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# MECHANICAL PROPERTIES OF METAL IN AREAS OF WELDED JOINTS OF MEDIUM-CARBON ALLOY STEELS HEATED TO TEMPERATURES FROM 350 TO 800 °C

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**ABSTRACT**

During welding, two characteristic areas are formed in the heat-affected zone (HAZ) of welded joints of medium-carbon alloy steels with hardened (located in the HAZ areas of overheating, normalization and partial recrystallization — high-temperature area) and tempered metal (located mainly in the HAZ areas of recrystallization and blue brittleness — low-temperature area). In welded joints made using manual arc and mechanized gas-shielded welding with small-diameter wires, the width of these areas can reach 2.5 and 8 mm, respectively. The influence of thermal cycles, characteristic for the high-temperature area of the HAZ, on the mechanical properties of the metal is well covered in technical literature. There is much less information on the influence of thermal cycles of welding on the mechanical properties of the low-temperature area of the HAZ. This paper presents the data on the course of the heating and cooling process of the HAZ metal of butt welded joints 12 mm thick, which were heated to temperatures of 780, 550 and 350 °C, and on the effect of such heating on the mechanical properties (hardness, strength, ductility, impact toughness) of medium-carbon alloy steels with different content of alloying elements.

**KEYWORDS:** medium-carbon alloy steels, mechanical properties, thermal cycles, alloying elements

## INTRODUCTION

Medium-carbon alloy heat-strengthened steels with high hardness (*HB* > 5000 MPa) and strength ($\sigma_t$ > 1400 MPa) can be used both to manufacture military products, exposed to considerable shock impact, and to produce heavy-duty components and mechanisms of machines for civil purposes, such as quarry excavator buckets, bodies of heavy trucks, etc. The above-mentioned steels acquire the required set of mechanical properties, high hardness, strength and impact toughness due to alloying with manganese, silicon, chromium, molybdenum, and nickel; microalloying with boron, titanium, aluminium, vanadium, etc., as well as a result of heat treatment, which consists in quenching and low-temperature (at not higher than 250 °C temperature) tempering of steel [1–6].

The majority of the products, manufactured with application of heat-strengthened medium-carbon alloy steel of a high hardness are welded. Arc processes are usually used for welding such products. They envisage local heating of the steel rolled stock up to temperatures, exceeding that of the steel tempering, and in the near-weld zone the temperature is close to its melting temperature. The HAZ of the welded joints can be conditionally divided into two areas: high- and low-temperature. The HAZ high-temperature area includes the area of overheating (temperature varies within 1100–1500 °C), area of normalization (temperature varies in the range of 930–1100 °C) and of partially incomplete recrystallization (temperature varies within 720–930 °C). In this area of the welded joint the metal transforms into austenite at heating, and at cooling, depending on the chemical composition and degree of metal overcooling, phase-structural transformations take place in it with formation of ferrite-bainite-martensite or mixed structures. The HAZ low-temperature area includes the areas of recrystallization (temperature varies within 450–720 °C) and of blue brittleness (temperature varies within 200–450 °C). The size and distance to the weld axis in the areas heated to the above-mentioned temperatures in the welded joint depend on many factors. The main of them are the welding mode, metal thickness and joint type. For the processes characteristic for manual, stick electrode and gas-shielded mechanized welding, the width of the HAZ high-temperature area can reach 2.5 mm and that of the low-temperature one is 8 mm.

At present, the questions of the influence of the welding modes and conditions of welded joint cooling on the structural transformations, occurring in the metal of the HAZ overheating area are quite well highlighted in technical publications [4–8]. The data on the influence of the above factors on the mechanical properties of the metal are presented in the scientific publications to a lesser extent, but also well [9–12]. As to the HAZ low-temperature areas, where the metal is heated to temperatures, higher than $A_{c1}$ temperature, the amount of such information is limited, and it mainly concerns the metal hardness values.

