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# WELDABILITY OF HIGH-STRENGTH ALLOYED STEELS WITH YIELD STRENGTH OF 590–785 MPA

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This paper summarizes the results of investigations of influence of the thermal cycles, characteristic for arc welding processes, on the structure and mechanical properties of high-strength alloyed steels with yield strength of 590–785 MPa, as well as on their susceptibility to cold crack formation. The structural transformations in the metal of heat-affected-zone of welded joints were investigated using a quick-response dilatometer, and its mechanical properties and susceptibility to cold crack formation were evaluated according to the results of tests of standard specimens and by the Implant method, respectively. The diagrams of the structural transformations of austenite in the region of metal overheating of heat-affected-zone of a number of high-strength alloyed steels, the dependences of change in their mechanical properties during welding, and also the data, characterizing the susceptibility of high-strength alloyed steels to cold crack formation at different concentrations of diffusion hydrogen in the deposited metal, are presented. 15 Ref., 4 Tables, 4 Figures.

***Keywords:*** *high-strength steels, arc welding, metal structure, mechanical properties, cold cracks*

The many year experience in application of high-strength alloyed steels with a yield strength of 590–785 MPa in welded structures is the evidence of their high technical and economic efficiency. Such structures are reliable in service under the most severe operating conditions, not only at static loads, but also at impact loads.

These steels found the most wide application in machine building in the manufacture of highly-loaded structure elements, among which there are mine supports and skips, arrows of cranes and concrete pumps, bodies of large-tonnage dump trucks, beam-arms, arrows, swinging circles and buckets of excavators.

A distinctive feature of high-strength alloyed steels (Tables 1, 2) is the fact that except of a remarkably high strength, they are characterized by high impact strength at a lower temperature. This is achieved due to rational alloying of steels with manganese, nickel, chromium, molybdenum, microalloying with boron, vanadium, aluminum, niobium and heat treatment, which consists of quenching to martensite from the temperature of 900–950 °C and high tempering at the temperature of 600–680 °C [1]. A particularly high cold resistance is in high-strength resistant steels with low sulfur and phosphorus content. To produce such steels at metallurgical enterprises the electroslag remelting (ESR), blowing with argon, treatment with synthetic slags [2, 3] or other measures are used, providing the efficient purification of molten metal from harmful impurities. To such steels the steels 12GN2MFAYU-Sh and 12GN3MFAUYDR-Sh belong, given in the Tables 1 and 2.

The disadvantage of high-strength steels is their susceptibility to cold crack formation [4–7]. This is connected with the fact that during the process of welding a low-plastic brittle martensitic structure can form in the metal of heat-affected-zone (HAZ) of welded joints. The process of cold crack formation is intensified by diffusion hydrogen, which enters the weld pool with the molten metal.

Unlike the steel rolled metal, the metal structure of which depends mainly on the chemical composition, the method and mode of heat treatment, the formation of the structure of HAZ metal of welded joints of high-strength alloyed steels is also affected by the thermal cycle of welding (TCW) [8–12]. The most significant changes in the structure of steel during welding occur in the region of overheating of HAZ metal, i.e., in that region which is located in the direct vicinity of the weld and is heated up to the temperatures of 1300–1150 °C.

The aim of this work consisted in generalizing the results of investigations carried out at the E.O. Paton Electric Welding Institute, directed to studying the influence of thermal cycles, characteristic for arc welding processes, on the structure and mechanical properties of HAZ metal of high-strength alloyed steels with a yield strength of 590–785 MPa, as well as on their susceptibility to cold crack formation depending on the conditions of cooling of welded joints and the content of diffusion hydrogen in the deposited metal.

