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IMPACT OF ARC WELDING AND HIGH-FREQUENCY MECHANICAL FORGING ON THE MECHANICAL PROPERTIES AND RESISTANCE TO BRITTLE FRACTURE OF WELDED JOINTS OF S420NL STEEL

S.L. Zhdanov, O.A. Haivoronsky, V.D. Poznyakov, A.V. Zavdoveev, A.M. Gerasymenko, R.V. Bogodist

E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine

ABSTRACT

The paper considers the regularities of phase-structural transformations in welded joints of low-alloy S420NL steel in the initial state, after high-frequency mechanical forging and accumulation of fatigue damage. Welded joints were produced by mechanized gas metal arc welding in a carbon dioxide environment using Filarc PZ 6114 S flux-cored wire. The grain, subgrain and dislocation structures of welded joints were studied by light and transmission electron microscopy (TEM). The experimental data on the impact of the structure on the change in the values of the impact toughness (*KCV*) and brittle fracture resistance (K_q) of welded joints without treatment with high-frequency mechanical forging, after accumulation of fatigue damage were obtained. The efficiency of increasing their fatigue resistance due to the use of high-frequency mechanical forging is shown.

KEYWORDS: low-alloy steel, arc welding, welded joints, structure, high-frequency mechanical forging, fatigue damage, brittle fracture

INTRODUCTION

One of the main service characteristics of welded joints is the ability to provide high durability under cyclic loads. However, their fatigue resistance limit may differ significantly from that of the base metal. The probability of failure due to metal fatigue is one of the factors that must be taken into account when designing structures [1, 2]. Fatigue failure starts with one or more cracks on the surface and propagates inwards under repeated force until a complete rupture occurs. The fraction of fatigue damage in welded structures is approximately 40 % of the total number of fractures and failures. The cause is that under cyclic loads, adverse residual stresses play a significant role, the concentration of which is determined by the shape of the weld and technological defects, the gradient of structures and mechanical characteristics at the interface between the weld metal and the HAZ. Additionally, the fatigue resistance is affected by the chemical composition and structure of the base metal, parameters of the welding thermal cycle, loading pattern, environment, etc. [3, 4]. The negative impact of the mentioned factors cannot always be minimized before or during welding. Therefore, in many cases, postweld treatment of welded joints is required [5–8]. The relevance of fatigue resistance technology has been a priority for engineers for many decades, and information about their achievements does not leave the pages of technical publications [1–3, 6, 7].

The world practice shows a general trend to search for high-tech methods in order to extend the safe operation of existing metal structures. Systematic studies [7–11] conducted at the E.O. Paton Electric Welding Institute of the NAS of Ukraine and other organisations have shown that advanced methods of welding, high-frequency mechanical forging (HMF) and automation of this process provide high physical and mechanical indices of the strengthened metal layer and at the present stage of development of resource-saving technologies, they are the most effective way to strengthen welded structures operating under cyclic loads.

In view of this, the aim of the study was to obtain comparative test results in determining the impact of arc welding and high-frequency mechanical forging, as well as the accumulation of fatigue damage on the physical and mechanical properties of welded joints and their resistance to brittle fracture.

RESEARCH PROCEDURE

The object of research was welded joints of low-alloy structural S420NL steel of the following chemical composition, %: 0.18 C; 0.58 Si; 1.01 Mn; 0.6 Ni; 0.11 Mo; 0.22 Cr; 0.17 V; 0.05 Nb; 0.48 Cu; 0.011 S; 0.018 P. During their welding in CO_2, Filarc PZ 6114 S flux-cored welding wire of 1.2 mm diameter was used, which ensures equal strength of the weld metal with the base metal in terms of static strength indices. The welding mode of butt joints of the specified steel of 14 mm thick with a V-shaped edge preparation was the following: I_w = 190–210 A; U_a = = 26–28 V; V_w = 14–16 m/h.

Postweld HMF was performed according to the practiced technology with the parameters of static loading (tool clamping) C = 150–200 N with the frequency and amplitude of transducer oscillations of 27 kHz and α = 15 μm and the longitudinal feed rate of the deforming tool V = 25 mm/s. A narrow area of the metal of the fusion line of the joint with the formation of a smooth groove of 2.0–2.5 mm wide and up to 1.0 mm deep after forging was subject to treatment.

