Lyudmila Nyrkova, Vitaliy Knysh, Sergiy Solovey, Svetlana Osadchuk

E.O Paton Electric Welding Institute of National Academy of Sciences of Ukraine, Kyiv, Ukraine

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Influence of Different Methods of Surface Treatment on Corrosion Resistance of Low-Alloy Steel

ABSTRACT

The influence of mechanical methods of surface treatment (polish and polish with the next strengthening by high-frequency mechanical pinning, HFMP) on the corrosion resistance of low-alloy steel 15HSND were presented. The deficiencies of surface strengthening by HFMP with one impact peen were analyzed, and an instrument in which shock elements are situated in a few rows was suggested. Speed of HFMP for the surfaces 35 sm^2/min was recommended. The differences in structure and microhardness of near-surface layers of 15HSND steel with polished surface and the polished surface with next strengthening by HFMP were established after investigations in the salt frog chamber and moisture chamber during 1200 hours. Application of HFMP technology increases of corrosion resistance of steel: corrosion rate after neutral salt fog decreased from 2,543 mm/year on the polished surface to 2,096 mm/year after HFMP treatment, and after increased humidity and temperature, from 0,104 mm/year to 0,080 mm/year.

Keywords: *accelerated climatic tests, corrosion resistance, high-frequency mechanical peening, low-alloy steel, metallography*

1. INTRODUCTION

To increase the corrosion resistance and corrosion fatigue of machine parts and structural elements, various methods of surface machining are widely used, which are aimed at reducing roughness, changing the structure of the surface layer of metal, introducing residual compressive stresses, etc. [1-5]. In recent years, there has been an increasing number of publications dedicated to researching the effectiveness of high-frequency mechanical peening (HFMP) with impact elements using ultrasound energy [6-12], which shows the expediency of strengthening the surface by HFMP technology in order to increase the corrosion resistance of various metals (stainless steels, aluminum, and zirconium-niobium alloys). The purpose of the work was to compare the effects of different surface treatment methods, namely grinding and grinding followed by strengthening by HFMP technology, on the corrosion resistance of weather-resistant steels. The research was carried out on specimens with dimensions of 70´50×10 mm, made of low-alloy steel 15HSND, which is widely used for the execution of elements of welded metal structures, in particular, bridge structures, has increased strength, is well welded, is stable in atmospheric conditions, and is capable of working in the temperature range from -70 ^{o}C to 45 ^{o}C.

2. EXPERIMENTAL

The investigations were carried out on low alloy 15HSND steel (σ_{YS} = 400 MPa, σ_{TS} = 565 MPa) such a chemical composition (weigh part, %): 0,142C, 0,466 Si, 0,31 Ni, 0,020 S, 0,013 P, 0,66 Cr and 0,37 Cu.

* Corresponding author: Kaushalendra Kumar Dubey
E-mail: lnyrkova@gmail.com
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Specimens with a polished surface and a surface treated (on all sides) using HFMP technology were used. Corrosion tests were performed on the surface treated by the following methods: polished (P) and polished + HFMP (G + HFMP) according to the procedure, described in [13]. Corrosion tests were carried out under the following conditions: exposure to neutral salt fog and elevated temperature of 35 °C with a humidity of about 98% in a salt fog chamber (hereinafter the SF-1 chamber) and exposure to an elevated humidity of 98% and a temperature of 40 °C in a humidity chamber G4 (further chamber G4). The corrosion rate of the specimens was determined by masometry method. Corrosion rate was estimated by the formula:

$$v_{cor} = \frac{8760 \times \Delta m}{dST} \quad (1)$$

where $\Delta m = m_1 - m_2$ the corrosion losses of the specimen, g;

m_1 is the specimen weight before testing, g;

m_2 is the specimen weight after corrosion tests;

S is the specimen surface area, m^2;

T is the study duration, hours;

8760 is the number of hours in a year;

d – steel density, equal to 6.7 g/cm^3.

Before and after the corrosion studies, the condition of the near-surface layers was monitored by the metallographic method. Metallographic sections were prepared according to standard methods. Grinding and polishing of the grindstones was carried out in ring mandrels with protacryl fixation of the specimen, the near-surface layers were examined for a length of ~ (15-20) mm, the total dimensions of these layers were about (30-40) mm.

