OPTIMISATION OF THE PROCESS OF STRENGTHENING OF WELDED JOINTS OF 09G2S STEEL BY HIGH-FREQUENCY MECHANICAL PEENING

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Based on investigation of the depth of plastically deformed metal layer after application of high-frequency mechanical peening, optimum parameters for strengthening low-alloyed steels were established, which enable plastic deformation of metal to the depth of down to 1 mm.

Keywords: *strengthening of welded joints, high-frequency mechanical peening, plastically deformed metal layer, microhardness, optimization*

Owing to its advantages, high-frequency mechanical peening (HFMP) or ultrasonic impact treatment is an advanced method of surface plastic deformation of metal that is finding ever wider application to increase fracture resistance of welded joints [1–9]. Starting from 1959, when the energy of ultrasonic oscillations was used for the first time for redistribution of residual stresses in welded joints [10], strengthening treatments with application of ultrasonic energy became successfully applied in improvement of service properties of welded joints in various metal structures. In a considerable part of publications special attention was given to effectiveness of HFMP technology application for improvement of cyclic fatigue life of welded joints, but, as a rule, without consideration of the issues of establishment of optimum strengthening parameters [11]. The main controllable technological parameters at strengthening by HFMP technology include oscillation amplitude of end face of waveguide of manual impact tool, ultrasonic generator frequency, diameter of strikers of replaceable working heads, linear speed of HFMP performance and force of impact tool pressing down. It should be noted that HFMP equipment was continuously improved, developing from stationary equipment with consumed power of 13 kW into compact and mobile one with consumed power of 300–500 W. In this connection, the issue of determination of optimum strengthening parameters should be solved, depending on applied equipment, pursued goals and solved tasks.

In order to improve fatigue resistance of welded joints, HFMP technology is used to treat a narrow zone of transition of weld to base metal that results in formation of a characteristic groove, under which a work-hardened (plastically deformed) metal layer is located. Achievement of maximum depth of plastically deformed metal layer under the groove bottom as a result of HFMP can be the main criterion of establishment of optimum strengthening parameters.

The purpose of this work was establishing the optimum parameters of strengthening of welded joints on 09G2S steel in order to improve their fatigue resistance. Here ultrasonic equipment with piezoelectric transducer USP-300 of 300 W power batch-produced by «Ultramet» Company (Ukraine) was used. Experimental studies of the depth of plastically deformed metal layer were conducted on samples from low-alloyed steel 09G2S widely applied in welded metal structures.

Starting from 1970s, practically all HFMP equipment (including USP) has been made with an intermediate impact element. Therefore, as shown in works [12, 13], with such a schematic of HFMP realization the force of impact tool pressing down to the surface being treated should be equal to about 50 N. Here, the change of pressing-down force from 30–80 N does not affect treatment efficiency, i.e. we will consider this technological parameter established.

Oscillation amplitude of the end face of manual impact tool waveguide and ultrasonic generator frequency in USP-300 equipment have constant values and are equal to 30 μm and 22 kHz, respectively. Thus, the main technological parameters that may be varied in this equipment, are diameter of strikers of replaceable working heads and linear speed of HFMP performance. Therefore, in this work the influence of these parameters on the depth of plastically deformed metal layer under the groove bottom was studied, which was determined by microhardness measurements. This is the simplest and most widely applied method to assess the depth of work-hardened metal layer [13, 14].

Depth of plastically deformed metal layer and characteristic groove after HFMP were determined by the following procedure. Three blanks of 110 × × 80 mm size were cut out of the rolled sheet 30 mm thick. Finishing was performed around the blank contour with subsequent grinding of the blank working surface from two sides and annealing. HFMP of the working surface of made samples of 100 × 70 mm size was conducted along three lines with 25 mm spacing (Figure 1). The first sample was strengthened using a replaceable single-row four-striker head with 2 mm diameter of cylindrical strikers, the second sample was strengthened with a single-row four-striker head with 3 mm cylindrical strikers, and the third sample was strengthened with a single-row three-striker head with 4 mm cylindrical strikers. HFMP treatment of each sample was performed in four passes by reciprocal motions of manual impact tool, but at three different peening speeds (1, 5 and 10 mm/s). At determination of peening speed, peening time was selected equal to the total treatment time of sample surface along a 100 mm line in four passes of the work tool of 100, 20 and 10 s, respectively. As a result, three grooves formed on the sample surface, corresponding to the preset constant speeds of tool displacement. A clock-type indicator was used to measure the groove depth, depending on striker diameter and linear speed of HFMP performance. From Table 1, presenting measurement results, one can see that the depth of characteristic groove after peening essentially depends on the speed of HFMP performance. Maximum groove depth (0.14 mm) is achieved at surface treatment with single-row four-striker head with 3 mm cylindrical strikers and 1 mm/s speed of HFMP performance. In [15] it is shown that there exists a satisfactory correlation between the groove depth and fatigue life of welded joints, while provision of the required groove depth can be the criterion of treatment quality.