An integrated approach of modern methods of light (Versamet-2, Neophot-32) and transmission electron microscopy (JEM-200SX, JEOL, Japan) was used to conduct experimental studies. Microhardness was measured using a LECO M-400 microhardness tester with a load of 100 g. The specimens for metallographic examinations were prepared according to standard procedures using diamond pastes of different dispersion. The microstructure was revealed by chemical etching in a 4 % alcohol solution of nitric acid.

To test the impact toughness of the heat-affected zone (HAZ) of welded joints, the specimens were made in accordance with DSTU EN ISO 9017:2015. The test results were used to assess the effect of HMF on the change in *KCV* indices at test temperatures down to –40 °C.

The ability of the metal to resist brittle fracture was determined using the approaches of fracture mechanics, according to which the specimens were used, preliminarily cut out from welded joints with a thickness of 10 mm with an induced fatigue crack at an apex of the notch in the initial state and after HMF. Then, under static bending loading, the critical stress intensity factor K_q was determined. Fracture mechanics formulas were used to determine the values of the critical stress intensity factor. The previously established dependence was taken into account, stating that with an increase in the values of K_q, the sensitivity to stress concentration decreases and the resistance of the metal to brittle fracture grows, or vice versa, with a decrease in the factor, the resistance drops.

Fatigue tests were carried out on 14 mm thick welded joints in the initial state and after HMF under cyclic bending loading. The welded joints were loaded at a frequency of 14 Hz at a symmetrical cycle stress of 100 MPa. The UMP-1 machine was used for the tests. During the tests, a number of cycles was recorded, at which a fatigue crack of critical length (3 mm) was initiated and the stress was formed at which the specimens remained undamaged after $2.1 \cdot 10^6$ load cycles.

RESULTS AND DISCUSSION

As a result of the impact toughness tests, it was found that the *KCV* indices for the HAZ near-weld metal in the case of high-frequency mechanical forging and without it are almost similar, but after HMF they are somewhat higher. Thus, at a test temperature of +20 °C, they are in the range of 319–327 J/cm², at –20 °C — 281–290 J/cm², at –40 °C — 238–250 J/cm² (see Table 1).

Light microscopy showed that the structure of the base metal of S420NL steel is ferrite-pearlite with a grain size of D_{gr} ~ 10–30 μm and a microhardness of $HV_{0.1}$ ~ 1600–1700 MPa. In a multipass welded joint without HMF treatment, the weld metal has a ferrite-pearlite (F + P) structure. In the upper pass, the microhardness is HV ~ 1650 MPa with a globular grain size D_{gr} ~ 10–50 μm and dendrites hx1 = 50–200×150–550 μm. In the lower pass, $HV_{0.1}$ ~ 1600–1700 MPa, the grain is also globular of the size D_{gr} ~ 10–50 μm and dendrites hx1 = = 50–100×150–450 μm.

In HAZ, a bainite structure (B) is observed, and when approaching the base metal, the F + P structure is observed. The size of the packages decreases from D_{gr} ~ 40–200 μm (HAZ overheating area) to D_{gr} ~ 5–39 μm (HAZ recrystallisation area). At the same time, $HV_{0.1}$ decreases, respectively, from 2210–2740 MPa to 1990–2280 MPa.

Compared to the initial state after HMF, at a depth of 125 μm from the surface of the specimen, the structure in the above HAZ regions of the welded joint is refined to D_{gr} ~ 15–100 μm (HAZ overheating area) and D_{gr} ~ 5–30 μm (HAZ recrystallisation area), while the $HV_{0.1}$ values grow by an average of 1.2 times — up to 3090 MPa and 2360, respectively (Figure 1).