Metallographic studies were carried out on a NEOPHOT 32 and NEOPHOT 21 microscope, and a digital image of the structure was obtained using a digital camera Olympus C 5050 and SIGETA UCMOS. Micro hardness was measured on a Leco micro hardness tester M-400 at a load of 25 g (0.25 N), 50 g (0.49 N), 100 g (0.98 N). The grain size was determined according to ISO 4499-2.

3. RESULTS AND DISCUSSION

3.1 Selection of optimal strengthening parameters by high frequency peening technology

To increase the fatigue resistance of welded joints using HFMP technology, a narrow transition zone of the weld metal to the base metal is processed. Processing is carried out with both automatic and manual tools with one impact element or several impact elements located in a row, thanks to which a characteristic groove is formed. A riveted (plastically deformed) layer of metal with a depth of up to 1 mm is located under the groove (**Fig. 1**). It is known [14] that there is a satisfactory correlation between the depth of the groove and the durability of welded joints, and ensuring the required depth of the groove can serve as a criterion for quality processing. A methodical approach to establishing optimal parameters for strengthening local zones of machine parts or welded joints in order to increase their resistance to fatigue is described in [15].

A number of features must be taken into account when strengthening surfaces. With an increase in the duration of forging, corrosion resistance initially increases, after which, with a further increase in forging time, corrosion resistance may decrease [8]. The work [16] gives the results of processing a flat surface with a tool with one impact element, which was displaced by 1 mm after each pass. It was shown that increasing the number of tools passes from one to three reduced the efficiency of the HFMP and led to the appearance of defects. However, the authors of the work [16] did not take into account that this approach to surface treatment leads to the artificial formation of internal defects (mainly in the form of subsurface cracks) due to the fact that high flows of riveted metal near the groove were wrapped and re-riveted when the tool was moved by 1 mm. Thus, discontinuities were artificially formed between layers of riveted metal.

Taking into account the above, a hand tool with a removable nozzle was developed for strengthening flat surfaces, in which the impact elements were arranged in several rows. Surface treatment is recommended to be strengthened with circular reciprocating movements at a speed of 35 cm^2/min. At the same time, the depth of the strengthened metal layer reached 130-150 microns.

