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INFLUENCE OF THERMAL CYCLE OF WELDING ON STRUCTURE AND MECHANICAL PROPERTIES OF HAZ METAL IN HIGH-STRENGTH STEEL PRODUCED BY CONTROLLED ROLLING

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At present there is a tendency to develop high-strength alloyed steels with yield limit of more than 590 MPa, in which heat treatment (quenching and tempering) is replaced by the process of controlled rolling with subsequent accelerated cooling. Application of technologies of welding such steels is now based only on recommendations of the manufacturer of metal and welding consumables, as well as on carbon equivalent. Considering that the new generation of steels, including alform 620M, was produced due to complex application of both microalloying and thermomechanical treatment with subsequent accelerated cooling, the obtained properties can be lost as a result of softening during processing stages, associated with steel heating. As the level of the change of mechanical properties of HAZ metal determines steel weldability, the influence of thermal cycles of welding on the properties and structure of HAZ metal in high-strength steel alform 620M is considered at the first stage of investigations. Performed investigations revealed that optimum combinations of mechanical properties and structure can be achieved at the rate of cooling of welded joint HAZ metal higher than 25 °C/s. 10 Ref., 2 Tables, 4 Figures.

Keywords: *high-strength steel, controlled rolling, thermal cycles of welding, heat-affected zone, structure, properties*

Lowering the specific weight of structures under the condition of ensuring their required service reliability is one of the main tasks solved daily by the developers of machines, mechanisms and metal structures. Successful fulfillment of this task is largely determined by the properties of steels, applied for their manufacture. First of all, we are talking about the strength of steel, both at static and at dynamic loads. One of the directions for increasing the strength of rolled steel is producing quenching structures by thermal refining of low-carbon metal (quenching and tempering) and limited alloying with manganese, chromium, nickel and molybdenum, in combination with the carbide- and nitride forming elements [1]. Alongside the high values of strength ($\sigma_{0.2} \geq 590$ MPa) alloyed steels such as 14Kh2GMR, 12GN2MFAYu, 14KhN2MDAFB, etc., have a sufficient margin of ductility, good brittle fracture resistance and weldability. This is indicated by half a century experience of operation of welded structures, made from them: powerful mine excavators, heavy-duty vehicles, construction and road machinery.

At present there are tendencies for development of high-strength alloyed steels with $\sigma_{0.2} \geq 590$ MPa, in which thermal treatment is replaced by the process of controlled rolling with subsequent accelerated cooling. Such steels began to enter the metal market of Ukraine, and can be applied in mechanical engineering, metallurgy, mining and processing industries. For instance, radial blowers [2] (exhausters) of H7500 type of riveted design are used in metallurgical works of Ukraine for pumping out the combustion products of open-hearth furnaces, sinter and converter gases. Replacement or repair of exhausters requires stopping the production line for the period from several hours up to several days that affects the productivity of sinter, open-hearth and converter process. The process of repair of the exhauster proper is a very long and labour-consuming one, as mostly exhausters with riveted impellers are operating (repair involves replacement of blades or blades and central disc). In connection with a short operating time and need for frequent scheduled repair of H7500 impeller, a fundamentally new welded structure was developed with the assistance of PWI specialists [2]. As is known, the most heavy-duty part of the impeller is its central disc. The main requirements at selection of material for manufacture of exactly this part were as follows: certain percent of carbon content (to ensure good weldability), as well as calculated values of yield limit (more than 600 MPa), (for preservation of structure integrity at operation in the higher temperature range)

Table 1. Chemical composition of steel alform 620M, wt.%

C	Si	Mn	P	S	Al	Cr	Mo	Ni	V	Nb	Ti	B
0.08	0.37	2.0	0.005	0.01	0.027	0.38	0.21	0.02	0.01	0.043	0.017	0.001

and relative elongation (to ensure structure ductility). Proceeding from these data, high-strength low-alloyed steel alform 620M, microalloyed by niobium and vanadium, was selected, which is produced by an Austrian company, and supplied in the condition after controlled rolling and accelerated cooling.