In order to study the depth of plastically deformed layer by microhardness measurement method transverse sections were prepared by cutting samples into 12 parts by the schematic given in Figure 1. To eliminate the influence of edge effects one-sided transverse microsections were prepared from the six extreme parts (see Figure 1, 1–3, 10–12), and two-sided microsections — from the remaining six parts (see Figure 1, 4–9). Thus, there were 6 points on 12 parts of the sample for measurement of microhardness characteristic for this striker diameter (2, 3 or 4 mm) at the set speed of HFMP performance (1, 5 or 10 mm/s). Microhardness on the surface of transverse sections was measured normal to peening direction in-depth of base metal, starting from the surface layer of groove bottom and up to stabilization of microhardness characteristic. LECO M-400 was used as measuring instrument, the principle of operation of which

Table 1. Groove depth (mm) depending on striker diameter and HFMP linear speed

Striker diameter, mm	Linear speed of HFMP, mm/s		
	1	5	10
2	0.11	0.07	0.05
3	0.14	0.11	0.04
4	0.09	0.07	0.05

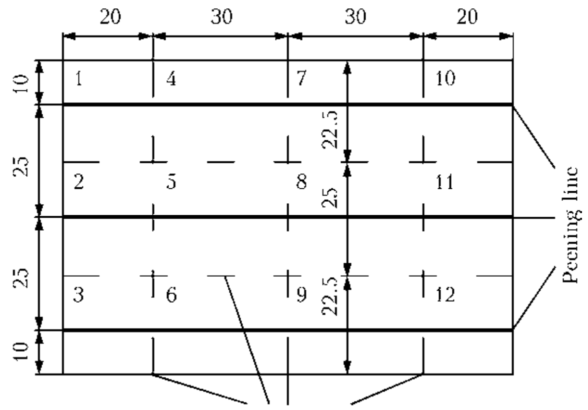

Figure 1. Schematic of sample cutting up after HFMP

is based on pressing in a diamond indenter with 0.1 N force. Measurement step here was 50 μm near the surface and 100 μm farther from it. Obtained results were averaged by six measurement values (see Figure 2). Note that at such a small force on the indenter the applied method becomes sensitive not only to metal strengthening due to the usually observed at HFMP increase of dislocation density and their redistribution

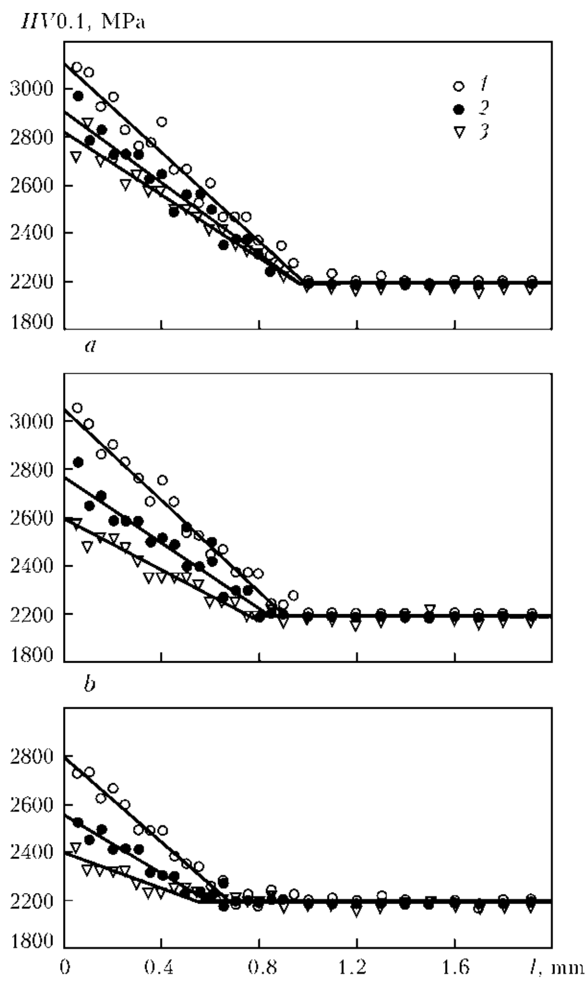

Figure 2. Dependence of hardness of subsurface metal layer strengthened by HFMP using single-row head with diameter of cylindrical strikers of 2 (*a*), 3 (*b*) and 4 (*c*) mm on distance from groove bottom *l* in-depth of the metal at speed of HFMP performance of 1 (*1*), 5 (*2*) and 10/s (*3*) mm