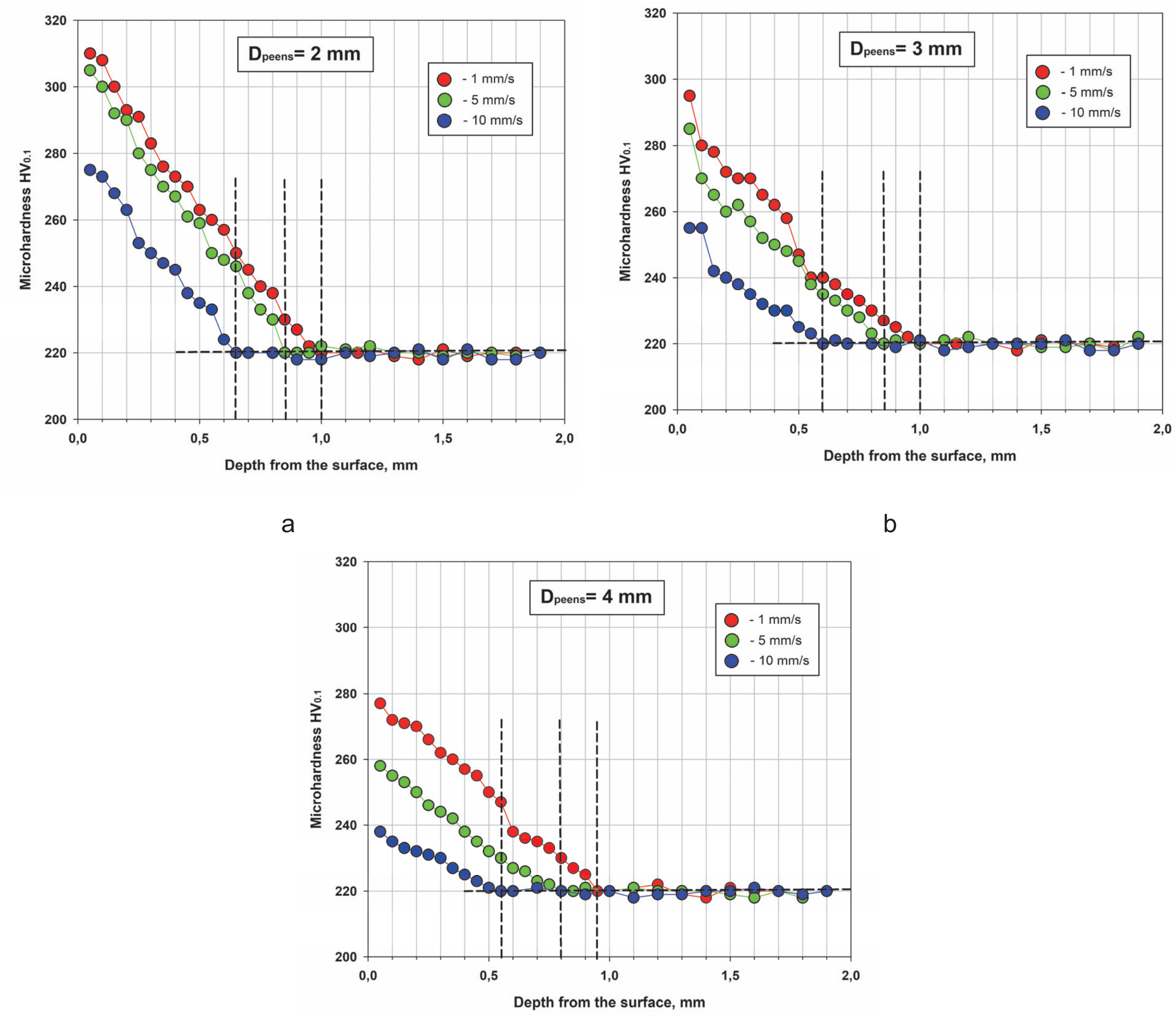

Fig. 1. Dependence of microhardness of near surface metal layer, strengthen by HFMP by using of one-row head with the diameter of cylindrical firing-pins of 2 mm (a), 3 mm (b) and 4 mm (c) from the distance from the bottom of groove to the depth of metal. Speed of implementation of HFMP (Reproduced with permission [15])

3.2 Corrosion and metallographic studies

After choosing the optimal parameters of the HFMP technology, comparative studies of the effect of surface treatment methods on the corrosion resistance of 15HSND steel were carried out. In **Fig. 2** show photographs of the microstructure of the near-surface layers of 15HSND steel with a polished surface (**Fig. 2, a**) (hereinafter P) and a surface processed by HFMP (hereinafter P+ HFMP) technology (**Fig. 2, b**).

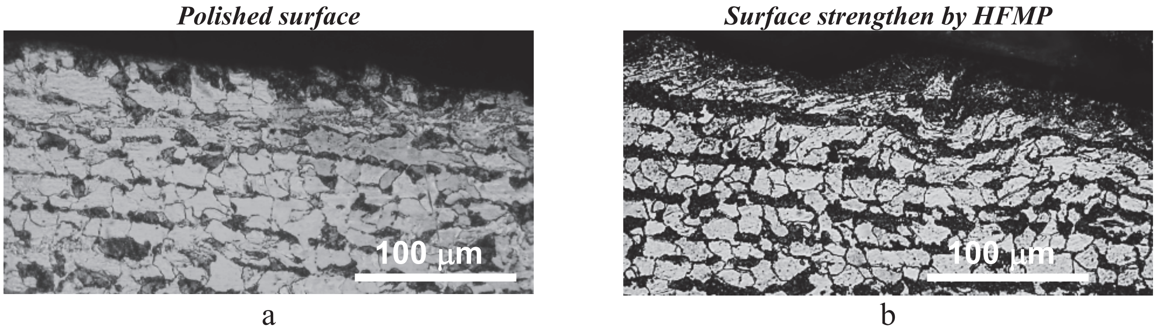

Fig. 2. Microstructure of near surface layers of 15HSND steel with polished surface (P) (a) and surface strengthen by HFMP (b) in the initial state

It should be noted that the surface P is not completely flat (**Fig. 2, a)** in some areas of the near-surface layers, a different degree of plastic deformation is observed, which leads to a change in the shape of the grains of ferrite and pearlite, with a shape factor from 1.8 to 4, the depth of penetration of plastic deformation is from 0.03 mm to 0.08 mm. After HFMP (**Fig. 2, b**), the surface of the specimen acquired uneven waviness, in the zone with more intensive deformation - from 0.06 mm to 0.08 mm. A change in the shape of the grains, their extraction with a shape factor from 3 to 5, grinding and the more frequent appearance of second-phase dispersed discharges were noted. In the zone with a lower degree of deformation, with a depth of 0.09 mm to 0.13 mm, practically no change in the shape of the grains was observed, only the distortion of the ferrite-pearlite striation of the structure was noted.