Table 1. Impact toughness of the HAZ metal in welded joints of S420NL steel produced using Filarc PZ 6114 S flux-cored wire in CO_2

No.	Postweld treatment	*KCV*, J/cm², at temperatures, °C		
		+20	–20	–40
1	Initial state	315–322 319	275–287 282	227–252 238
2	High-frequency mechanical forging	325–330 327	281–298 290	235–262 250

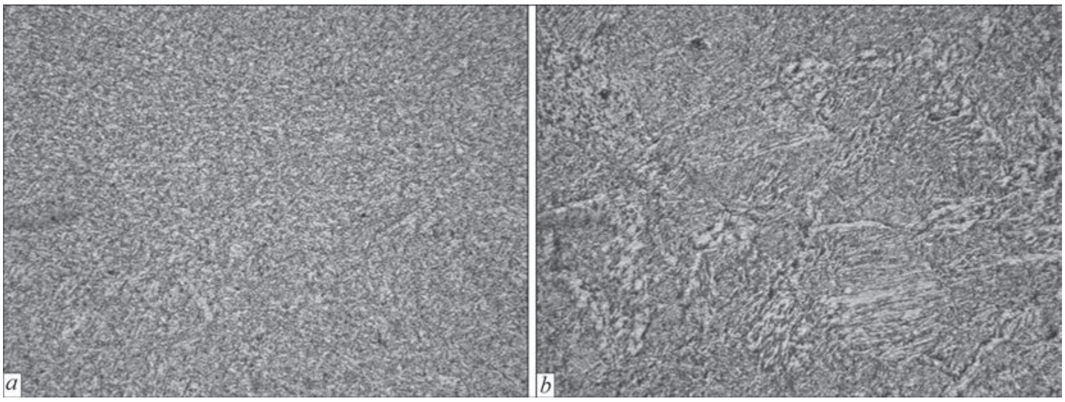

Figure 1. Microstructure (×500) of the weld metal (*a*) and HAZ (*b*) of the welded joint of S420NL steel produced using Filarc PZ 6114 S wire in CO_2 after HMF

The TEM method has found that a substructure (0.3–1.5 μm) is formed in the weld metal. The density of dislocations (ρ) in the weld metal structure is in average $\rho = 3–6\cdot10^9$ cm^{-2}. A lath bainite structure is formed in the heat-affected zone. The upper bainite has a lath thickness of h_1 = 0.3–1.1 μm with a substructure of the size d_s = 0.16–0.3×0.35–1 μm at a dislocation density of $\rho = 4–6\cdot10^{10}$ cm^{-2}. The lower bainite has the size of h_1 = 0.5–1.3 μm with d_s = = 0.15–0.4×0.25–0.9 μm at a dislocation density of $\rho = 2–5\cdot10^{10}$ cm^{-2}.

Thus, it was found that in the metal of the welded joint of S420NL steel using Filarc PZ 6114 S wire, relatively small gradients in the weld metal and HAZ