**Table 1.** Requirements to chemical composition of high-strength alloyed steels, wt.%

| Steel | C | Si | Mn | Cr | Ni | Mo |
|---|---|---|---|---|---|---|
| 12GN2MFAYu | 0.09–0.16 | 0.3–0.5 | 0.9–1.2 | 0.2–0.5 | 1.40–1.75 | 0.15–0.25 |
| 12GN2MFAYuSh | 0.09–0.16 | 0.3–0.5 | 0.9–1.2 | 0.2–0.5 | 1.40–1.75 | 0.15–0.25 |
| 14KhG2SAFD | 0.12–0.18 | 0.4–0.7 | 1.4–1.9 | 0.5–0.8 | <0.3 | – |
| 14Kh2GMR | 0.10–0.16 | 0.17–0.37 | 0.9–1.2 | 1.1–1.5 | <0.3 | 0.4–0.5 |
| 12GN3MFAYuDR-Sh | 0.10–0.15 | 0.17–0.37 | 1.2–1.5 | – | 2.8–3.0 | 0.3–0.4 |
| 14KhGN2MDAFB | 0.12–0.17 | 0.17–0.37 | 1.1–1.4 | 0.9–1.3 | 1.7–2.2 | 0.2–0.3 |

**Table 1** (cont.)

| Steel | Cu | V | Nb | B | Al | S | P |
|---|---|---|---|---|---|---|---|
| 12GN2MFAYu | <0.3 | 0.05–0.10 | – | – | 0.05–0.10 | ≤0.035 | ≤0.035 |
| 12GN2MFAYuSh | <0.3 | 0.05–0.10 | – | – | 0.05–0.10 | ≤0.010 | ≤0.020 |
| 14KhG2SAFD | 0.3–0.6 | 0.08–0.16 | – | – | 0.03–0.07 | ≤0.02 | ≤0.035 |
| 14Kh2GMR | 0.20 | <0.3 | 0.01–0.04 | 0.001–0.004 | 0.02–0.08 | ≤0.035 | ≤0.035 |
| 12GN3MFAYuDR-Sh | 0.3–0.5 | 0.04–0.08 | – | – | 0.02–0.05 | ≤0.010 | ≤0.020 |
| 14KhGN2MDAFB | 0.3–0.6 | 0.10–0.20 | 0.03–0.08 | – | 0.03–0.10 | ≤0.008 | ≤0.020 |

In arc welding, the TCW parameters depend on many factors. The most important among them are the input energy of welding, the initial temperature of the metal and its thickness. With the increase in the input energy and the initial temperature of steel, the period of staying HAZ metal in the temperature range of 800–500 °C ($t_{8/5}$) increases, and its cooling rate in the temperature range of 600–500 °C ($w_{6/5}$) decreases. With an increase in the metal thickness, these values, on the contrary, decrease and increase, respectively. Depending on this fact, the structure and, consequently, the mechanical properties of HAZ metal are changed.

To determine the effect of the chemical composition and the conditions of cooling the metal on its structure, the diagrams of austenite transformation are usually used, which are plotted with account for the processes occurring in arc welding. In order to provide a high resistance of austenite, characteristic for welding, as the standard for plotting the diagrams, such conditions for heating the specimens ($w_h$) are selected at which the individual features of steels began to be sufficiently clearly manifested with respect to the susceptibility to grains growth. The cooling rate of dilatometric specimens is selected, coming from the need to provide such conditions in the range of temperatures of the lowest stability of austenite, which will be as close as possible to the cooling conditions of HAZ metal of welded joints [13]. To simulate the conditions, typical for arc welding processes, the heating rate of the specimens is set in the range of 150–180 °C/s.

The heating rate of the specimens is controlled by changing the value of the current passing through the specimen according to the set program, and the rate of cooling is controlled by passing water through the devices in which the specimen is fixed, blowing the specimens with inert gas or by passing a low current through them.

The diagrams, characterizing the transformations of austenite in HAZ metal of high-strength alloyed steels during continuous cooling of specimens according to the thermal cycle of welding are shown in Figure 1. The chemical composition and mechanical properties of the investigated steels are given in Tables 3 and 4.

The typical characteristic for the considered high-strength alloyed steels is that the formation of martensite in them begins at the relatively low cooling rates ($w_{6/5}$ = 2–4 °C/s). With increase in $w_{6/5}$, the amount of martensite in HAZ metal of such steels increases. This occurs more sharply in steels 14Kh2GMR, 12GN3MFAYuDR-Sh and 14KhGN2MDAFB. At