inside the grains (formation of subgrain boundaries and cell boundaries) [16, 17], but also to an increase of the level of residual compressive macrostresses [16, 18].

As is seen from Figure 2, at strengthening of samples of 09G2S steel by HFMP technology the maximum depth of plastically deformed layer (approximately 1 mm) is achieved when using single-row four-striker head with 2 mm diameter of cylindrical strikers. At strengthening by HFMP technology, using single-row four-striker head with 3 mm cylindrical strikers, maximum depth of plastically deformed layer decreases to about 0.8 mm, and when single-row three-striker head with 4 mm cylindrical strikers is used, it is about 0.6 mm. For the considered range of speeds of HFMP performance, the depth of plastically deformed layer is determined, mainly, by diameter of striker pins (by impact force in the contact zone), as well as tool displacement speed, as change of work-hardened layer depth for one striker diameter, depending on tool displacement speed, does not exceed 0.1 mm. Hardness of plastically deformed layer of metal depends both on striker diameter, and on peening speed. At treatment at the considered speeds by 2 mm strikers the hardness of surface-deformed layer of metal directly under the groove is 1.3–1.4 times higher than base metal hardness, for 3 mm strikers it is 1.2–1.35 times, and for 4 mm strikers is 1.1–1.25 times. For all the samples a lowering of hardness is observed when moving away from the surface into the metal depth. Here, hardness decreases with increase of the speed of HFMP performance. As the depth of plastically deformed metal layers (1.0 and 0.9 mm) and their maximum hardness values (HV0.1-3100 and HV0.1-3050 MPa) practically do not differ, when using replaceable single-row four-striker heads with 2 and 3 mm striker diameter at low peening speeds (1 mm/s), cylindrical strikers of 3 mm diameter are the most advantageous in terms of technology from the view point of lowering of stress concentration factor, and provide the greatest groove depth (0.14 mm). Therefore, the optimum parameters at treatment of 09G2S steel welded joints by HFMP technology are 3 mm diameter of strikers of replaceable working heads and linear speed of HFMP performance of about 60 mm/min. Despite the fact that technological parameters of strengthening by high-frequency peening are established for low-alloyed steel 09G2S, they can be taken as the optimum ones for most of the low-alloyed steels, as the latter have close mechanical properties.

Metallographic investigations of metal grain structure in the peening zone were also conducted to establish the nature of grain transformation as a result of strengthening by HFMP technology on transverse microsections of samples from 09G2S base metal, earlier used to determine the depth of plastically deformed metal layer by microhardness method after strengthening by HFMP technology at the speed of 1, 5 or 10 mm/s, using single-row four-striker heads with 3 mm strikers. «Neophot-32» microscope was