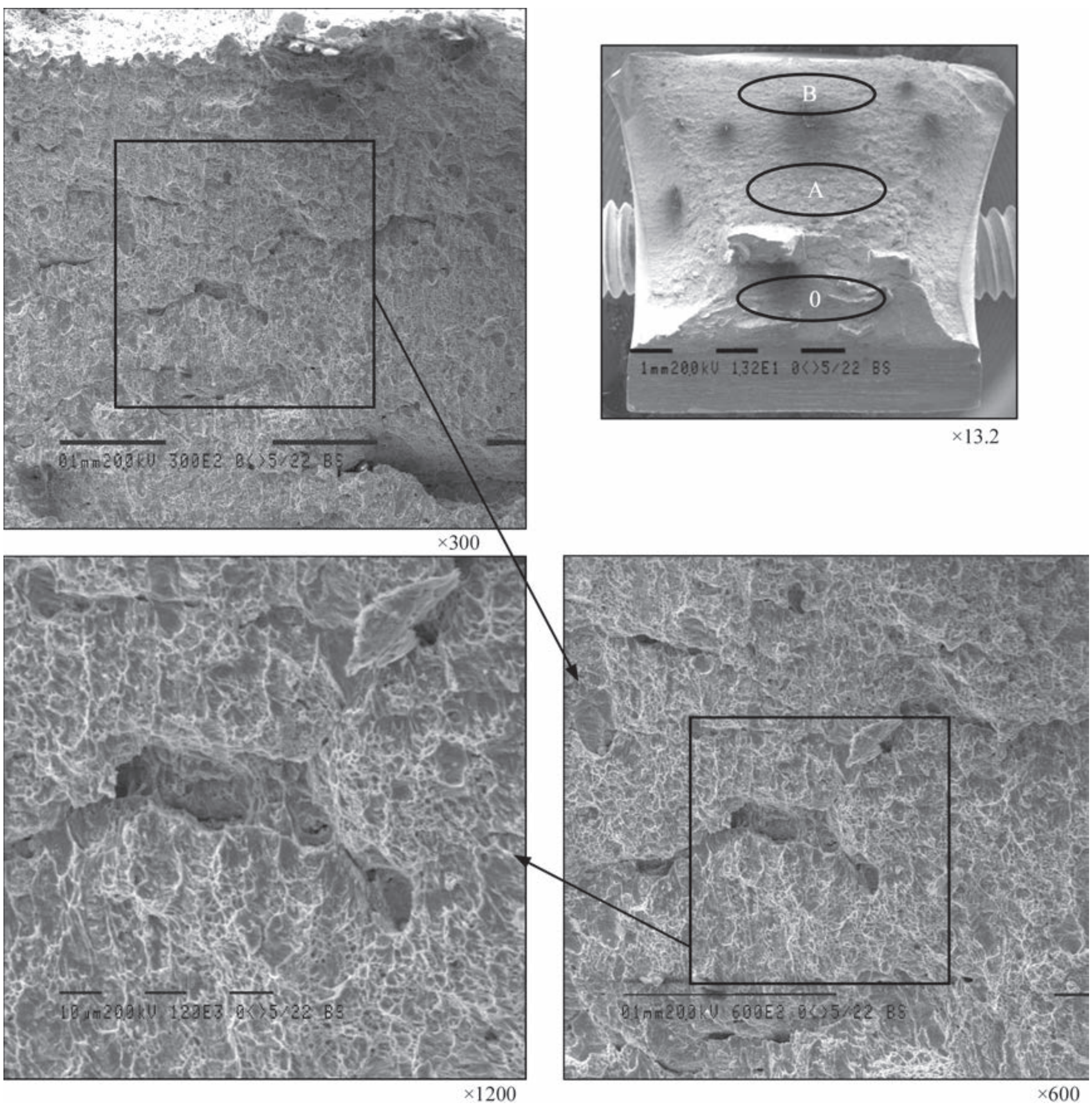

Figure 2. Photo with a fracture of welded joint specimens after impact bending test at +20 °C (zone of slow crack propagation)

in terms of dislocation density and formation of substructural components are observed, which will probably provide the crack resistance, as well as strengthening of the weld and HAZ areas.

Fractographic examinations of the welded joints after the impact toughness tests at temperatures of +20, –20, and –40 °C were performed using the scanning electron microscopy method for characteristic fractures (near the notch — slow crack propagation; main crack propagation, ultimate fracture and side bevels). For all the studied fractures, the following was shown: fracture occurred over the HAZ metal, the fracture pattern is ductile with a pitted microrelief. In the zones of slow crack propagation, delamination and isolated secondary microcracks are observed (Figures 2, 3). No defects, ultimate fracture and side bevels were found in the zones of main crack propagation at all test temperatures. This indicates high crack resistance of the metal and is confirmed by high impact strength indices (see Table 1). Based on the results of the research on resistance to brittle fracture, the following was established. In the initial state, welded joints of S420NL steel without HMF treatment during the tests of the HAZ metal, have K_q indices at a level of 95.8 MPa$\sqrt{m}$ at a test temperature of +20 °C, 92.4 MPa$\sqrt{m}$ at –20 °C and 86.7 MPa$\sqrt{m}$ at –40 °C (Figure 4). The values of the stress intensity factor for the HAZ metal after HMF of the welded joints are somewhat higher. Depending on the test temperature, they are 97.1, 93.5, and 89.1 MPa$\sqrt{m}$, respectively. An increase in the resistance to brittle fracture of the HAZ metal of welded joints of S420NL steel as a result of HMF is within 2.5 %.

