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FATIGUE LIFE OF SPECIMENS FROM 40Kh STEEL AFTER WEAR-RESISTANT SURFACING WITH A LOW-ALLOY STEEL SUBLAYER

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Studied was the resistance of a multilayer material to fatigue fracture, in which wear-resistant layer was deposited with the PP-Np-25Kh5FMS flux-cored wire with a sublayer from a low-alloy material, deposited with the PP-Np-12KhlMF wire. The design of surfaced specimens and their test procedure simulated the operating conditions of steel mill rolls. The integrated procedure of evaluation of fatigue fracture resistance of multilayer surfaced specimens to included three stages: determination of cyclic fatigue life of specimens after fabrication surfacing; studying the cyclic crack resistance of different deposited layers; determination of fatigue life of specimens, having fatigue cracks in the deposited layer during previous testing, after their repair surfacing. It was found that the cyclic fatigue life of specimens from 40Kh carbon steel, deposited with the PP-Np-25Kh5FMS flux-cored wire with a sublayer of 12KhlMF low-alloy steel is in the range of 346–716 thou cycles at maximum stress level of 500 MPa. Features of fatigue fracture kinetics of the studied multilayer material were determined. It was established that the fatigue crack propagates in the deposited metal in an unstable manner (in the wear-resistant layer and in a low-alloy steel sublayer), constantly changing its rate and direction. It is shown that cutting out fatigue cracks and subsequent surfacing of their removal areas allows restoring the cyclic fatigue life of the specimen to the initial level, i.e. twice increasing the overall life. 16 Ref., 4 Tables, 7 Figures.

Keywords: *arc surfacing, repair surfacing, sublayer, fatigue life, fatigue cracks, stress intensity factor*

It is widely known that in metallurgical and machine-building industries, a large number of parts and tools are operated in the conditions of cyclic mechanical loads [1]. Such complex operating conditions lead, in particular, to the appearance of fatigue cracks on the surface of parts, which, on the example of mill rolls, can lead to a rejection of metal-rolling products, failure of equipment and, as a consequence, significant material losses [1–6].

In order to increase the life of such parts, produced of medium-carbon steel of type 35KhM, 45, 50, 40Kh, 50Kh, etc., a production or repair-restoration surfacing of external wear-resistant layer of metal are often used. Most often, for this purpose electrode materials are used that provide a deposited metal of type of medium- or high-alloy semi-heat-resistant or heat-resistant tool steels 25Kh5FMS, 30Kh4V2M2FS, 35V9Kh3SF, etc. [7, 8].

It is widely known that to improve weldability of the base and deposited metal, especially if they relate to dissimilar classes of metals, surfacing of the intermediate ductile layer of metal (sublayer) is used. Also, with the use of a substrate material with an intermediate value of the temperature expansion coefficient, residual surfacing stresses can be slightly reduced, which can positively affect the overall fatigue life of a deposited specimen or part [7, 8]. From practical experience it is known that as a sublayer mateirals low-carbon, low-alloyed materials are used, that provide a ductile metal of type of steels 08kp(rimmed), 08G2S, etc. [8].

Therefore, in [9], it was shown that the use of ductile metal of type 08kp as a sublayer provided a 1.4 times increase in the fatigue life of experimental specimens at a cyclic mechanical load as compared to similar specimens without a sublayer. In the works [10, 11], as a result of an integrated evaluation of fatigue life of specimens with the same sublayer material, but deposited by another technology, it was found that during produciton surfacing using the wire Sv-08A on a steel 40Kh with a subsequent surfacing of a wear-resistant and heat-resistant layer of steel of type 25Kh5FMS, fatigue life of the specimens is 2 times higher as compared to the specimens, deposited without a sublayer.

The aim of the work is an experimental comparative study of the influence of low-alloy metal sublayer on the fatigue life of a multilayer material in the produciton and repair (restorative) wear-resistant surfacing.