The results of measuring the micro-hardness of ferrite grains in the near-surface layers of the studied steel, subjected to various types of surface treatment, are presented in Table 1, from which it can be seen that processing using the HFMP technology somewhat (about 1.07–1

Photographs of specimens at the initial state (before cossosion rests) with polished surface (**Fig. 3, a)** and surface strengthen by HFMP **(Fig. 4, a)** and after exposure in SF-1 (**Fig. 3, b, c, Fig. 4, b, c)** and G4 (**Fig. 3, d, e, Fig. 4, d, e)** are shown below.

TABLE 1. *Micro-hardness of ferrite grains in the near surface layers of 15HSND steel after the different methods of surface treatment before investigations*

The method of surface treatment	Micro-hardness of ferrite grains, $HV_{0,25\ H}$		Coefficient of hardening of ferrite grains[a]
	near the surface (at a distance 0,02-0,04 mm)	in the volume of metal (with the injection step 0,08 – 0,12 mm)	
P	153–161–172–77–168* / 166	147–153–161–161–153 / 155	1,07
P+HFMP	199–178–169–181–172 / 180	160–153–154–154–147 / 154	1,17

[a] Coefficient of hardening of ferrite grains, micro-hardness of ferrite grains: in the numerator – measured, in the denominator - average.

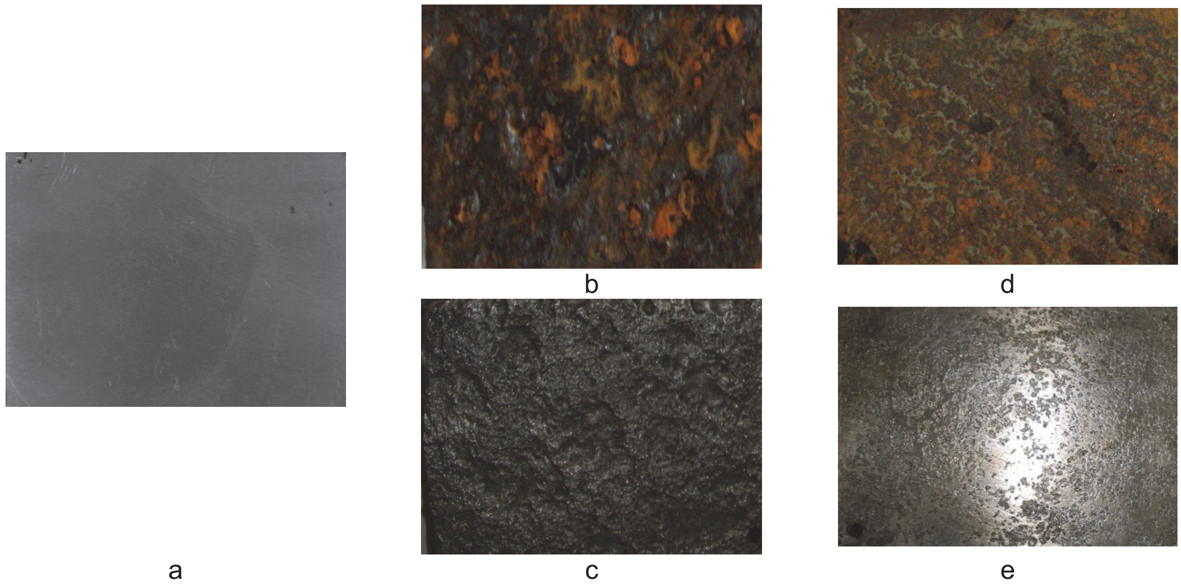

Fig. 3. Appearance of surface of 15HSND steel specimens with polished surface (P) before (a) and after investigations (b, c, d) in the salt frog chamber SF-1 (b, c) and moisture chamber G4 (d, e) during 1200 hours

Analyzing the experimental results, it can be noted that after the tests under the influence of neutral salt fog and elevated temperature, all the examined specimens (with surfaces P and P+HFMP) were covered with a thick layer of corrosion products of uneven thickness of brown-black color (**Fig. 3**, **b, Fig. 4, b**), which were firmly attached to the surface and were very difficult to remove. Areas of the surface without corrosion products with a metallic luster were not observed. After removing the corrosion products, it was noted that the surface is uneven, and corrosion spots are visible over the entire area, with ulcers and pitting inside (**Fig. 3**, c**, Fig. 4, c**). There are also no areas not affected by local corrosion. Areas with the remains of the reinforcing layer are not visually visible on specimens strengthened by HFMP technology. The corrosion rate after 1200 hours was 2.543 mm/year on the surface of P and 2.096 mm/year on the surface of P+HFMP (**Fig. 5**).