By the data of EN10025-2 standard, this steel is characterized by the following mechanical properties: increased strength properties (σ_y > 620 MPa; σ_t = 730 MPa); high ductility (δ_5 = 23 %) and impact toughness (KCV_{-40} > 34 J/cm^2). Such mechanical properties are due to finely dispersed structure, produced by controlled rolling and subsequent accelerated cooling. These steels have predominantly bainite structure [3–5]. Vanadium, niobium and titanium additives promote metal reaustenitization, preventing austenitic grain growth. Dispersion hardening is effectively controlled by vanadium content. One of the most important mechanical characteristics is impact toughness, which also has differences both in niobium and in niobium-vanadium steels [6, 7]. Maximum impact toughness of steel with niobium corresponds to cooling rate of 20 °C/s, whereas for steel with vanadium additive this temperature shifts to 60 °C/s. With lowering of the cooling rate to 6 °C/s, an essential decrease in impact toughness of both the steels is observed, that is associated with formation of granular bainite. Lowering of ductility of these steels is associated with precipitation of brittle inclusions along the bainite grains, coarsening of the austenitic grain during welding and changing of bainite morphology from lamellar to granular one.

Today application of the technologies of welding high-strength steels produced by the methods of controlled rolling is based only on the recommendations of the manufacturer of metal [8, 9] and welding consumables, as well as on carbon equivalent. This is obviously not enough for development of critical welded structures, using processing involving heating from 300 up to 1500 °C, which are exposed to dynamic and alternating loading. Considering that the new generation of steels, including alform 620M, are produced due to complex use of both microalloying, and themomechanical treatment with subsequent accelerated cooling, the obtained properties can be lost as a result of softening during processing operations associated with steel heating. It is known that the metal structure and mechanical properties can change significantly under the impact of welding thermal cycles (WTC). The influence of welding thermal cycles on the properties and structure of HAZ metal was established by the results of studies performed on high-strength steel S460M [10], produced by controlled rolling with subsequent accelerated cooling. It is shown that with increase of HAZ metal cooling rate $w_{6/5}$ from 3 up to 25 °C/s the ferrite-pearlite structure transforms into bainite structure that results in hardness increase from *HV* 190 up to *HV* 280, as well as increase of strength characteristics [10]. However, the question of studying the weldability of steel of a higher strength class remains urgent. As the level of change of mechanical properties of the HAZ metal determines the steel weldability, the first stage of studies is devoted to consideration of the influence of welding thermal cycles on the properties and structure of HAZ metal in high-strength low-alloyed steel alform plate 620M, microalloyed by niobium and vanadium.

Table 2. Mechanical properties of steel alform 620M

σ_y, MPa	σ_t, MPa	δ_5, %	ψ, %
667	731	24	77

Experimental procedure. Structural steel alform 620M which is supplied in the condition after controlled rolling was used for the experiments. Chemical composition of this steel is given in Table 1, and its mechanical properties are shown in Table 2.

As was already mentioned, the structure and properties of rolled steel HAZ metal can change under the impact of welding thermal cycles. Therefore, this impact on alform 620M steel was studied at the initial stage of the work. Rate of cooling of metal, heated up to temperatures of 1200–1300 °C, in the temperature range of 600–500 °C ($w_{6/5}$), was taken as WTC criterion. Investigation results were used to determine the limit cooling rates ($w_{6/5\min}$ and $w_{6/5\max}$), below and above which lowering of strength and ductility values of HAZ metal occurs, compared to the specified requirements to welded joints. Change of mechanical property values, depending on the cooling rate of HAZ metal in the temperature range of 600–500 °C was studied with application of model samples of 120×12×12 mm size, which were heat-treated in MSR-75 unit, in keeping with welding thermal cycles. Heat treatment process was as follows. First the samples were heated by passing current up to temperatures of 1200–1300 °C, which are characteristic

