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WAYS TO INCREASE THE FATIGUE FRACTURE RESISTANCE OF WELDED JOINTS OF HIGH-HARDNESS ARMOR STEELS

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ABSTRACT

The influence of mechanical impact methods of treatment on the fatigue resistance of joints of high-hardness armor steels, compared to low tempering, in welding with high-alloy welding materials was studied. The paper presents the results of tests by cyclic out-of-plane bending of welded joints of HB500MOD armor steel, made using KhORDA 307Ti wire (08Kh20N9G7T alloying system), which were additionally subjected to layer-by-layer low-frequency peening of the deposited metal during welding, high-frequency peening of the fusion zone and adjacent HAZ metal and shot peening of the joint surface after their welding. It was established that thermal tempering of armor steel joints with a high-alloy weld does not contribute to an increase in the fatigue resistance. The most effective methods to increase the fatigue resistance of joints are mechanical high-frequency peening or enhanced shot peening after welding.

KEYWORDS: high-hardness armor steel, welded joints, fatigue fracture resistance, low tempering, mechanical low-frequency peening, mechanical high-frequency peening, shot peening

INTRODUCTION

The required set of mechanical and service properties of high-hardness armor steels is achieved through a special level of alloying with elements that strengthen ferrite and increase the steel temperability (C, Cr, Ni, Mo, V, B) and appropriate heat treatment — hardening followed by low tempering. High indices of strength ($\sigma_{0.2} \geq 1200$ MPa) and hardness ($HB \geq 500$) combined with relatively high ductile properties ($d_5 \geq 8\%$) ensure adequate bullet resistance of structures in light armored vehicles (LAV). High-hardness armor steels include domestic steel grade 71 and its foreign analogues, such as HB500MOD, ARMOX500, RAMOR500, etc.

According to the alloying system, high-hardness armor steels are classified as medium-carbon alloy steels. Welding of these steels is associated with the main problem — a high probability of cold crack formation in the HAZ metal of welded joints, which is predetermined by the formation of hardening structures of increased brittleness [1, 2]. This requires additional technological solutions in the manufacture of LAVs. Thus, to prevent the occurrence of cracks in welding with low-alloyed materials of the Mn–Si–Mo–Ti system, it is necessary to preheat welded joints, the temperature of which, depending on the level of steel alloying, can exceed 150 °C. If a high-alloyed wire of the Cr–Ni–Mo–Ti system is used, it is possible to weld without preheating due to the formation of hardening structures in the near-weld HAZ metal with a significantly lower level of internal stresses. This is

evidenced by the results of studies described in detail in [3]. This welding method produces a hardenable martensitic-bainitic metal structure in the HAZ near-weld zone with an increased ability to microductile deformation without the formation of microcracks. The weldability of high-hardness armor steels in this area was studied in detail and technologies for welding LAV armor structures with high-alloy materials were developed, which are now used in production and ensure high-quality welded joints.

However, there is another problem in welding high-strength steels. It is associated with a limited durability and the formation of fatigue cracks in welded joints during the operation of products [4]. This is especially true for welded joints of armor structures located near the fasteners of the product propulsion system, which was repeatedly observed during the inspection of these areas. The mentioned cracks are located in the transition zone from the weld to the base metal and are initially small in size (up to 10 mm), but if they are not repaired in due time, they will further propagate actively with a transition to the base metal (Figure 1). In Soviet times, when armor steels were of lower hardness and less alloyed, and low-alloy materials were used in welding of LAV products, it was mandatory to perform a low tempering of a product no later than 24 hours after its welding to reduce the stress level and the probability of crack formation in welded joints during operation. Regarding the conditions for welding LAV structures with high-alloy materials, the feasibility of low tempering has not yet been fully determined. It should also be noted that this

technological operation requires specialized large-sized equipment, significant energy consumption and time. At the same time, the cost of low tempering can amount up to 30 % of the total cost of armored structures.