**Table 2.** Requirements to mechanical properties of high-strength alloyed steels (not less than)

| Steel | $\sigma_{0.2}$ | $\sigma_t$ | $\delta_5$ | $KCU_{-40}$ | $KCV_{-40}$ |
|---|---|---|---|---|---|
| | MPa | | % | J/cm$^2$ | |
| 12GN2MFAYu | 590 | 690 | 14 | 29 | – |
| 12GN2MFAYuSh | 590 | 690 | 14 | – | 39 |
| 14KhG2SAFD | 590 | 690 | 14 | 39 | – |
| 14Kh2GMR | 590 | 690 | 14 | 39 | – |
| 12GN3MFAYuDR-Sh | 685 | 780 | 16 | – | 39 |
| 14KhGN2MDAFB | 785 | 885 | 15 | 39 | – |

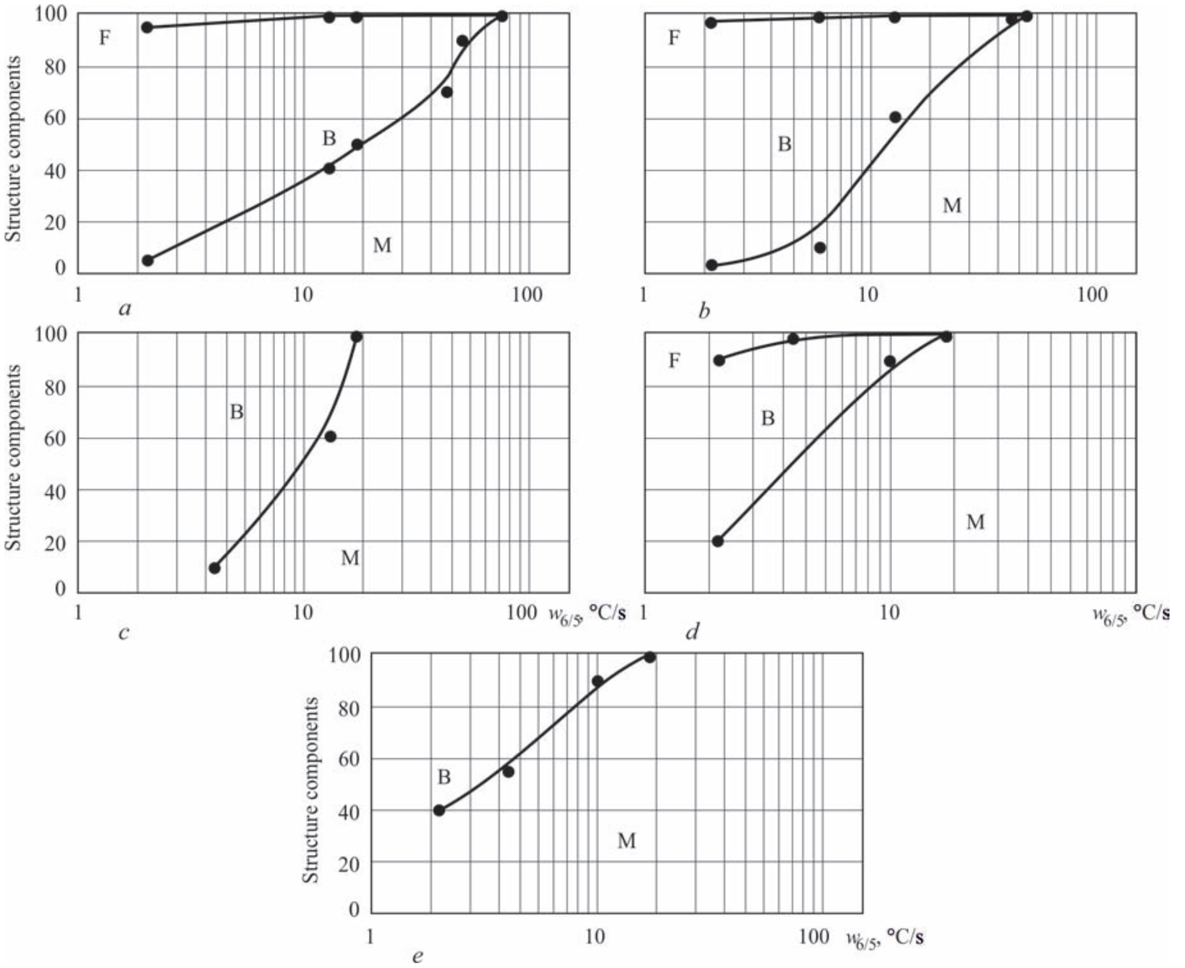


**Figure 1.** Diagrams of structural transformations of austenite in the overheating region of HAZ metal of high-strength alloyed steels 12GN2MFAYu (*a*), 14KhG2SAFD (*b*), 14Kh2GMR (*c*), 12GN3MFAYuDR (*d*) and 14KhGN2MDAFB (*e*)