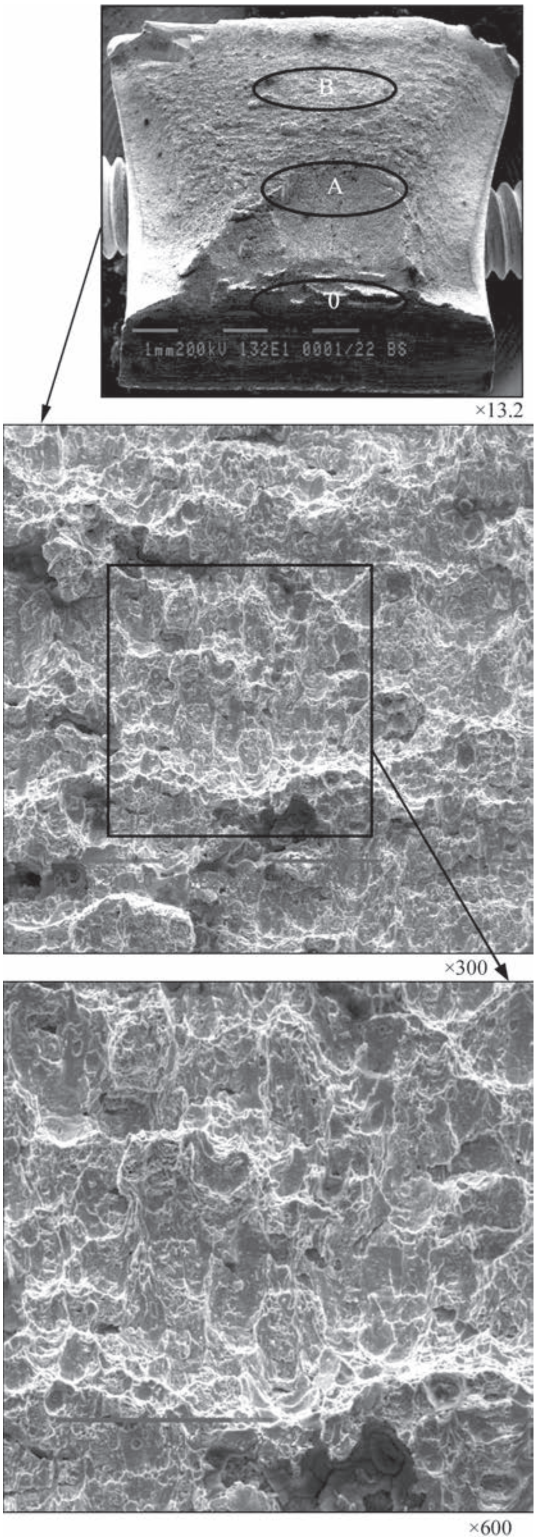

Figure 3. Photo with a fracture of welded joint specimens after impact bending test at –40 °C (zone of slow crack propagation)

The results of the carried out studies on fatigue resistance indicate that the welded joint specimen of S420NL steel in the initial state was affected by a fatigue crack with a critical length of 3 mm after 14,200,000 loading cycles. In contrast, the specimens subjected to HMF remained undamaged after $N = 2.1 \cdot 10^6$ load cycles. It can be assumed that an increase in the fatigue resistance of welded joints of S420NL steel occurred as a result of changes in the structure in the near-surface layer on the fusion line and in the HAZ metal.

From the literature [11–13] and from the practice of operation of welded structures of different purposes, it has been found that fatigue damage can accumulate in the most loaded assemblies. It causes prema-

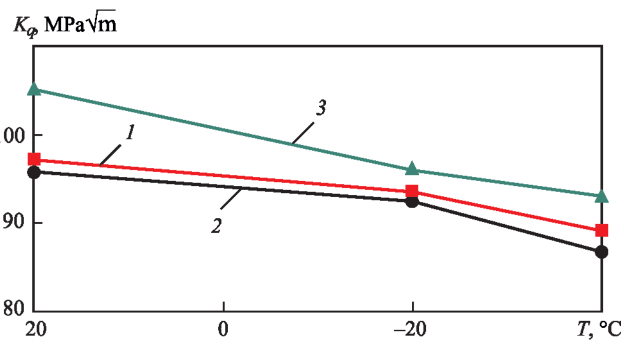

Figure 4. Dependence of the critical stress intensity factor K_q on the test temperature of the HAZ metal of welded joints of S420NL steel: *1* — with HMF; *2* — without HMF; *3* — base metal for comparison

ture cracking, which in turn significantly reduces the cyclic durability of damaged elements in the structure as a whole. Therefore, the paper also studied the effect of the level of accumulated fatigue damage on the resistance to brittle fracture in the HAZ metal of the butt welded joints made with the above welding consumables. The difference from the tests discussed earlier was that the specimens were first subjected to cyclic loading with a different number of cycles. In our case, it was $N = 800{,}000$ and $N = 1{,}200{,}000$, which is 60 and 80 % of the total number of load cycles, at which (see above) fatigue cracks are formed (1,420,000 cycles). Based on the research results, it was found that with an increase in the level of accumulated damage, the value of the stress intensity factor K_q decreases slightly but remains at a high level (Figure 5). Thus, at a test temperature of +20 °C, with an increase in the level of accumulated damage from 60 to 80 %, the values of the factor drop from 96 to 94.5 MPa√m, and at a temperature of –40 °C — from 83.5 to 81.9 MPa√m, respectively.