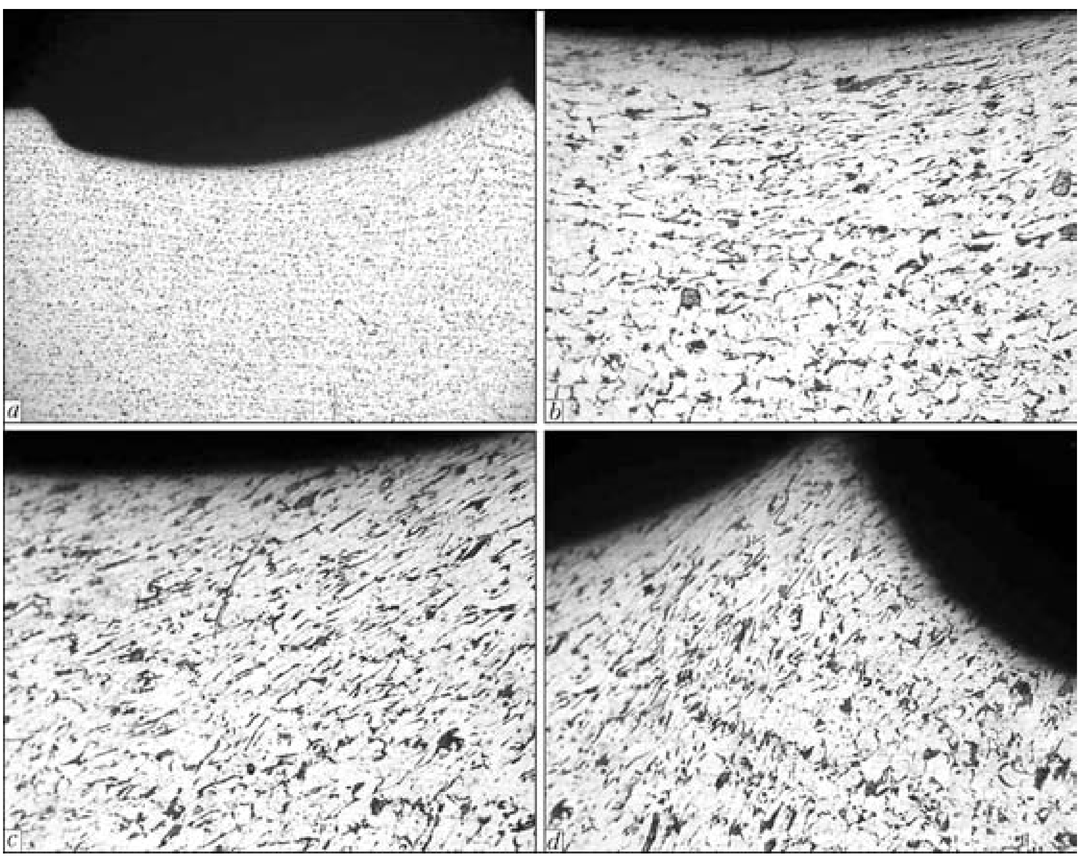

Figure 3. Microstructures of groove zones: *a* — ×50; *b*–*d* — ×200 (for descriptions see the text)

Table 2. Degree of grain deformation in subsurface metal layer strengthened by HFMP using a single-row head with 3 mm striker diameter

HFMP speed, mm/s	Studied region	$K_{f_{av}}$	δ, mm
1	1	11.80	200
	2	6.10	500
	3	3.61	600
5	1	8.50	125
	2	6.50	150
	3	2.94	245
10	1	No intensive deformation of grains was found	
	2		
	3		

used for analysis. Change of structure of low-alloyed 09G2S steel as a result of HFMP was studied at different magnifications (Figure 3).

General view of the groove zone is given in Figure 3, *a*. Subsurface zone with structural changes can be conditionally subdivided into three regions. In the first zone (Figure 3, *b*) deformed ferrite grains are located practically parallel to the tangent to groove bottom, and to sample surface, respectively. Pearlite component of the structure is also elongated. Moving away from the groove bottom to the edge, a certain change of grain shape and dimensions (second region) is found. In this region (Figure 3, *c*) grains are located at an angle to sample surface, but remain parallel to the tangent to groove surface. On the boundary with base metal not subjected to HFMP (third region), isolated deformed grains are observed, located practically normal to sample surface (Figure 3, *d*). Thus, intensive plastic deformation, leading to a change of grain shape, runs through grain elongation in the direction normal to the groove, which is formed by the surface of a sphere of cylindrical striker end face. Such grain behaviour in the surface layers of Armco-iron was reported by the authors of [19], where at compression in the ultrasonic field an essential elongation of grains is observed in the direction parallel to the treated surface. Results of analysis of grain shape change at intensive deformation induced in the subsurface layer by HFMP technology are presented in Table 2. Obtained data show that grain form factor $K_{f_{av}}$ (characterizing the degree of ferrite grain deformation) and depth of propagation of grains, which have changed their shape δ, depend on the speed of HFMP performance. At low peening speeds $K_{f_{av}}$ and δ values are maximum. In [20] parameter γ is used to determine the actual deformation of surface layer *e* at attrition, which is similar to grain form factor $K_{f_{av}}$: $\sqrt{3e} = \gamma = a/b$, where *a*, *b* are the elongated grain length and width, respectively. It is shown that grain shape change is caused by intensive deformations of