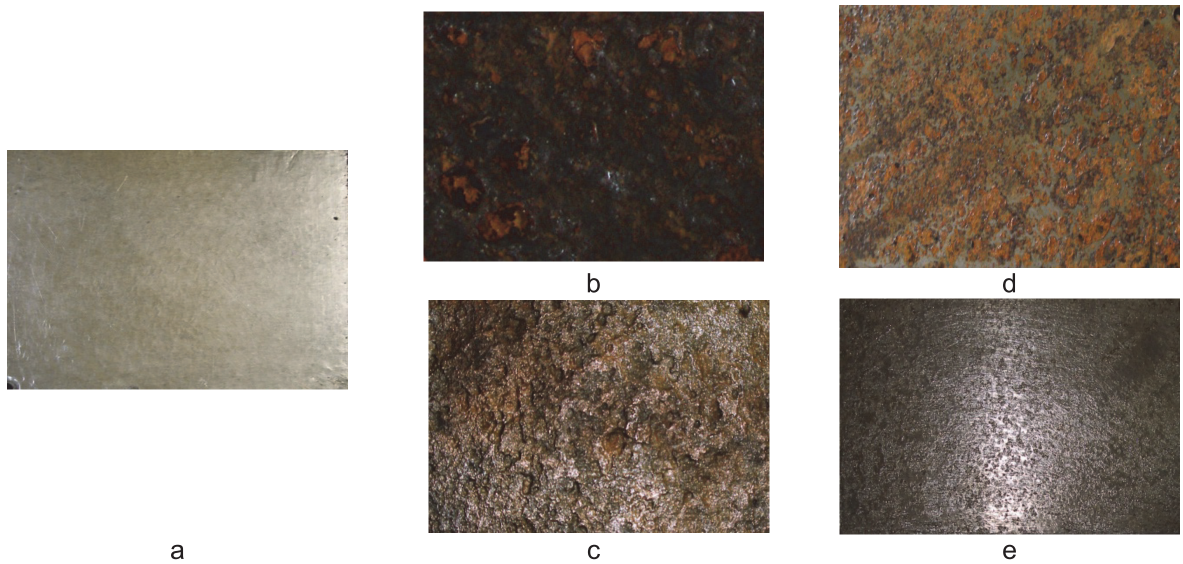

Fig. 4. Appearance of surface of 15HSND steel specimens with surface strengthen by HFMP before (a) and after investigations (b, c, d, e) in the salt frog chamber SF-1 (b, c) and moisture chamber G4 (d, e) during 1200 hours

After tests in G4, specimens with the surface P and P+HFMP (**Fig. 3, d, Fig. 4, d**), are covered with an uneven layer of brown corrosion products with black spots. Areas of the surface with almost no corrosion products with a metallic luster are noted, which occupy about 5-7%. After removal of corrosion products, corrosion spots are visible on the surface, smaller in size than after exposure in SF-1, inside some of them pitting has formed, there are areas practically unaffected by local corrosion (**Fig. 3, e, Fig. 4, e**). The corrosion rate was 0.104 mm/year on the P surface and 0.080 mm/year on the P+HFMP surface (**Fig. 5**).

Thus, surface treatment of HFMP contributed to some extent to increase the corrosion resistance of the studied steel.

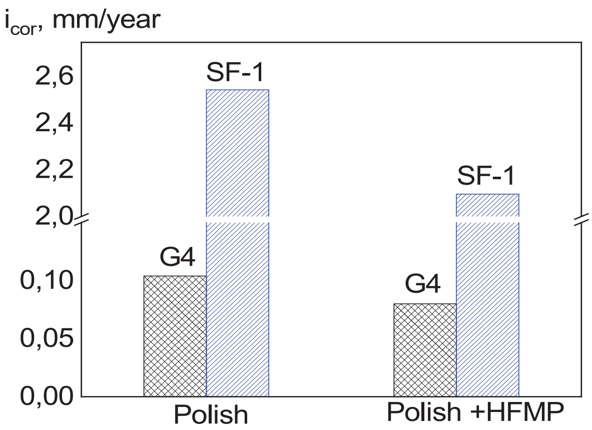

Fig. 5. *Comparative diagram of corrosion rate of 15HSND steel with polished surface (P) and surface strengthen by HFMP after accelerated corrosion tests in the salt frog chamber SF-1 and moisture chamber G4 after 1200 hours*