Procedures, technologies and research materials. In order to compare the influence of the sublayer material on the fatigue life of the deposited speci-

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Table 1. Mechanical properties of base and deposited metals

Grade of material	Mechanical properties (after normalization)					
	Conventional yield strength $\sigma_{0.2}$, MPa	Tensile strength σ_t, MPa	Relative elongation δ, %	Reduction in area ψ, %	Impact toughness *KCU*, J/cm^2	Hardness *HB*
40Kh	345	590	12.5	52	7.5	174–217
08kp*	196	320	33	60	–	≤131
12Kh1MF	255	470	21	55	98	≤217
4Kh5MFS*	1570	1710	12	54	51	444–478

*In the literature there are no data on mechanical properties of the metal, deposited by the wires Sv-08A and PP-Np-25Kh5FMS. Therefore, the data for their analogues (the most close as to chemical composition and mechanical properties), respectively, steels 08kp and 4Kh5MFS are given.

Table 2. Chemical composition of base and deposited metals 112]

Grade of material	Mass fraction of elements, %							
	C	Mn	Si	Cr	V	Mo	S	P
40Kh	0.36–0.40	0.5–0.8	0.17–0.37	0.8–1.1	–	–	≤0.035	≤0.035
Sv-08A**	0.05–0.12	0.2–0.4	0.1–0.3	–	–	–	≤0.04	≤0.04
08kp	0.05–0.12	0.25–0.5	≤0.3	≤0.10	–	–	≤0.035	≤0.04
12Kh1MF	0.10–0.15	0.4–0.7	0.17–0.37	0.9–1.2	0.15–0.3	0.25–0.35	≤0.025	≤0.035
PP-Np-25Kh5FMS**	0.20–0.32	0.5–1.0	0.80–1.30	4.6–5.8	0.2–0.6	0.9–1.5	≤0.04	≤0.04
4Kh5MFS**	0.32–0.40	0.2–0.5	0.90–1.20	4.5–5.5	0.3–0.5	1.2–1.5	≤0.04	≤0.04

**Mass fraction of elements in the deposited metal is given.

mens, in this work, a sublayer of a low-alloy steel of type 12Kh1MF was used. The steel of this grade was chosen based on its higher mechanical properties as compared to steel 08kp (Table 1).

In order to establish the rationality of using low-alloy steel sublayers with the aim of increasing the fatigue life of multilayer deposited specimens, the previously developed surfacing technology was used, described in detail in [10, 11]. In order to obtain reliable results of studies of the steel grade of the base metal and a deposited wear-resistant metal layer (steel 40Kh and 25Kh5FMS, respectively) during surfacing without a sublayer and with a sublayer of different types were the same. For surfacing of the intermediate layer, an experimental flux-cored wire of grade PP-Np-12Kh1MF of 1.8 mm diameter was used. The chemical composition and mechanical properties of materials used in the work are given in Tables 1, 2 [12].

The studies were performed in three stages and for each one 3–5 prismatic specimens with the sizes of 350×40×20 mm were manufactured, which subsequently were tested using a developed integrated procedure for evaluating the resistance of a multilayer material to fatigue fracture [10, 11]. This procedure includes the following stages: establishment of cyclic life of specimens after a fabrication surfacing; study of cyclic crack resistance of different layers of metal; determination of fatigue life of specimens, which had fatigue cracks in a deposited layer in the process of preliminary tests and after repair surfacing. In more details, surfacing modes and technologies, as well as research procedures are described in [10, 11].

Results of experiments and their discussion. *Specimens of the first series.* Initially, three specimens of the first series of carbon steel 40Kh, deposited using the flux-cored wire PP-Np-25Kh5FMS with a low-alloy steel 12Kh1MF were tested at the levels of maximum stresses of 600 MPa, characteristic of specimens manufactured with low-carbon steel sublayers [11]. Due to the presence of inner defects in the deposited layer, it was failed to obtain reliable results of fatigue life. Therefore additional specimens were manufactured and it was decided to perform tests at the levels of maximum stresses of 500 MPa, characteristic to the specimens produced without a sublayer [10]. The results of studies of fatigue life of specimens, deposited by the wire PP-Np-25Kh5FMS with a sublayer of low-alloy steel 12Kh1MF, are shown in Table 3.