$w_{6/5}$ = 4–8 °C/s the amount of martensite in the structure of HAZ metal of these steels reaches 50 %, and at $w_{6/5}$ = 20 °C/s — 100 %. In steels 12GN2MFAYu and 14KhG2SAFD, martensite in the amount of 50 % is formed at the higher cooling rates, $w_{6/5}$ = 20 and 14 °C/s, respectively, and 100 % of martensite in them is observed at $w_{6/5}$ = 70 and 50 °C/s. Moreover, it should be noted that as compared to high-strength alloyed steels of other grades, in steel 12GN3MFAYuDR-Sh the martensitic transformation are finished at the lower temperatures (200–250 °C). The mentioned factors, as is known, can have a significant effect on mechanical properties of HAZ metal of welded joints and their resistance to cold crack formation.

**Table 3.** Chemical composition of the investigated high-strength alloyed steels, wt. %

| Steel | C | Si | Mn | Cr | Ni | Mo | Cu | V | Nb | Ti | Al | S | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12GN2MFAYu | 0.15 | 0.41 | 1.14 | 0.38 | 1.56 | 0.22 | 0.19 | 0.07 | – | – | 0.06 | 0.032 | 0.014 |
| 14KhG2SAFD | 0.13 | 0.57 | 1.42 | – | – | – | 0.39 | 0.08 | – | – | 0.08 | 0.015 | 0.019 |
| 14Kh2GMR | 0.15 | 0.28 | 1.10 | 1.30 | – | 0.43 | 0.20 | – | 0.02 | – | 0.05 | 0.023 | 0.024 |
| 12GN3MFAYuDR | 0.13 | 0.23 | 1.36 | – | 3.08 | 0.33 | 0.40 | 0.05 | – | – | 0.02 | 0.004 | 0.020 |
| 14KhGN2MDAFB | 0.14 | 0.25 | 1.30 | 1.15 | 1.94 | 0.24 | 0.42 | 0.14 | 0.04 | – | 0.05 | 0.008 | 0.014 |

**Table 4.** Mechanical properties of the investigated high-strength alloyed steels

| Steel | $\sigma_{0.2}$ | $\sigma_t$ | $\delta_5$ | $\psi$ | $KCU_{-40}$ | $KCU_{-40}$ |
|---|---|---|---|---|---|---|
| | MPa | | % | | J/cm$^2$ | |
| 12GN2MFAYu | 625 | 720 | 20.8 | 62.2 | 80 | 52 |
| 14KhG2SAFD | 635 | 750 | 20.0 | 54.3 | 65 | 52 |
| 14Kh2GMR | 680 | 780 | 18.1 | 55.3 | 55 | 48 |
| 12GN3MFAYuDR-Sh | 821 | 887 | 19.2 | 52.6 | 186 | 130 |
| 14KhGN2MDAFB | 860 | 920 | 17.3 | 60.0 | 120 | 64 |

Taking into account that the structure of separate regions of HAZ metal of welded joints is not homogeneous, and the sizes of these regions are extremely small, the model specimens of 150×13×13 mm size were used to determine the effect of cooling conditions on mechanical properties of HAZ overheating region. The same as in dilatometric investigations, they were forcibly heated and cooled as to thermal welding cycles in accordance with the procedure, described in the work [14].

The rate of heating the specimens up to the temperature of 1350 °C was controlled with the help of a programming device of the installation MSR-75, and the cooling rate $w_{6/5}$ was changed from 2.7 to 50 °C/s by using the forced air cooling with different intensity.

To determine the effect of arc welding processes on mechanical properties of the overheating region of HAZ metal of the mentioned steels the specimens for tensile tests (type II according to GOST 6996–66) and impact bending (type VIII and type XI according to GOST 6996–66) were manufactured from the billets treated by TCW. The tensile tests of specimens were carried out at the temperature of 20 °C, and the tests on impact bending were carried out at the temperature of –40 °C. Their results are shown in Figures 2 and 3.