After the corrosion studies, metallographic studies were carried out, during which the type of corrosion, the size and distribution of corrosion damages were determined. The type of corrosion was determined by comparing it with the types of corrosion defects given in GOST 9.908 (appendix 2), distribution – according to GOST 9.908 (appendix 3) [17]. Corrosion resistance indicators were determined quantitatively and qualitatively. During the influence of the surface treatment method on the corrosion resistance of the specimens before and after the action of climatic factors, the following types of corrosion damage were detected:

– continuous uniform corrosion, which is characterized only by surface unevenness;

– local uneven corrosion, in which only part of the surface is susceptible to corrosion damage;

– spot corrosion – a small (shallow) corrosion lesion, usually of an irregular shape with different sizes of the corrosion damage area;

- corrosion by ulcers; surface damage, the depth and width of which are almost the same;

– subsurface corrosion – corrosion damage that occupies a small area on the surface of the specimen and is concentrated mainly under the surface of the metal;

– intergranular corrosion (IGC) – a corrosion lesion characterized by the presence of a corroded zone along the boundaries of metal grains, which may touch the boundaries of all grains or selectively the grains of individual structural components;

- selective corrosion - corrosion damage to which individual grains of any structural component are exposed, including that which is accompanied by the formation of corrosion products that can have different depths of occurrence.

The total length of the studied near-surface layers is 15 mm × 2.

3.3 Results of metallographic studies of specimens after exposure to neutral salt fog and temperature

Some types of surface damage after exposure in SF-1 and G4 are shown in **Fig. 6, b, c**. After exposure in SF-1, continuous uneven corrosion was observed in the surface layers of the specimen with surface P (**Fig. 6, a**), against the background of which deep corrosion lesions were observed in the form of corrosion spots, for example, 2.8 × 0.5 mm, 2.1 × 0.7 mm in size and, less often, corrosion ulcers, for example, in size 1,7 × 1.58 mm. IGC, which started from the boundaries of the ferrite and pearlite grains, and selective corrosion along the pearlite grains were also detected. In addition, in the near-surface layers at a depth of 0.02-0.03 mm, separately located areas with subsurface corrosion from 0.38 mm to 0.413 mm in length were found.

The surface of the specimen P+HFMP was exposed to continuous uneven corrosion (**Fig. 6, b**): mainly, spot corrosion of various sizes, for example, from 0.13×0.03 mm to 1.56×0.26 mm, was detected; in the near-surface layers - by subsurface corrosion of various areas, for example, 0.38×0.012 mm, 0.1×0.007 mm, mainly at a depth of 0.05-0.07 mm, with direct access to the surface of the v; IGC along the boundaries of ferrite grains at a depth of nearly 0.1 mm; selective corrosion of pearlite grains.

Corrosion lesions are less deep compared to the surface P: for example, 0.7×0.01 mm, 0.15×0,007 mm, and corrosion by ulcers, for example, 0.15×0.13 mm.

The results of metallographic studies of specimens of the base metal of 15HSND steel after exposure to high humidity and temperature. A feature of the surface of the specimens after exposure in G4 is the presence of a large number of areas with subsurface corrosion of different lengths (0.1–1.32 mm) and depths (0.01-0.07 mm), mainly with direct access to the surface.