## THE OBJECTIVE

of this work consisted in having determined the coordinates of the HAZ tempering area, assessing the running of the thermal processes of welding in it

**Table 1.** Chemical composition of the studied medium-carbon alloy steels

| Steel marking | Weight fraction of elements, % | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | C | Si | Mn | Cr | Ni | Mo | V | S | P | B |
| “1” | 0.23 | 0.25 | 0.82 | 0.50 | 0.90 | 0.30 | 0.030 | 0.004 | 0.016 | 0.003 |
| “2” | 0.31 | 0.16 | 0.74 | 1.66 | 2.26 | 0.30 | 0.202 | 0.010 | 0.016 | – |
| “3” | 0.21 | 0.45 | 0.92 | 0.58 | 0.38 | 0.20 | 0.010 | 0.005 | 0.023 | 0.004 |

(heating–cooling of metal, depending on the welding modes), reproducing these processes on model samples and establishing how the above-mentioned changes influence the mechanical properties of the tempered metal.

## MATERIALS AND METHODS OF INVESTIGATIONS

Investigations were performed using several medium-carbon alloy steels with the yield point above 1200 MPa, differing by their chemical composition (see Table 1).

Welding of butt welded joints 12 mm thick was performed by mechanized method in shielding gas atmosphere (82 % Ar + 18 % $CO_2$) with 1.2 mm wire of ChORDA 307 Ti brand (08Kh20N9G7T alloying system), using the following mode: welding current $I_w$ = 160–180 A; arc voltage $U_a$ = 23–25 V; welding speed $V_w$ = 10–12 m/h.

Location of the tempering area was determined based on measurement of metal microhardness in the welded joint HAZ. Measurement step was equal to 1 mm.

Impact toughness of the metal in the tempering area was assessed by the results of impact bend tests of standard samples of 10×10×55 mm size with a round notch of Mesnager type, cut out of the welded joints. Sample tests were conducted at the temperature of 20 °C.

The thermal cycle of welding was recorded for three areas of the welded joint tempering zone, namely, areas heated up to temperatures of 780, 550 and 350 °C. Chromel-alumel thermocouple of 0.5 mm diameter was used for this purpose.

Values of strength ($\sigma_{0.2}$ and $\sigma_t$) and ductility ($\delta_5$ and $\psi$) were determined by the results of tensile tests of standard samples, processed in keeping with the thermal cycles characteristic for the tempering zone of the HAZ metal of the joints, which were welded in the above-given modes. Heating of model samples of 12×12×120 mm size was conducted in MRS-75 unit by current flowing through the sample by the preset program [13]. The cooling rate of the samples was regulated by their blowing with air with different intensity.

## TESTING RESULTS AND THEIR DISCUSSION

Measurements of microhardness of the metal of welds, HAZ and steel rolled stock (Figure 1) showed that the weld metal hardness is almost the same in all the cases, and it is in the range of *HB* 230–260. This is natural, as the same wire and welding modes were used for welding. As regards the metal microhardness in the areas of HAZ and steel, which are located at different distances from the weld, these indices depend on the steel chemical composition. The highest values of hardness (approximately, *HB* 530) are characteristic for the strengthened area of overheating of the HAZ (located at 1 mm distance from the fusion line of welded joints of steels “2” and “3”). Somewhat lower hardness values (*HB* 450) are found in the metal of the overheating area of the HAZ of welded joints on steel “1”. Hardness of the tempering area (located in the range of 4–9 mm), as that of the base metal (located in the range of 10–13 mm) is also the lowest in the joints of steel “1”. The highest *HB* values, almost at the level of base metal hardness, are characteristic for the tempering area of welded joints of steel “2”.

Thus, by the results of these studies it was determined that depending on the chemical composition of steels, the high hardness of the metal which it acquires through heat treatment of the steel, can be reduced as a result of heating by the thermal cycle of welding. The smaller is the concentration of alloying elements in the steel, the lower the values of metal hardness in the HAZ tempering area.