As follows from Figure 2, under the influence of TCW, the impact toughness of the metal in HAZ overheating region relative to the initial state of the steel is reduced. But, despite this, at $w_{6/5} > 5$ °C/s, these values for most of the investigated high-strength alloyed

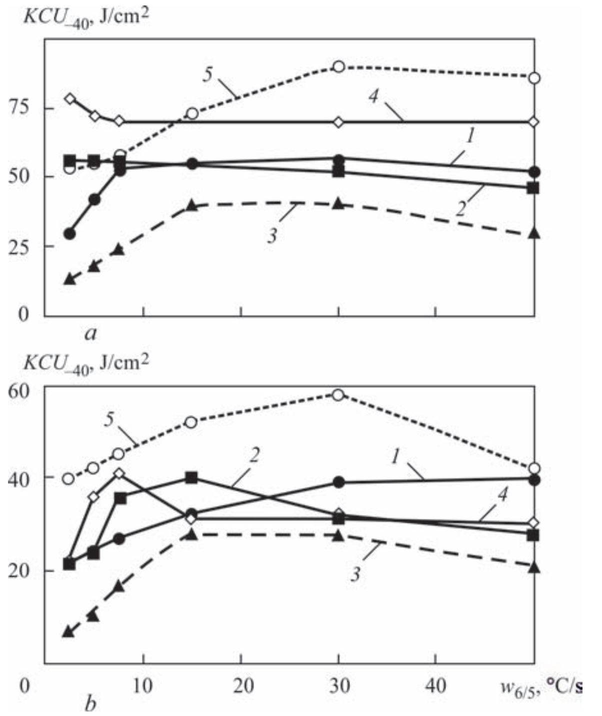


**Figure 2.** Influence of cooling rate $w_{6/5}$ on $KCU_{-40}$ (*a*) and $KCU_{-40}$ (*b*) of metal in the region of overheating of HAZ of steels: 12GN2MFAYu (*1*), 14Kh2GMR (*2*), 14KhG2SAFD (*3*), 14KhGN2MDAFB (*4*), 12GN3MFAYuDR-Sh (*5*)