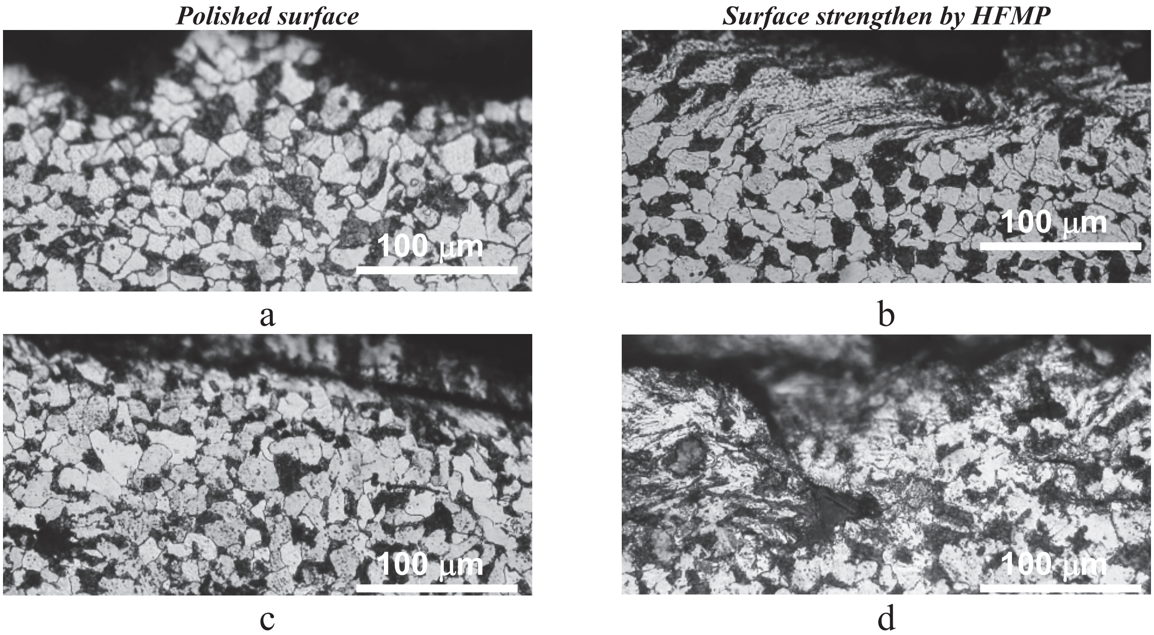

Fig. 6. Microstructure of near surface layers of 15HSND steel with polished surface (P) (a, c) and surface strengthen by HFMP (b, d) after investigations in the salt frog chamber SF-1 (a, b) and moisture chamber G4 (c, d) during 1200 hours.

In the near-surface layers of the specimen with surface P, continuous uneven corrosion was recorded after the tests (**Fig. 6, c**, and **Table 2**). In addition, relatively shallow (0.03-0.08 mm) corrosion damage is observed, mainly in the form of spots, for example, 0.3×0.05 mm and 0.11×0.017 mm in size; shallow IGC from the boundary of elongated pearlite grains; and more intense selective corrosion along the grains of the pearlite component.

A plastically deformed layer of ferrite and pearlite grains with a depth of 0.01 to 0.13 mm and a grain shape factor (K_{gsh}) equal to 3-50 is observed in the near-surface layers of the specimen with a surface of P+HFMP. The near-surface layers of the specimen were subjected to continuous uneven corrosion (**Fig. 6, d**), relatively shallow (0.026-0.1 mm) spot corrosion was recorded (**Table 2**). In addition, there are areas with subsurface corrosion of different areas, lengths (0.06-0.9 mm), and depths of occurrence (0.01-0.07 mm), both with direct exit and without exit to the metal surface. IGC is not intense and spreads along the boundaries of both ferrite and pearlite grains; selective corrosion of pearlite grains is observed.

Table 2. Corrosion damage parameters in the near surface layers of 15HSND steel

Suface treatment method	Tests conditions	Deformed layer depth, mm	Spot corrosion			Subsurface corrosion			Intergranular corrosion			Selective corrosion
			Damage degree, %	Penetration depth, mm	Total projection of the affected area, mm²	Damage degree, %	Penetration depth, mm	Total projection of the affected area, mm²	Damage degree, %	Penetration depth, mm	Total projection of the affected area, mm²	
P	SF-1	-	42,9	0,05-1,0	17,16	6,03	0,01-0,07	2,41	0,88	0,003-0,06	0,35	along pearlite grains
P+HFMP	SF-1	0,02-0,066	80	0,013-0,163	25,6	0,93	0,017-0,065	0,3	0,5	0,022-0,044	0,16	along pearlite grains at a depth of 0.3 mm
P	G4	0,007-0,017	8	0,03-0,08	2,41	14,2	0,01-0,07	4,27	0,18	0,03	0,054	
P+HFMP	G4	0,01-0,132	27,7	0,026-0,065	8,32	10	0,017-0,035	3,01	along the boundaries of individual ferrite grains			

According to the results of measuring the micro-hardness of ferrite grains in the near-surface layers of 15HSND steel subjected to various methods of surface treatment, no difference in micro-hardness was found after tests in SF-1 and G4. In order to assess the effect of the applied methods of metal processing on its corrosion resistance under various conditions, the degree of damage to the specimens by corrosion, in addition to the depth of corrosion penetration, was determined not only by the area but also by the total projection of the damaged plane in the cross-section of the specimen, related to its total length, the results of which are given in **Table 2**.