At present, less energy-consuming technological methods are known that provide an increase in the fatigue resistance of welded joints during long-term operation; they are scientifically substantiated and tested in the manufacture of civilian metal structures [5–7]. Among them, the most common are deformation technologies, in which, due to the introduction of mechanical energy, ductile deformation of welded joint areas occurs and the metal structure is refined. Under the influence of deformation, it is also possible to significantly reduce residual stresses in the welded joint and their concentration level in the transition zone from the weld to the base metal. All these positive changes should contribute to an increase in the crack resistance of welded joints of armor steels under cyclic loads and their durability in general. Such deformation technologies may include mechanical impact treatment methods, among which the most common are low-frequency (up to 10 Hz) layer-by-layer peening of weld metal during joint welding and post-weld high-frequency (over 5 kHz) peening of the fusion zone and overheating area of HAZ. Impact methods also include shot peening of metal, including welded joints, which is a common technological operation in the manufacture of LAVs.

In this regard, studies to determine the possibility of using energy-saving treatment technologies without low tempering to increase the crack resistance and durability of high-hardness armor steel joints are relevant.

THE AIM

of this work was to conduct a comparative assessment of the effect of mechanical impact treatment methods for welded joints of high-hardness armor steels, in the manufacture of which high-alloy welding materials are used, on their resistance to fatigue crack formation. This will allow making a final determination of the feasibility of low tempering and the choice of effective technological operations in the modern manufacture of LAVs to increase their service life.

MATERIALS AND METHODS OF RESEARCH

Welded joints of typical high-hardness armor steel HB500MOD of the following composition were used as an object of the studies, wt.%: 0.26 C; 0.21 Si; 0.78 Mn; 0.42 Cr; 0.74 Ni; 0.27 Mo; 0.06 V; 0.002 V. For comparative tests, V-groove butt joints of 400×480 mm in size and 10 mm thick were prepared, which were produced with a full penetration and a partial root welding on the back side. The joints were mechanically welded in a mixture of shielding gases (82 % Ar + 18 % CO₂) using high-alloyed KhORDA



Figure 1. Fatigue crack in a welded joint of a LAV product after long-term operation

30 7Ti wire of domestic production (analogue of Sv-08Kh20N9G7T wire) with a diameter of 1.2 mm on the following mode: welding current 160–180 A, arc voltage 26–28 V, welding speed 12–15 m/h. No preheating was used during their welding. To compare the effect of low tempering, in welding under similar conditions using low-alloyed Sv-10GSMT wire (Soviet era technology), the metal preheating was 100 °C.

The following technological operations (methods) of treatment were used to prepare welded joints for their testing:

- No. 1 (basic) — without low tempering of the joint and any impact treatment methods;
- No. 2 — low tempering (230 °C, 3 h) within 15–20 h after welding;
- No. 3 — low-frequency peening (up to 10 Hz) of the deposited metal layers during the welding process;
- No. 4 — high-frequency peening (more than 5 kHz) within 4 days after welding;
- No. 5 — shot peening within 4 days after welding of the joint according to the accepted technology of LAV manufacturer;
- No. 6 — enhanced additional shot peening of the weld metal and HAZ area along the welded joint.

The peculiarities of using impact treatment methods for welded joints were as follows. For example, low-frequency layer-by-layer peening of the deposited metal was performed during the welding process after the joints were cooled to a temperature of 100–50 °C. Since the thickness of the metal was 10 mm and the butt joint was welded in three layers, only the 2nd layer of the weld was peened (until the surface pattern of the deposited metal changed by 70–90 %). The root and final layers were not peened, as is recommended when using this method. To implement the peening process, a conventional electromechanical tool with a diameter of 3–5 mm at the tip of the strike was used. The rate of treatment of the weld layer surfaces was 100 mm per 1 min.

High-frequency (more than 5 kHz) peening was performed on the surface of the fusion zone and the