During fatigue tests of the first series of specimens, deposited with the wire PP-Np-25Kh5FMS with a low-alloy steel substrate, it was found that their cyclic life before fracture at maximum applied stresses of 500 MPa is in the range of 346000–716800 cycles.

It should be noted that fracture of the specimens without a sublayer at the levels of maximum stresses of 500 MPa occurred in the range from 560800 to 1420100 cycles of stress changes [10], and the specimens with low-carbon steel sublayers withstood more than 20000000 cycles of stress changes [11].

On the specimens of the second series from a sharp notch in the wear-resistant layer of metal, an initial crack

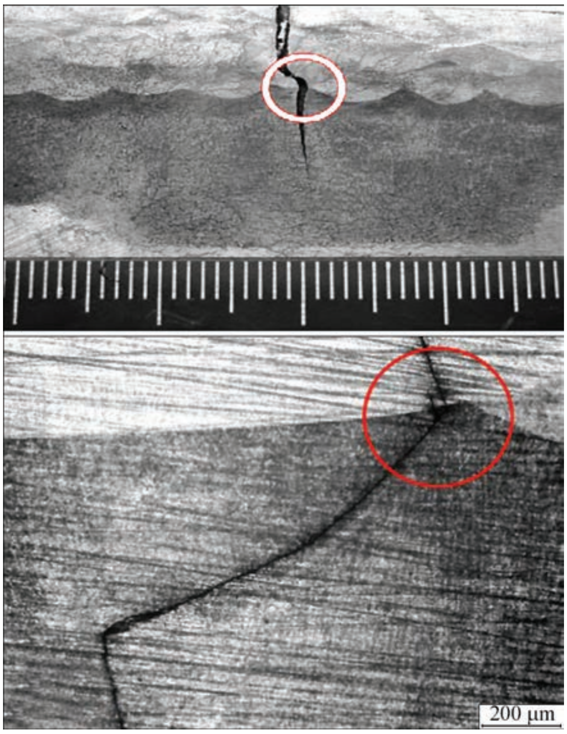

Figure 1. Nature of fatigue crack propagation in the specimens of 40Kh steel, deposited with the wire PP-Np-25Kh5FMS with a sublayer of a low-alloy 12Kh1MF steel

with a depth of 1 mm at the levels of maximum stresses of 400 MPa was grown. During further tests of the specimen at the levels of maximum stresses of 400 MPa, the length of the fatigue crack and the corresponding number of variable load cycles N were recorded.

Experimental studies of the features of fatigue crack propagation in these specimens were confirmed by the previously obtained data that the fusion zone of individual beads and layers plays an important role in the process of fatigue fracture of deposited parts, because the cracks are mostly propagating either on the fusion boundary of the individual beads, or close to this boundary (Figure 1).

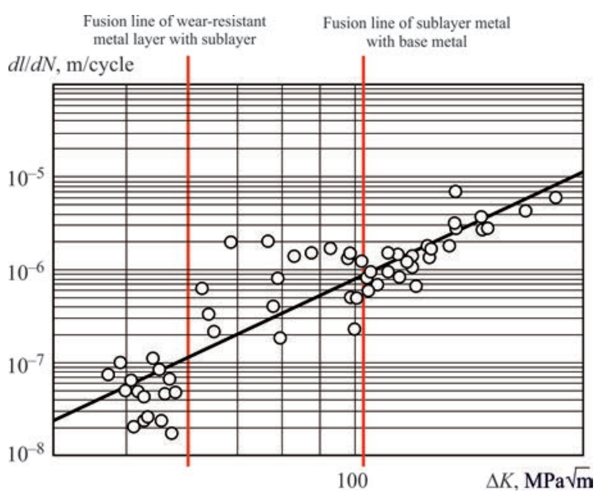

Figure 2. Kinetic diagram of fatigue fracture of multilayer material formed by wear resistant surfacing wit the use of a sublayer of a low-alloy steel

Table 3. Results of fatigue tests of specimens of the first series

Number of specimen	Maximum cycle stresses, MPa	Cyclic life before fracture, cycles
1	600	18.000*
2	Same	72.400*
3	»	261.000
4	500	716.800
5	Same	381.800
6	»	528.700
7	»	346.000

*In the specimens defects were found formed during surfacing.