It is obvious that a decrease in the resistance of HAZ metal of welded joints to brittle fracture occurs as a result of changes in the metal structure under long-term loads.

The conducted structural examinations show that as a result of long-term cyclic loading, certain changes occurred in the HAZ metal structure of the welded joint of S420NL steel associated with the formation of local band structures. This indicates the propagation of dislocation redistribution processes in this zone. At the same time, no changes occur in the phase composition, grain size and microhardness. Thus, as noted above, in the overheating area of HAZ joints, there is a bainite structure with a microhardness of 1870–2450 MPa, the size of the packages is 40–200 μm.

The pattern of fracturing metal of welded joints after accumulation of fatigue damage at a number of 1,200,000 load cycles at temperatures from +20 °C to –40 °C was studied by the scanning electron microscopy.

At a temperature of +20 °C in the zone of main crack propagation, the fracture pattern is mainly ductile (V_{fr} = 85–90 %). There are no small pits on the surface with a size of d_p = 0.5–5 μm and large ones with a size of d_p = 8–30 μm. There are also areas of quasi-brittle fracture (V_{fr} = 10–15 %) with the size of quasi-spall facets $d_f \sim$ 5–25 μm.

When the test temperature is lowered to –20 °C, the volume fraction of brittle fracture grows to V_{fr} = 30–35 %, the size of the quasi-spall facets does not change.

At a test temperature of –40 °C, the volume fraction of brittle fracture grows to V_{fr} = 60–65 %, the size of the quasi-spall facets does not change ($d_f \approx$ 5–25 μm).

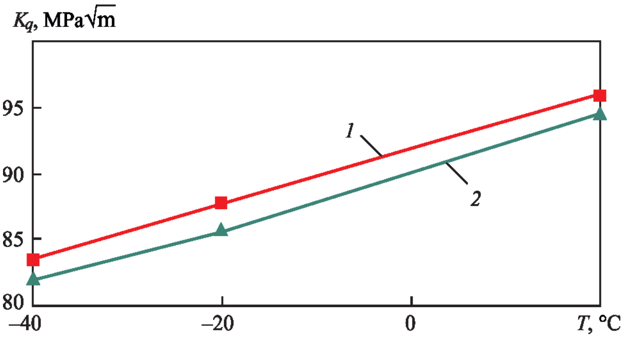

Figure 5. Influence of fatigue damage accumulation on the resistance to brittle fracture in the HAZ metal of welded joints of S420NL steel: *1* — 60 % of accumulated damage N = 800,000 cycles); *2* — 80 % of accumulated damage N = 1,200,000 cycles)

Also, the metal contains long secondary cracks of L_{cr} = 20–110 μm.

Thus, when the test temperature is lowered to –40 °C, a predominantly brittle type of fracture (60–65 %) is observed in the region of the main crack propagation. This is confirmed by a slight decrease (by 12 %) in the fracture toughness from K_q = = 94.5 MPa√m (T_{test} = 20 °C) to K_q = 82–85 MPa√m (at subzero temperatures), which indicates sufficient crack resistance of welded joints of S420NL steel under operating cyclic loads.

CONCLUSIONS

1. Metallographic examinations found that under the action of HMF at a depth of 125 μm from the surface of the specimen, the bainite structure of the HAZ metal of the welded joint is refined, small gradients in the density of dislocations and the formation of substructural components are observed, while the hardness values grow compared to the initial state. Also, after HMF, the impact toughness of the HAZ metal values of welded joints of S420NL steel is somewhat higher than in the state without forging.

2. It was established that the use of HMF for welded joints of S420NL steel leads to an increase in the resistance of HAZ metal to brittle fracture, as evidenced by a slight increase in the stress intensity factor K_q within the range of up to 0.5 %.