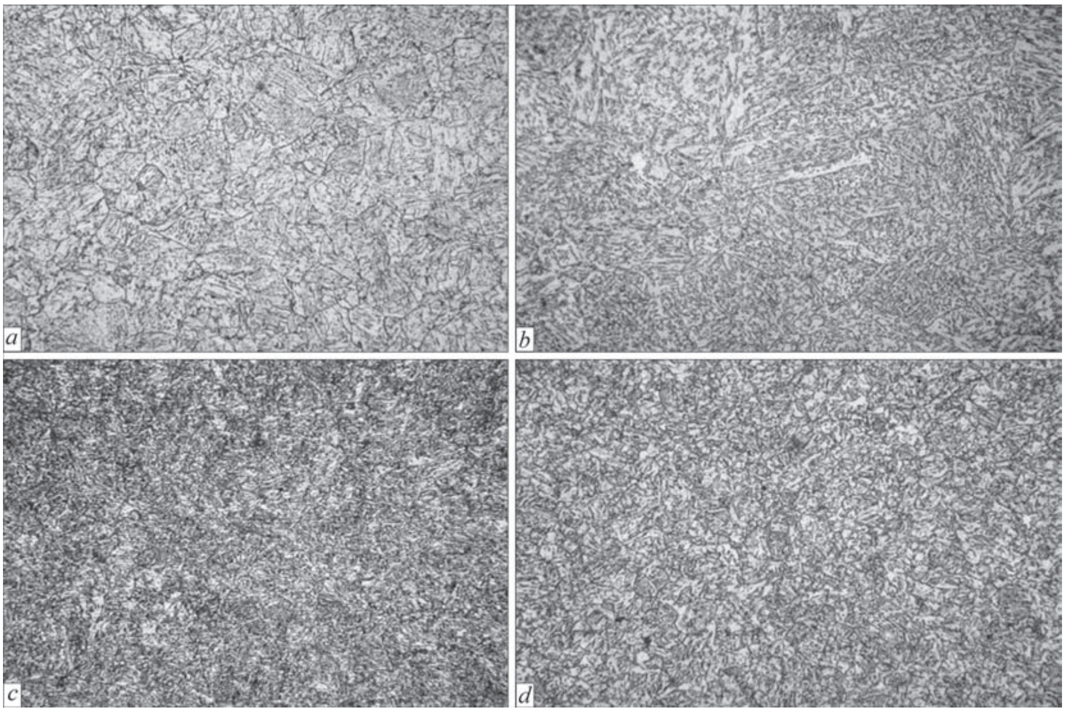

Figure 1. Microstructure (×500) of steel alform 620M, depending on cooling rate $w_{6/5}$: *a* — base metal; *b* — 3; *c* — 12; *d* — 25 °C/s

for the overheated zone of welded joint HAZ. Sample heating rate was equal to 150–170 °C/s that corresponds to the conditions of metal heating in the heat-affected zone at arc welding processes. At this temperature, the samples were soaked approximately for two seconds, and then were cooled forcedly. The rate of sample heating-cooling was controlled by chromel-alumel thermocouple of 0.5 mm diameter. Samples of type II to GOST 6996–96 were mechanically cut out of the steel for static tensile testing (three samples for each cooling rate). Testing was performed to GOST 6996–66 at the temperature of 20 °C.

Results and discussion. Structure and mechanical properties of thermomechanically strengthened steel alform 620M were studied in this work. Thermomechanical rolling in the temperature range of 900–700 °C with controlled cooling leads to formation in steel alform 620M of a bainite structure (predominantly lower bainite — 90 %) with grain size of the order of 40 μm and hardness *HV* 280.

Impact toughness values of steel alform 620M are essentially higher than the normative values and are equal to KCV_{-40} = 307 J/cm^2. Therefore, by the values of static strength, ductility and impact toughness steel alform 620M can be considered to be promising from the viewpoint of its application for blower fans of the equipment of ore-dressing complex.

In their turn, the dependencies characterizing the change of strength and ductility values in modeled HAZ metal of steel alform 620M under the impact of WTC are given in Figure 2. Results of the conducted investigations are indicative of the fact that at the cooling rate $w_{6/5}$ = 3 °C/s in the temperature range of 600–500 °C, the values of yield limit of HAZ metal decrease, compared to the initial state, namely $\sigma_{0.2}$ from 667 to 553 MPa; with $w_{6/5}$ increase up to 12 °C/s the yield limit rises up to 580, and up to 585 MPa at $w_{6/5}$ = 25 °C/s. Ultimate strength σ_t decreases slightly to 723 MPa at $w_{6/5}$ 3 °C/s, and then rises up to 790 MPa at $w_{6/5}$ = 25 °C/s. At the same time, ductile properties of modeled HAZ metal compared to the initial state change only slightly (changes do not exceed 5–10 %).