To construct kinetic diagrams of fatigue fracture (KDFF), the calculation of values of the stress intensity factor (CIF) for a prismatic specimen with a transverse edge crack at a three-point bending was made according to the expressions given in [13]. Experimental dependence of the growth rate of the fatigue crack from the range of CIF in different layers of the multilayer specimen metal is presented as a corresponding KDFF obtained by the results of testing three specimens (Figure 2). Separately, Figure 3 shows a kinetic diagram of the fatigue fracture of the base metal of 40Kh steel.

In a deposited metal (in a wear-resistant layer and in a low-alloy steel sublayer), a fatigue crack propagates in an unstable way. Therefore, in the range of CIF being 45–60 MPa√m, when a crack propagated in the metal of a wear-resistant layer, its rate constantly changed in the range of values 10^{-8}–10^{-7} m/cycle. At a further propagation in the metal of the sublayer, the growth rate of the fatigue crack increases by an order to $2\cdot10^{-7}$–$2\cdot10^{-6}$ m/cycle in the range of CIF being 60–100 MPa√m. In the base metal, a crack was steadily propagated at an ever-increasing rate from $6\cdot10^{-7}$ to $7\cdot10^{-6}$ m/cycle until fracture of the specimen at the values of CIF being 160–180 MPa√m, which corresponds to the established KDFF of 40Kh steel.

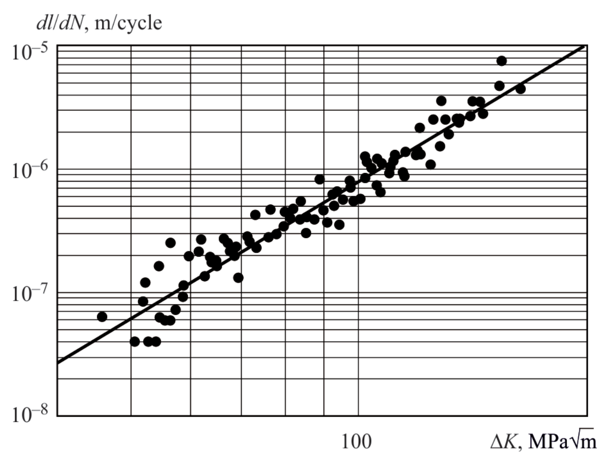

Figure 3. Kinetic diagram of fatigue fracture of base metal of 40Kh steel

On the specimens of the third series, the initiation and propagation of fatigue cracks from possible defects in a deposited wear-resistant layer of metal was originally modeled. Therefore, the specimens were tested at a cyclic load to till formation of fatigue cracks at a depth of 10–12 mm, which subsequently were subjected to elimination by repair surfacing. After performing repair surfacing, measurements of residual stresses by nondestructive ultrasonic method were carried out [14]. This method does not allow measuring residual stresses in the cast metal, so the measurement of residual stresses oriented along and across the specimen was carried out at a distance from the low-carbon fusion line with the base metal (determined by the macrostructure) deep into the metal. The values of residual stresses, given on the diagrams are averaged over the thickness of the specimen. The schematic representation of the measurement places of residual stresses is shown in Figure 4, and the diagrams of distribution of residual stresses in the initial state and after repair surfacing are in Figures 5, 6.

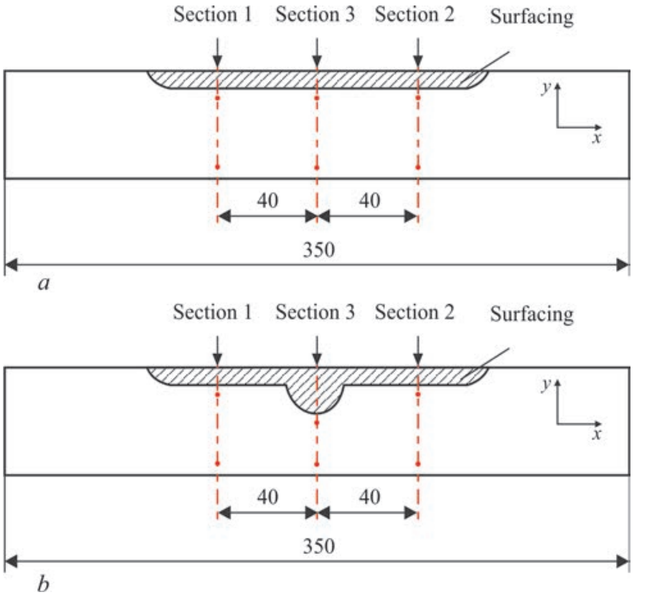

Figure 4. Schematic representation of places of measurement of residual stresses in the specimen before (*a*) and after (*b*) repair surfacing