3. The influence of the level of accumulated damage on the resistance of welded joints of S420NL steel to brittle fracture was evaluated. The obtained data indicate that with an increase in the level of damage from 60 to 80 % of the total number of loads, under which fatigue cracks are formed, the value of the factor K_q decreases by 1.5–2.0 %. This can be explained by certain changes in the structure of the HAZ metal of welded joints (without changing the phase composition) associated with the formation of local band structures and the propagation of processes of dislocation redistribution in this zone.

4. It was established that it is possible to increase the fatigue resistance of welded joints of S420NL steel by using HMF after their welding. At the same time, after HMF, the welded joint remains undamaged after $N = 2.1 \cdot 10^6$ load cycles, while without HMF, a fatigue crack of critical length is formed after 1,420,000 cycles.

REFERENCES

1. Kudryavtsev, V.I., Naumchenkov, N.E. (1976) *Fatigue of welded structures*. Moscow, Mashinostroenie [in Russian].
2. Trufyakov, V.I. (1998) Increasing the fatigue resistance of welded joints and structure. *Avtomaticheskaya Svarka,* **11**, 11–19 [in Russian].
3. Pokhmursky, V.I., Khoma, M.S. (2008) *Corrosion resistance of metals and alloys*. Lviv, SPOLOM [in Ukrainian].
4. Knysh, V.V., Solovej, S.A., Kyrian, V.I. et al. (2017) Application of high-frequency peening to improve the performance of butt welded joints in the atmosphere of temperate climate. *The Paton Welding J.*, **4**, 14–18. DOI: https://doi.org/10.15407/tpwj2017.04.03
5. Degtyarev, V.A. (2011) Assessment of the high-frequency mechanical forging mode effect on fatigue strength of welded joints. *Strength Mater.*, **43**, 154–160. DOI: https://doi.org/10.1007/ s11223-011-9281-1
6. Nekhoroshkov, O.N., Pershin V.P., Semukhin B.S. (2006) Application of the method of ultrasonic impact treatment for welded joints of structural steels. *Bulletin of TSUACE*, **2**, 120–125 [in Russian].
7. Knysh, V.V., Kuzmenko A.Z., Vojtenko O.V. (2006) Increasing fatigue resistance of welded joints by high-frequency mechanical peening. *The Paton Welding J.*, **1**, 30–33.
8. Zhang, H., Wang, D., Xia, L. et al. (2015) Effects of ultrasonic impact treatment on pre-fatigue loaded high-strength steel welded joints. *Inter. J. of Fatigue*, **80**, 278–287. DOI: https://doi.org/10.1016/j.ijfatigue.2015.06.017
9. Panin, V.E., Kablov, E.N., Pleshanov, V.S. (2006) Effect of ultrasonic impact treatment on the structure and fatigue resistance of welded joints of high-strength steel VKS-12. *Fizicheskaya Mezomechanika*, **3**, 85–96 [in Russian].
10. Lobanov, L.M., Kirian, V.I., Knysh, V.V., Prokopenko, G.I. (2006) Improvement of fatigue resistance of welded joints in metal structures by high-frequency mechanical peening (Review). *The Paton Welding J.*, **9**, 2–8.
11. Knysh, V.V., Solovej, S.A., Kuzmenko, A.Z. (2011) Influence of preliminary cyclic loading on effectiveness of welded joint strengthening by high-frequency peening. *The Paton Welding J.*, **10**, 36–39.
12. Knysh, V.V., Solovej, S.A., Kuzmenko, A.Z. (2012) Improvement of fatigue resistance of welded joints with accumulated damage under multistage and block loading. *The Paton Welding J.*, **7**, 19–23.
13. Knysh, V.V., Kuzmenko, A.Z., Solovej, S.A. (2009) Accumulation of fatigue damage in tee welded joints in as-welded and after high-frequency peening under block loading. *Machynoznavstvo*, **9**, 27–31.

ORCID

S.L. Zhdanov: 0003-3570-895X,
O.A. Haivoronsky: 0000-0002-5922-5541,
V.D. Poznyakov: 0000-0001-8581-3526,
A.V. Zavdoveev: 0003-2811-0765

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

S.L. Zhdanov
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: patonlab48@ukr.net

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