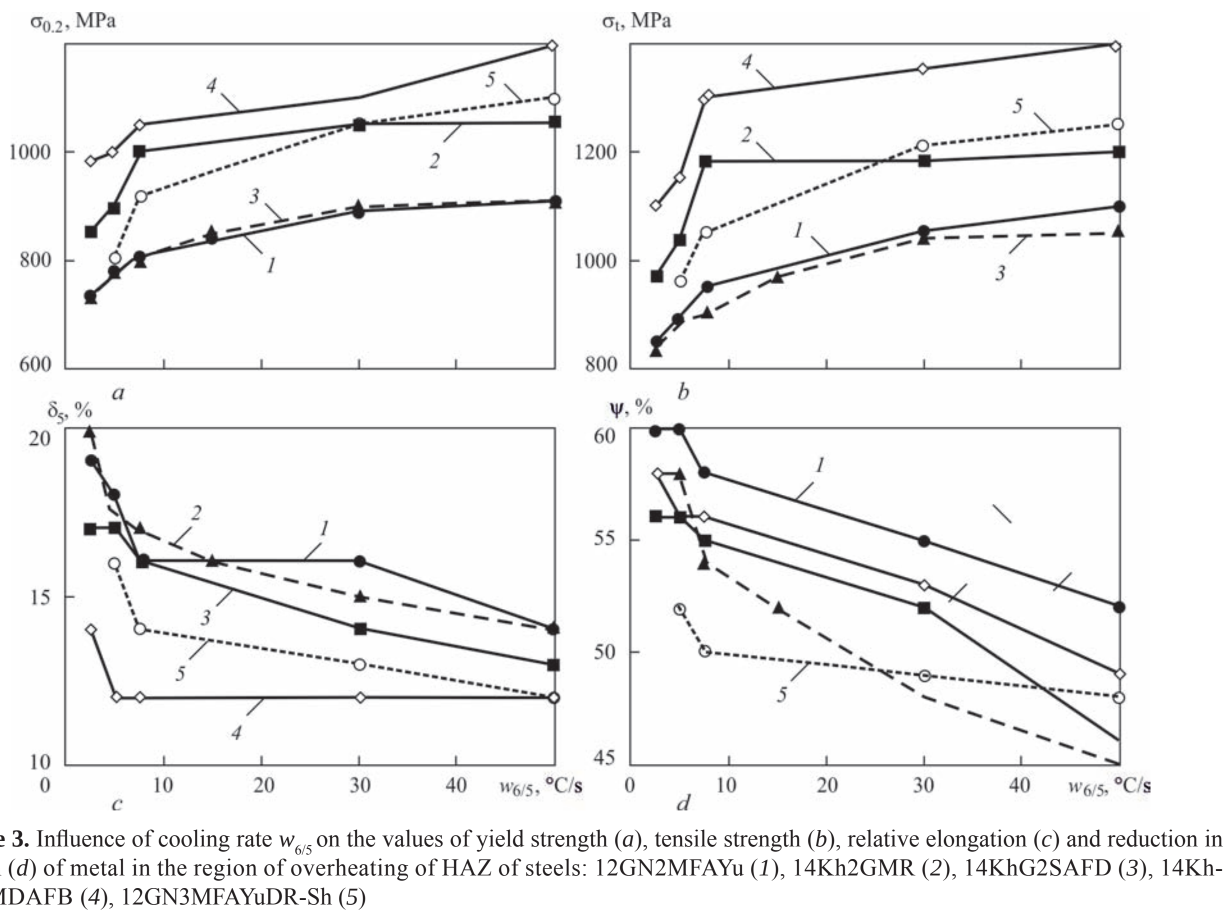


**Figure 3.** Influence of cooling rate $w_{6/5}$ on the values of yield strength (*a*), tensile strength (*b*), relative elongation (*c*) and reduction in region (*d*) of metal in the region of overheating of HAZ of steels: 12GN2MFAYu (*1*), 14Kh2GMR (*2*), 14KhG2SAFD (*3*), 14KhGN2MDAFB (*4*), 12GN3MFAYuDR-Sh (*5*)

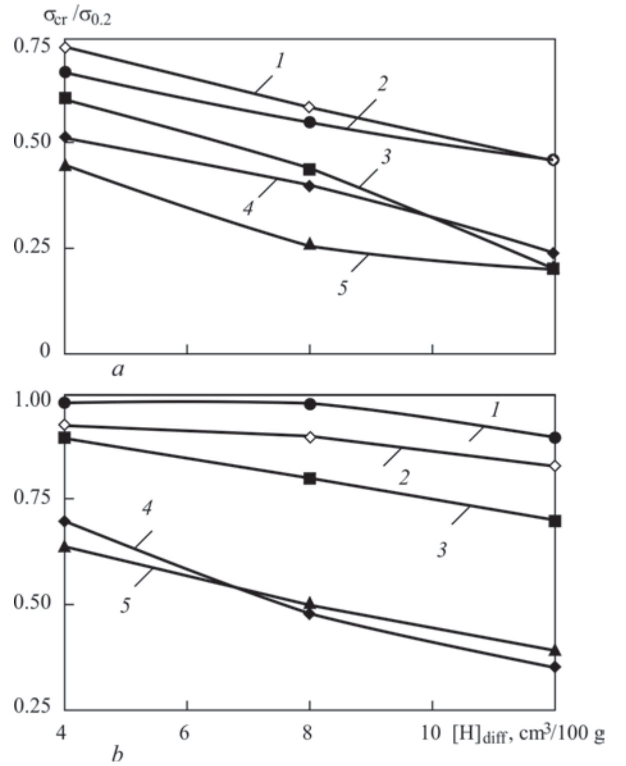


**Figure 4.** Resistance of steels 12GN2MFAYu (*1*), 12GN3MFAYuDR (*2*), 14KhG2SAFD (*3*), 14KhGN2MDAFB (*4*), 14Kh2GMR (*5*) to cold crack formation depending on the content of diffusion hydrogen in the deposited metal and the conditions of cooling HAZ metal: *a* — $w_{6/5}$ = 25 °C/s; *b* — 10

steels are at the level of the requirements specified to steel rolled metal. The exception is the steel of grade 14KhG2SAFD. The required level of impact toughness values in HAZ metal of welded joints of the mentioned steel can be obtained only in that case when welding is performed at the modes which provide its cooling at a rate of $w_{6/5}$ = 15–30 °C/s.