Data of measurements of residual stresses in the specimen of 40Kh steel with a surfacing of a wear-resistant layer with a sublayer of 12Kh1MF steel given in Figure 5, show that the maximum tensile stresses σ_x, which are oriented along the specimen (coincided by the direction with applied working stresses during fatigue tests of specimens) are by 20 % higher as compared to the maximum levels of tensile stresses σ_x, formed in a multilayer material with a sublayer of steel 08kp [11].

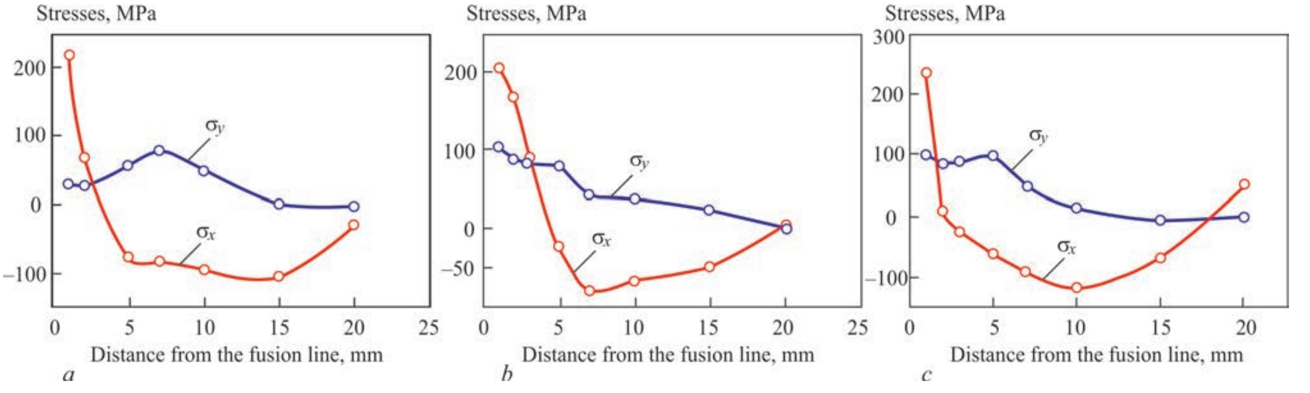

Figure 5. Distribution of residual stresses, oriented along σ_x and across σ_y of the specimen before repair surfacing, in the section 1 (*a*), section 2 (*b*) and section 3 (*c*) according to Figure 4, *a*