After research in conditions of neutral salt fog (**Table 2**), the depth of penetration of the detected types of corrosion damage in the near-surface layers of 15HSND steel is different: the greatest depth of spot corrosion (1 mm) is recorded on the surface P, the smallest (0.163 mm) is on the surface P+HFMP; the depth of subsurface corrosion for all methods of surface treatment is almost the same - (0.065-0.07 mm), but on the surface P+HFMP the number of areas with this type of corrosion is less than on the surface P. The smallest depth of IGC (0.044 mm) is established in the near-surface layers on the surface P+HFMP, the largest (0.06 mm) – after on the surface P. After research in conditions of high humidity and temperature, the manifestation of corrosion damage in the near-surface layers of the metal is, in general, similar to the above. Thus, research has established that more intense corrosion in the near-surface layers of metal occurs in conditions of neutral salt fog, in which the depth of penetration of all detected types of corrosion is greater compared to conditions of high humidity. The highest corrosion resistance is provided by the surface layers of 15HSND steel subjected to high-frequency mechanical forging, despite some disagreement regarding the degree of damage by spot corrosion.

4. CONCLUSIONS

An analysis was carried out regarding the selection of the most technologically effective parameters for strengthening low-alloy steels using the HFMP technology. To strengthen the surfaces, it is recommended to use a removable nozzle in which the impact elements are located in several rows. The speed of HFMP should be 35 cm^2/min.

According to the results of metallographic studies, it was established that processing using HFMP technology strengthens the ferrite component of the near-surface layers of low-alloy steel 15HSND by about 1.07–1.17 times compared to the polished surface.

The influence of various methods of surface treatment of low-alloy steel 15HSND (grinding and processing using HFMP technology) on its corrosion resistance under the influence of climatic factors was studied. It was established that the surface after

HFMP treatment helps to some extent increase the corrosion resistance of the studied steel: the corrosion rate after exposure to neutral salt fog after 1200 hours decreases from 2.543 mm/year on a polished surface to 2.096 mm/year after HFMP treatment, and after exposure to high humidity and temperature – from 0.104 mm/year to 0.080 mm/year, respectively.

The corrosion rate of steel with a polished surface is lower, but the HFMP technology is planned to be used in the future to increase the durability against corrosion-fatigue failure.

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CONFLICT OF INTEREST

The authors declare no financial or commercial conflict of interest.

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IZVOD

UTICAJ RAZLIČITIH METODA POVRŠINSKE OBRADE NA OTPORNOST NISKOLEGIRANOG ČELIKA NA KOROZIJU

Prikazan je uticaj mehaničkih metoda površinske obrade (poliranje i poliranje sa sledećim ojačanjem visokofrekventnim mehaničkim piningom, HFMP) na otpornost na koroziju niskolegiranog čelika 15HSND. Analizirani su nedostaci površinskog ojačanja HFMP-om sa jednim udarnim peenom i predložen je instrument u kome su udarni elementi smešteni u nekoliko redova. Preporučena je brzina HFMP-a za površine 35 sm^2/min. Razlike u strukturi i mikrotvrdoći pripovršinskih slojeva 15HSND čelika sa poliranom površinom i polirane površine sa sledećim ojačanjem pomoću HFMP utvrđene su nakon ispitivanja u slanoj komori i komori za vlagu tokom 1200 sati. Primena HFMP tehnologije povećava otpornost čelika na koroziju: stopa korozije nakon neutralne slane magle smanjena je sa 2.543 mm/godišnje na poliranoj površini na 2.096 mm/godišnje nakon HFMP tretmana, a nakon povećane vlažnosti i temperature sa 0.104 mm/godišnje na 0.080 mm/god.

Ključne reči: *ubrzana klimatska ispitivanja, otpornost na koroziju, visokofrekventno mehaničko kaljenje, niskolegirani čelik, metalografija*

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The ORCID Ids of all the authors are as follows:

1. *Lyudmila Nyrkova: https://orcid.org/0000-0003-3917-9063*
2. *Vitaliy Knysh: https://orcid.org/0000-0003-1289-4462*
3. *Sergiy Solovey: https://orcid.org/0000-0002-1126-5536*
4. *Svetlana Osadchuk: https://orcid.org/0000-0001-9559-0151*