The graphical material shown in Figure 3, indicates that with increase in the cooling rate, the values of yield strength and the tensile strength of the metal in the overheating region of HAZ are firstly sharply increased, and then increase monotonically. The elongation and relative reduction in area decrease. This is quite natural, since, as was indicated above, as the cooling rate in the metal increases, the amount of the martensitic component increases, and the martensite, as is known, has a high strength, but also has a low ductility.

The evaluation of susceptibility of high-strength alloyed steels to cold crack formation was carried out according to the Implant method. The effect of the diffusion hydrogen content ($[H]_{diff}$) and the cooling rate of welded joints on the resistance of steels to cold crack formation was studied. The specimens-implants of 6 mm diameter with a stress concentrator in the form of a spiral groove were used. The welding of specimens installed in the holes of the base plate of 20 mm thickness was performed by the electrodes of grade ANP-9 (type E85) of 4 mm diameter at the mode: $I_w$ = 160–170 A; $U_a$ = 25–26 V; $v_w$ = 8.5–9.0 m/h. The loading of specimens was started during cooling at the temperature of 150–100 °C.

The rate of HAZ metal cooling $w_{6/5}$ from 25 to 10 °C/s was regulated by the preheating temperature of base plates, which in its turn was selected according to the oscillograms of thermal welding cycles for high-temperature regions of HAZ of specimens-implants. The cooling rate of HAZ metal at the level of 25 °C/s was obtained during welding without preheating, and at 10 °C/s it was obtained during preheating of base plates to the temperature of 120 °C. The amount of diffusion hydrogen in the deposited metal depended on the temperature and the time of calcination of electrodes and varied from 4 to 12 $cm^3$/100 g. Its content was determined by the chromatographic method [15].

Since HAZ metal of the investigated high-strength steels has a different static strength, as a criterion characterizing its resistance to cold crack formation, a dimensionless value was used, namely the ratio $\sigma_{cr}/\sigma_{0.2}$, where $\sigma_{0.2}$ is the conditional yield strength of HAZ metal, which it possesses under the specific welding conditions (cooling of welded joints), and $\sigma_{cr}$ is the critical (maximal) value of stresses, which the specimens are able to withstand without crack formation.

The results of testing the specimens using the Implant method (Figure 4) prove that at the content of diffusion hydrogen in the deposited metal, limited to 4 $cm^3$/100 g, the HAZ metal of welded joints of high-strength alloyed steels of type 12GN2MFAYu and 12GN3MFAYuDR-Sh is distinguished by a high resistance to cold crack formation. It is shown by the fact, that even in the case when welding is carried out without preheating ($w_{6/5}$ = 25 °C/s), the value $\sigma_{cr}/\sigma_{0.2}$ of these steels is in the range of 0.7–0.75. The susceptibility of steels of grades 12GN2MFAYu and 12GN3MFAYuDR-Sh to cold crack formation, as well as of other high-strength alloyed steels, is pronounced and intensified with increase in content of $[H]_{diff}$ in the deposited metal.

To reduce the risk of cold crack formation in welded joints of high-strength alloyed steels of grades 14Kh2GMR, 14KhGN2MDAFB and 14KhG2SAFD, it is necessary not only to considerably limit the content of diffusion hydrogen in the deposited metal, but also to preheat them to the temperature of not lower than 120 °C.

## Conclusions

1. High-strength alloyed heat-hardened steels combine the high strength and cold resistance.

2. Under the influence of thermal cycles, characteristic for arc welding processes, the transformation of austenite in HAZ metal of the considered high-strength alloyed steels occurs in the bainite and martensite regions.

3. The increase in cooling rate of HAZ metal of high-strength alloyed steels causes improvement in the strength properties ($\sigma_{0.2}$ and $\sigma_t$), however it decreases its ductility ($\delta_5$ and $\psi$).

4. To produce welded joints of high-strength steels with the required complex of mechanical properties and sufficient resistance to cold crack formation the content of diffusion hydrogen in the deposited metal should not exceed 4 $cm^3$/100 g and the modes of welding and the temperature of preheating should be selected in such a way that they could provide the cooling rate of HAZ metal in the range of 5–20 $^o$C/s.


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