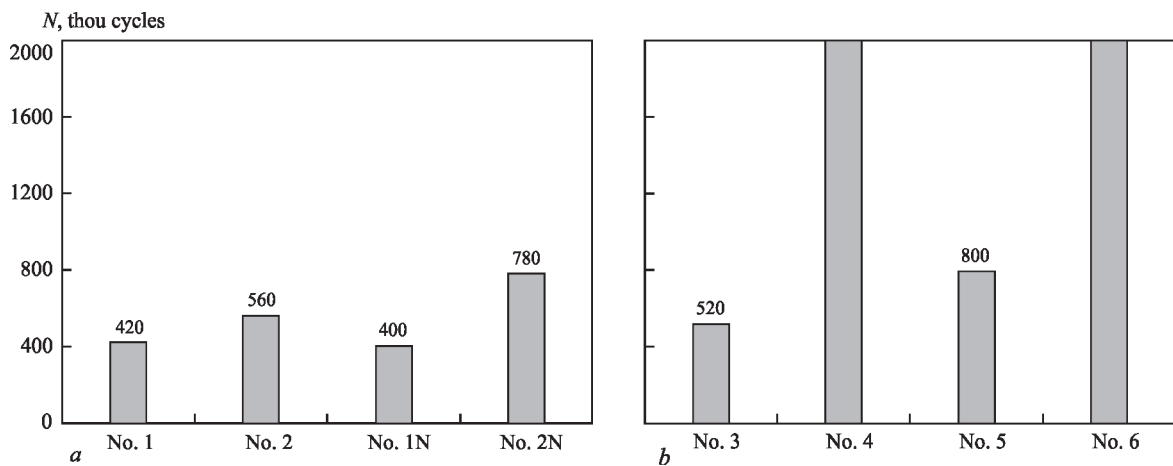


Figure 2. Fatigue cracks resistance of welded joints of armor steel HB500MOD made using KhORDA 307 Ti and Sv-10GSMT wire (N marking), Nos 1–6 — treatment methods: *a* — effect of low tempering; *b* — effect of impact treatment methods

adjacent HAZ metal of the welded joint, the width of the treated area was 2.0–2.5 mm. Here, a specialized tool was used according to the developed recommendations for the use of this method [7, 8]. The speed of the tool movement during peening was 1 mm/s. At the same time, a characteristic round-shaped groove of 0.3 mm deep was formed in the treatment area.

Shot peening is a technological operation in the manufacture of LAV products at specialized enterprises, which is necessarily performed on a finished product before its painting. In our work, shot peening of welded joints was performed under the conditions of the SE “ZhBTZ” with the equipment and treatment technology used in mass production. The shot diameter was 2–3 mm. Shot peening was performed on the facial and back sides over the entire surface of welded plates using conventional technology (No. 5) and with enhanced additional treatment of the joint surface (No. 6). The treatment rate was 100 mm per 1 min.

Then, from each butt joint prepared by the mentioned method (Nos. 1–6), 3 specimens of 480×120 mm were cut out, which were tested at cantilever bending under symmetrical cyclic loading with maximum cycle stresses of 60 MPa in accordance with generally accepted methods for testing the durability of welded joints [9, 10]. For this purpose, a specialized fatigue resistance testing machine of the UMP-1 type was used. The cyclic loading frequency was 14 Hz. The evaluation criterion was the number of loading cycles (N), at which a critical fatigue crack of 3 mm length was formed in the welded joint. If no typical signs of a crack were detected within 2 mln cycles, the loading was stopped and this was an index of the best resistance of welded joints to fatigue crack formation.

Metallographic examinations of welded joints were performed using light microscopy (Versamet-2, Neofot-32), microhardness was measured in the Leco M-400 microhardness tester.

RESEARCH RESULTS AND THEIR DISCUSSION

The summarized results of comparative fatigue tests of welded joints under cyclic out-of-plane bending are shown in Figure 2. It should be noted that under all the considered welding and treatment variants, fatigue cracks were initiated at the transition from the weld to the base metal and further propagated deep into the welded joint in the HAZ metal (Figure 3).

As is seen from the data in Figure 2, *a*, low tempering of joints with high-alloy welds, which was performed after the specimens had been aged for 15–20 h (No. 2), had a negligible effect on increasing their durability. The number of load cycles before the formation of fatigue cracks increased by 30 % (from 420000 to 560000, respectively), and in welding with low-alloy material (No. 2N), the value increased almost twice (from 400000 to 780000 cycles). In the initial state without heat treatment, the durability of joints in welding with high- and low-alloy materials is

