = 203 \) K (-70°C). The obtained results made it possible to obtain the distribution of \( T_{0.4} \) in various local zones of each welded joint.

In figure 5a there is a graph of the \( T_{0.4} \) distribution in various local zones of a welded joint made of steel 38Kh2N2MA (0.38\% C, 1.5\% Cr, 1.5\% Ni, 0.25\% Mo) obtained by EBW, and in figure 5b there is a graph for a welded joint of steel 18Kh11MNFb (0.18\% C, 11\% Cr, 1\% Mo, 0.75\% Ni, 0.3\% V, 0.3\% Nb) obtained by MMA welding. Analysis of figure 5a and 5b shows that the welded joint obtained by MMA welding is more cold-resistant than the welded joint obtained by EBW. At the same time, the distribution of \( T_{0.4} \) for EBW joint is smoother.

According to the graphs similar to the graphs of figure 5, it is possible to identify the most unfavorable cold resistance local zone for each welded joint and evaluate its critical brittleness temperature. This makes it possible to more reasonably recommend the operating temperature of products with welded joints in conditions of low climatic temperatures.
4. Conclusions

The possibility of an operative evaluation of instrumented indentation of the critical brittleness temperature of local welded joints zones, including parent metal, heat-affected zone and weld metal, is performed. The metal critical brittleness temperature $T_{0.4}$, determined by the criterion value of impact strength $KCV = 0.4 \text{ MJ/m}^2$, can be estimated by the proposed cold resistance parameter $\gamma$, which is equal to the ratio of hardness at a given low temperature to hardness at room temperature. The larger the parameter $\gamma$, the higher is the $T_{0.4}$ and lower the cold resistance of the metal. The distribution chart of $T_{0.4}$ in various local zones of the welded joint allows identifying the upper value of $T_{0.4}$ and to recommend the appropriate operating temperature range for the weld joint in conditions of low climatic temperatures.

References

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