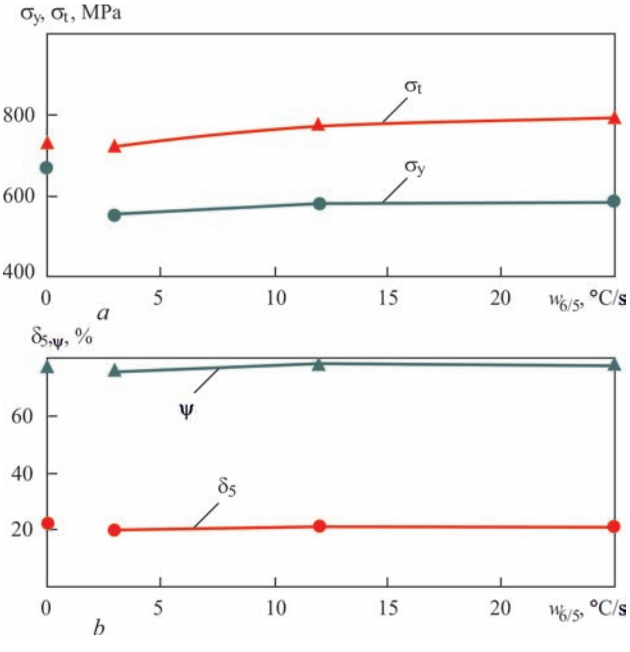

Figure 2. Mechanical properties of steel alform 620M, depending on cooling rate $w_{6/5}$

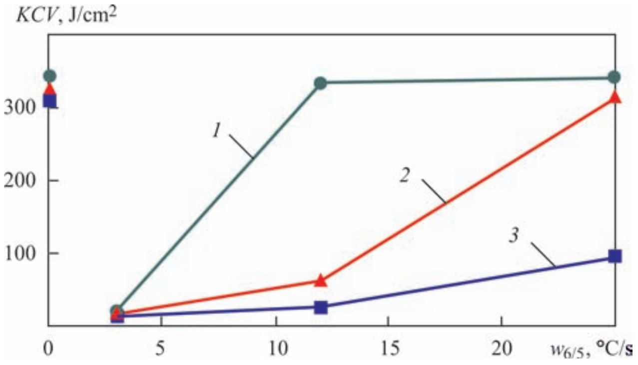

Figure 3. Impact toughness of steel alform 620M, depending on cooling rate $w_{6/5}$ (*1* — 20; *2* — –20; *3* — –40 °C)

At impact bend testing of samples with a sharp V-shaped notch it was established that impact toughness of HAZ metal of steel alform 620M decreases relative to base metal (Figure 3). The most significant lowering of *KCV* values is observed in samples, which cooled down at the rate of $w_{6/5}$ = 3 °C/s (from 341 to 21.2 J/cm^2 at testing temperature of 20 °C, from 329 to 19.5 J/cm^2 at the temperature of –20 °C and from 307 to 14.3 J/cm^2 at the temperature of –40 °C). With increase of cooling rate up to 12 °C/s, they increase somewhat for impact toughness values at negative temperatures and increase significantly for testing at room temperature: KCV_{20} = 332 J/cm^2, KCV_{-20} = = 62 J/cm^2 and KCV_{-40} = 27 J/cm^2. With increase of cooling rate to 25 °C/s, they rise up to the following values: KCV_{20} = 340 J/cm^2, KCV_{-20} = 312 J/cm^2 and KCV_{-40} = 94 J/cm^2.

Such changes of mechanical properties of HAZ metal of steel alform 620M are due to different structural transformations in the range of the studied cooling rates. This is evidenced by the results of metallographic studies. These studies showed that a structure consisting of different morphological forms of lower and upper bainite with prevalence of the latter (Figure 2, *b*), with average grain size of the order of 65 μm, formed in the overheated zone of the HAZ metal of steel alform 620M at the cooling rate $w_{6/5}$ = 3 °C/s. Hardness of such metal is equal to *HV*220.

At $w_{6/5}$ increase up to 12 °C/s an equiaxed bainite structure forms with lower bainite content of 60 %. Grain size decreases and corresponds to 15–25 μm, hardness increasing up to *HV*250.

At further increase of the cooling rate up to $w_{6/5}$ = = 25 °C/s, a structure consisting of a mixture of upper (20 %) and lower (80 %) bainite forms in the modeled HAZ metal. Due to that metal hardness rises up to *HV*270 that, in its turn, leads to increase of the values of its static strength and decrease of its ductile properties.