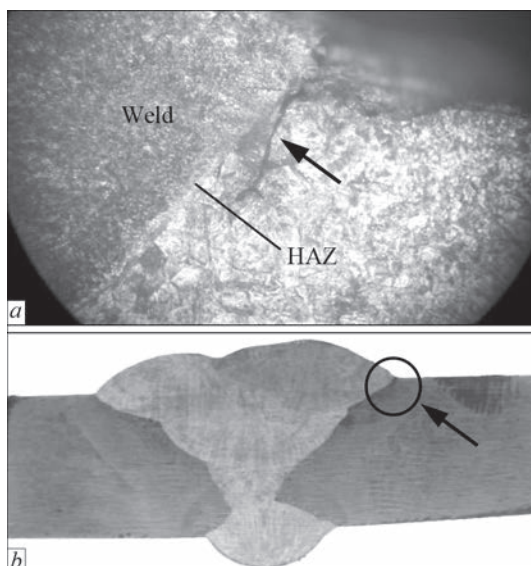


Figure 3. Typical fatigue crack formation and propagation (*a*, ×100) in welded joints (*b*) of armor steel HB500MOD

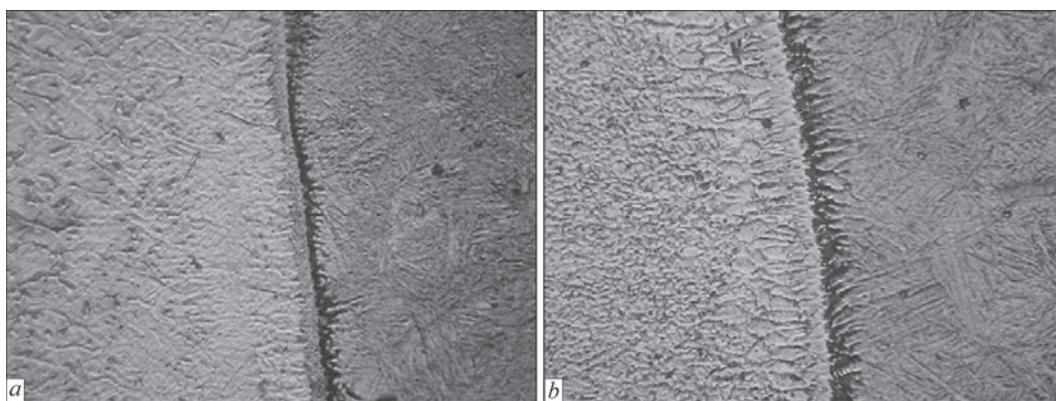


Figure 4. Typical fusion zone in welded joints of HB500MOD steel with high-alloy weld ($\times 500$): *a* — in the middle part of the joint; *b* — in the upper part of the joint

approximately the same (No. 1 and No. 1N). A slightly higher fatigue cracking resistance (by about 5 %) of the joints made using KhORDA 307 Ti wire is associated with the peculiarities of hardened structure formation in the HAZ metal when using high-alloy wire.

In our opinion, a slight increase in the resistance to fatigue fracture of welded joints of steel with a high-alloyed weld is associated with the embrittlement of the fusion zone at thermal tempering due to the development of carbon diffusion processes. The formed brittle inter-layers are small in size (up to 5 μm) (Figure 4), but their presence is sufficient to reduce the resistance of metal to fatigue crack formation under external load.

Layer-by-layer peening of the deposited metal during the welding process promoted an increase in the durability of the joint by only 25 %. The number of cycles before fatigue crack formation increased from 420 to 520 thou (Nos 1 and 3). However, it should be considered, that in welding with high-alloy materials, this treatment method can be used to reduce deformations in joints and preserve the geometric dimensions of the armor structure.

The greatest impact on an increase in the durability of welded joints of armor steel HB500MOD with a high-alloy weld was caused by a high-frequency peening of the fusion zone and the adjacent HAZ metal. At the same time, a fatigue crack did not form in

the welded joint even under a load of 2 mln cycles or more (the test was stopped at 3 mln cycles).