The data on the conditions of heating and cooling of individual tempering areas of the HAZ metal are given in Figure 2. Three tempering areas are considered, which were heated to temperatures of 780, 550 and 350 °C as a result of the effect on the metal of the heat from welding arc burning. For this purpose, the thermocouples were mounted at the distance of 4, 6 and 9 mm from the fusion line. Analysis of the obtained results showed that the intensity of reduction

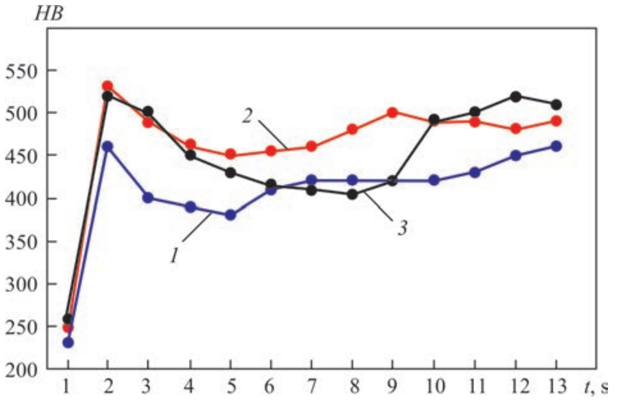


**Figure 1.** Microhardness values of the weld metal, HAZ and base metal of butt welded joints 12 mm thick of steels: “1” — Row 1; “2” — Row 2; “3” — Row 3

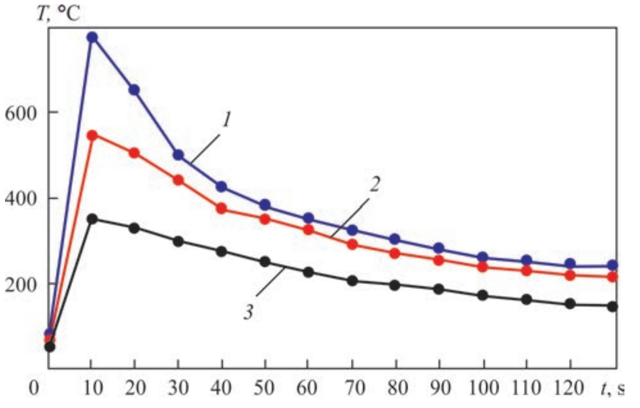


**Figure 2.** Thermal cycles of welding the tempering areas of the HAZ in butt welded joints 12 mm thick, which were heated to temperatures of: 780 °C — Row 1; 550 °C — Row 2; 350 °C — Row 3

of the metal temperature at the initial stage of its cooling is significantly different. The higher the heating temperature, the higher is the cooling rate. In the temperature range of 400–300 °C the intensity of metal cooling is equalized in all the HAZ tempered areas.

The data given in Figure 2 were furtheron used for modeling the thermal cycles of welding during treatment of the above-mentioned samples by these cycles.

Results of testing samples for tension (made from heat-treated model samples) and for impact bending (made from welded joints) are given in Table 2.

As indicated by the data given in Table 2, the values of strength ($\sigma_{0.2}$ and $\sigma_t$) of the HAZ metal heated up to temperatures from 350 to 780 °C, in all the cases decrease relative to the initial strength of steel. The extent of these changes depends on the steel chemical composition and on the temperature, to which the HAZ metal was heated during welding. The lower the concentration of the alloying elements and boron in steel, or the higher the heating temperature, the more significant is the reduction of the metal hardness. So, $\sigma_{0,2}$ and $\sigma_t$ values of the HAZ metal which was heated up to the temperature of 780 °C during welding, decrease by almost 40 % for welded joints of steel "1" relative to the base metal, and for steels "2" and "3" — by 20–25 %, which is two times smaller. The smallest changes in the strength values are observed in the metal, heated to the temperature of 350 °C during welding: they decrease by 10 % in the welded joints of steel "1" and "3" and remain almost unchanged in joints of steel "2".

As regards the ductility properties ($\delta_5$ and $\varphi$) of the metal, unlike the strength values, they grow by 30–50 % in welded joints of steels "1" and "3", irrespective of the temperature to which the metal was heated, and almost do not change in joints of steel "2".