Analysis of fractographic data obtained after impact bend testing of the samples, showed that with increase of cooling rate (from $w_{6/5}$ = 3 °C/s up to $w_{6/5}$ = = 25 °C/s) at negative testing temperatures (T_{test} = –20 and –40 °C), the nature of fracture in the zone of the main crack propagation changes from 100 % of brittle fracture (Figure 4, *a*) to mixed mode: 70–75 % of quasibrittle and 25–30 % of ductile fracture (T_{test} = = –20 °C, Figure 4, *b*). With increase of the cooling rate, the size of elements of fracture surface decreases more than 2 times from 50 μm ($w_{6/5}$ = 3 °C/s) to 25 μm ($w_{6/5}$ = 25 °C/s). This circumstance is indicative of the fact that from the viewpoint of mechanical properties a cooling rate of $w_{6/5}$ = 25 °C/s provides an optimum combination of strength, ductility and impact toughness, the closest to those values for base metal.

Thus, it was found that lowering of the strength and impact toughness of HAZ metal of steel alform 620M at cooling rate $w_{6/5}$ = 3 °C/s, is due to an essential grain growth (up to 65 μm) and formation of predominantly upper bainite structure. Increase of cooling rate $w_{6/5}$ = 12 °C/s leads to reduction of average grain size to 15–25 μm, increase of specific fraction

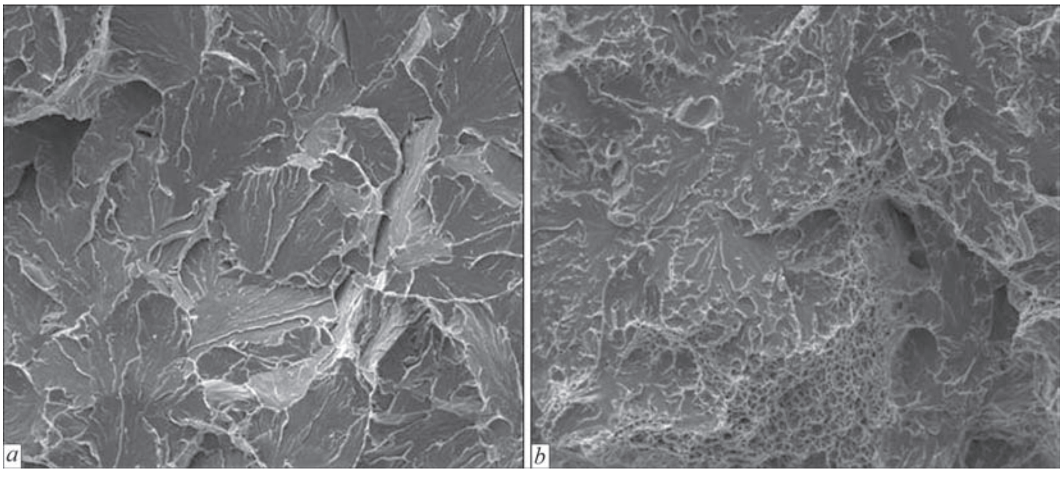

Figure 4. Fractograms of fracture surface of samples of steel alform plate 620M after impact bend testing (×810): *a* — T_{test} = –20 °C, $w_{6/5}$ = 3 °C/s; *b* — T_{test} = –20 °C, $w_{6/5}$ = 25 °C/s

of lower bainite to 60 % and, consequently, to increase of strength values. However, the values of cold resistance (impact toughness at negative temperatures) are at an unsatisfactory level. The latter fact is attributable to a high content of upper bainite (40 %) in the produced structure. Cold resistance values can be increased by increasing the cooling rate of HAZ metal to $w_{6/5} \geq 25$ °C/s. This is achieved due to formation of a finely-dispersed structure (15 μm), consisting predominantly of lower bainite (80 %).

Conclusions

Performed studies of the influence of welding thermal cycles on the structure and properties of steel alform 620M showed the following:

- at the cooling rate of modeled HAZ metal $w_{6/5} = 3$ °C/s (characteristic for submerged-arc welding processes) an essential lowering of the yield limit to 554 MPa, and of impact toughness to values not meeting the Euronorm standards (less than 34 J/cm^2) is observed, that is due to a significant coarsening of grains of the structure, produced at such cooling conditions;
- the values of strength and impact toughness can be increased by increasing the cooling rate of the modeled HAZ metal $w_{6/5}$ to 25 °C/s. Here, a finely dispersed structure forms in the HAZ metal with grain size of the order of 15–25 μm, and the fracture surface of the samples, tested for impact bending, has a mixed structure of brittle-ductile fracture.

Thus, it is found that optimum combinations of mechanical properties and structure can be achieved at the cooling rate of welded joint HAZ metal $w_{6/5} \geq 25$ °C/s.

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