Metallographic examinations have demonstrated that the structure of armor steel welds in the initial state is austenitic-ferritic, with a microhardness in the weld centre $HV\ 2210\text{--}3660\ \text{MPa}$. A bainitic-martensitic (B–M) structure with a microhardness of 3360–4640 MPa and a package size of 40–200 μm is formed in the metal of the HAZ overheating area. The structure in the base metal is also B–M, but of a lower hardness (3220–4010 MPa) and more dispersed (25–70 μm). After high-frequency peening, the microhardness of the metal increases by an average of 1.2 times (up to 3360–4210 MPa) in the adjacent deformed weld area. The structure refinement to 10–30 μm is observed. Similar changes occurred in the HAZ overheating area. At a depth of up to 125 μm , the size of packages is already 25–50 μm (4 times decreased), and the microhardness increases to 4640–5520 μm . Typical changes in the metal structure after high-frequency peening are shown along the fusion line in Figure 5, *a*. For comparison, Figure 5, *b* shows the changes in the structure when namely the base metal was peened. It also shows the structure refinement from 25–70 to 15–25 μm and an increase in the microhardness from 3220–4010 to 4210–4880 MPa to a depth of 125 μm .

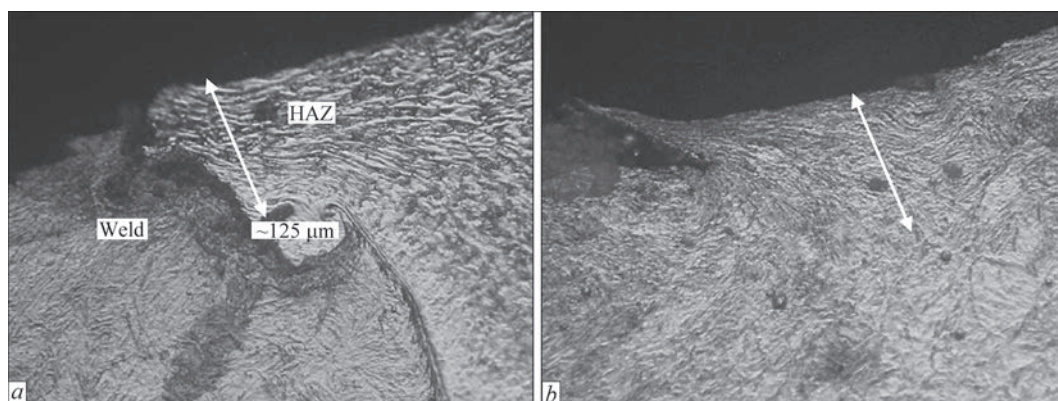


Figure 5. Changes in the weld metal and HAZ structure (*a*) after high-frequency peening along the fusion line of the welded joint and in the base metal (*b*) ($\times 500$)

Shot peening of the entire surface of the plates after welding using conventional LAV preparation technology (No. 5) can increase the fatigue fracture resistance of the joint by almost 2 times, up to 800 thousand cycles. After enhanced additional treatment (No. 6) of the joint itself, fatigue tests did not cause crack formation even at a load of 2 million cycles or more, as in the case of high-frequency peening. Metallographic examinations were not carried out at this treatment variant, but it can be assumed that similar structural changes occur in the metal structure of the joints. The physics of the processes of their influence on the formation of metal properties in both methods is approximately the same. As a result of the treatment, the weld metal and HAZ are cold work hardened, and compressive stresses are formed in the surface layer of the joints. Such positive changes contribute to a significant increase in the durability of welded joints of armor steel HB500MOD.

CONCLUSIONS

1. Low tempering of welded joints of high-hardness armor steel HB500MOD made using low-alloy materials such as Sv-10GSMT with preheating allows increasing their fatigue fracture resistance twice. In welding of armor steel joints without preheating using high-alloy KhORDA 307 Ti wire, the use of low tempering is not effective, which is associated with embrittlement of the fusion zone during thermal tempering due to the development of carbon diffusion processes.

2. Layer-by-layer peening of the deposited metal during welding of high-hardness armor steel using high-alloy materials contributes to an increase in the durability of fatigue fracture resistance of joints by 25%. This is a slight increase, but this treatment method can more effectively reduce the level of deformations in joints and preserve the geometric dimensions of armor structures during their manufacture.

3. It is possible to significantly increase the durability of welded joints of armor steel HB500MOD without the formation of fatigue cracks at a load of 2 million cycles or more by high-frequency peening of the fusion zone and near-weld metal of HAZ joints or by their enhanced shot peening. In this case, the structure is refined several times in the near-surface metal layer to a depth of 125 μm , and compressive stresses are formed in the treatment area, which has a positive effect on the resistance of welded joints to fatigue fracture.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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