As to the impact toughness values, these characteristics of the metal essentially depend both on the temperature to which the metal was heated during welding, and on temperatures, at which the samples were tested. The most essential changes of *KCU* values are observed in the metal tested at the temperature of 20 °C. In samples, where the notch was made in the areas where the metal was heated to temperatures of 550 and 780 °C, the impact toughness values increased 1.3–2.2 times. The highest values are characteristic for samples cut out of welded joints of steel "1" with a notch located in the zone, where the metal was heated to the temperature of 780 °C. As regards the results of testing samples, in which the notch was made in the metal heated to the temperature of 350 °C during welding, their impact toughness turned out to be lower relative to base metal. As was noted above, this temperature belongs to the temperature range, where metal blue brittleness occurs with reduction of its impact toughness values, characteristic for this phenomenon. It should be noted that *KCU* reduction is characteristic both for samples tested at the tem-

**Table 2.** Mechanical properties of medium-carbon alloy steels, which were studied and of the metal of HAZ areas heated to temperatures of 780, 550 i 350 °C

| Steel marking | Heating temperature, °C | *HB* | $\sigma_{0,2}$ | $\sigma_t$ | $\delta_5$ | $\varphi$ | *KCU*, J/cm$^2$ | |
|---|---|---|---|---|---|---|---|---|
| | | | MPa | | % | | +20 °C | –40 °C |
| "1" | 0 | 450 | 1447 | 1690 | 11.0 | 47.2 | 93 | 85 |
| | 350 | 420 | 1294 | 1497 | 21.0 | 63.0 | 89 | 76 |
| | 550 | 380 | 937 | 1044 | 20.0 | 69.1 | 176 | 173 |
| | 780 | 400 | 892 | 981 | 23.2 | 68.5 | 208 | 183 |
| "2" | 0 | 490 | 1475 | 1835 | 14.1 | 46.1 | 61 | 59 |
| | 350 | 500 | 1409 | 1773 | 13.6 | 45.4 | 50 | 37 |
| | 550 | 450 | 1378 | 1620 | 13.9 | 46.4 | 85 | 57 |
| | 780 | 490 | 1210 | 1463 | 14.8 | 47.0 | 98 | 62 |
| "3" | 0 | 520 | 1542 | 1844 | 11.5 | 44.3 | 52 | 51 |
| | 350 | 500 | 1402 | 1594 | 14.6 | 61.3 | 36 | 32 |
| | 550 | 430 | 1389 | 1520 | 14.9 | 60.0 | 74 | 52 |
| | 780 | 420 | 1242 | 1383 | 15.0 | 57.2 | 83 | 55 |

perature of 20 °C, and for those which were tested at the temperature of –40 °C.

## CONCLUSIONS

Results of investigations of the influence of the thermal cycles of welding on the mechanical properties of the metal in the low-temperature areas of the HAZ of welded joints of medium-carbon alloy steels of high hardness (*HB* 500) with different chemical composition showed the following:

1. High hardness of the metal which it acquires heat treatment of the steel during manufacturing of the rolled stock, can be reduced as a result of metal heating by the thermal cycles characteristic for HAZ low-temperature areas. The smaller is the concentration of the alloying and microalloying elements in steel, the lower the values of metal hardness in the HAZ tempering area.
2. The strength of the metal in the HAZ areas of welded joints of heat-strengthened medium-carbon alloy steels heated up to temperatures of 350–780 °C, decreases, while ductility increases relative to the base metal.
3. Impact toughness of the metal of HAZ areas of welded joints of heat-strengthened medium-carbon alloy steels, heated to temperatures of 550–780 °C, is increased relative to the base metal, and in the case of heating to the temperature of 350 °C, it decreases. The latter is related to the fact that the temperature of 350 °C is included into the range of blue brittleness temperatures of the studied steels.

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## CONFLICT OF INTEREST

The Authors declare no conflict of interest


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