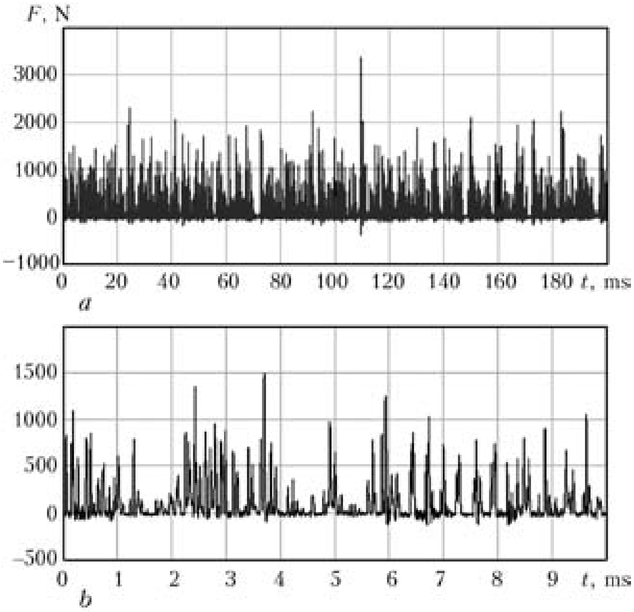

Figure 4. Oscillograms of impact force of 3 mm striker, when using USP-300 equipment, recorded in 200 ms (*a*) and with a scan of first 10 ms (*b*)

the order of $e \geq 1$. Lower degrees of deformation do not lead to grain shape change, but cause accumulation and redistribution of dislocations inside grains.

In our case, the size of the zone with significant changes of grain shape under the groove (zone with a high degree of deformation $e > 1$) is limited by 200 μm, whereas the zone of plastically deformed metal layer, according to microhardness measurements, is equal to 1 mm. The high level of residual compressive stresses forming during deformation at HFMP [16, 18, 21], which have some influence on microhardness value, should be also taken into account.

A piezoceramic transducer and high-resolution oscillograph were used to record also the oscillogram of the force of impact of 3 mm striker on the surface during HFMP performance (Figure 4). As is seen from Figure 4, *a*, application of the load during treatment is performed by blocks of pulses of different width with maximum values of impact force in the block, exceeding 1000 N. Here, duration of force impact pulses is not longer than 100 μs (Figure 4, *b*). Frequency of appearance of pulses above 1000 N is equal to approximately 1 kHz. In individual blocks the impact force is higher than 2000 N, whereas the maximum fixed value of impact force in 200 ms was equal to 3400 N.

CONCLUSIONS

1. Based on investigation of the depth of plastically deformed metal layer after application of HFMP by batch-produced equipment of 300 W power, the following optimum parameters for strengthening low-alloyed steels were established: 3 mm striker diameter and 1 mm/s linear speed of HFMP performance.

2. Performance of HFMP technology at the established optimum parameters allows plastic deformation

of metal to the depth of down to 1 mm with formation of a characteristic groove of down to 0.14 mm depth. The size of the zone under the groove with considerable changes of grain shape (grain form factor $K_{f_{av}} = 11.8$) is equal to 200 μm.

3. At HFMP treatment of metal surface the load is applied by blocks of pulses of different width with maximum value of impact force in the block higher than 1000 N. Duration of such pulses of force impact does not exceed 100 μs, and frequency of their appearance is equal to approximately 1 kHz.

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SIMULATION OF THE EFFECT OF HIGH-VOLTAGE CABLES ON CURRENT RIPPLE IN WELDING GUNS WITH AUTOMATIC BIAS

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The mechanism of formation of current ripple in welding electron guns with automatic bias caused by ripple of the cathode bombardment current is studied by using computer mathematical simulation. It is shown that when using the coaxial high-voltage cable the ripple of the cathode bombardment current does not affect the ripple of the beam current. In case of a multi-core cable or four separate single-core high-voltage cables the ripple of the cathode bombardment current causes the ripple of the beam current because of the parasitic capacitance currents flowing through the beam current control circuit. To decrease the beam current ripple factor to 0.05, the cathode bombardment current ripple factor at a frequency of 20 kHz should not exceed 0.05 either.

Keywords: *electron beam welding, high-voltage cable, distributed capacitances, electron gun, triode emission system, automatic bias, cathode bombardment current ripple, beam current ripple*

Despite the high-usage pulse modulation of the electron beam current with a depth of 100 %, it is important that in the steady-state operation mode the peak-to-peak amplitude of the beam current ripple be no more than 5 % (ripple factor 0.05), which is specified by international standard EN ISO 14744-1 [1]. This requirement is caused, in particular, by the need to