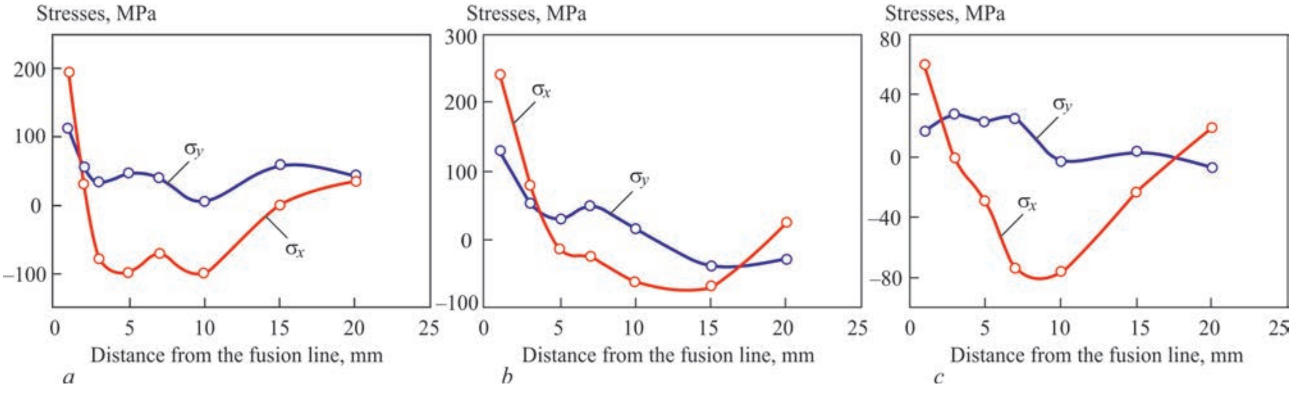

Figure 6. Distribution of residual stresses, oriented along σ_x and across σ_y of the specimen before repair surfacing, in the section 1 (*a*), 2 (*b*) and 3 (*c*) according to Figure 4, *b*

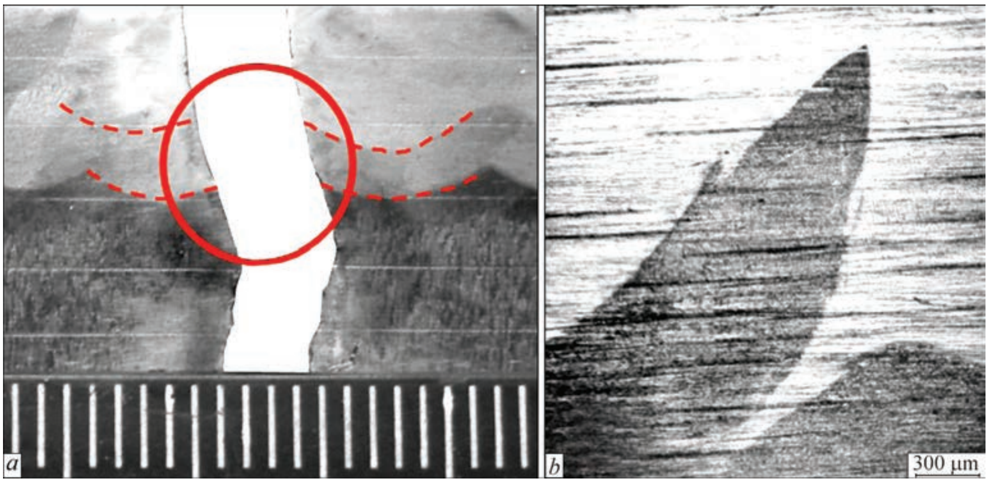

Figure 7. Appearance of the specimen area after repair surfacing with a fatigue crack, that passes on the boundary between the adjacent deposited beads (*a*) and the zone of macroheterogeneity — the boundary between the «old» deposited metal, and the metal, deposited in the course of repair (*b*)

After repair surfacing, the maximum of specimen residual tensile stresses σ_x, in intersections 1 and 2 are almost remained unchanged, while in the intersection 3 they significantly decrease to 60 MPa (Figure 6).

After measurements of residual stresses, the specimens of the third series were tested on fatigue at a three-point zero-to-tension cyclic bending. Cyclic life of specimens before and after repair surfacing is given in Table 4. Moreover, it should be noted that all the specimens after repair during fatigue tests were fractured at more than 20 mm from the cross-section 3, i.e., in the places with higher residual tensile stresses σ_x.

After performing repair surfacing, as in the case of fabrication surfacing, the initiation and propagation of fatigue cracks in all the specimens of the third series occurred either on the fusion boundary of individual beads, or directly near this boundary, obviously, as a result of chemical and structural heterogeneity in the mentioned area (Figure 7, *a*.). Summary, the specimens deposited with a low-alloy steel sublayer, after a premature wear until the initiation of a crack, repair surfacing and the next cyclic load withstood in average about ~ 600 thou cycles. Therefore, the life of specimens after production and repair surfacing is approximately the same and amounts to ~ 300 thou cycles.

A particular attention should be paid also to the technology of repair surfacing, because while performing preparation in accordance with the parameters determined previously and during its subsequent filling, the unfavorable zones of macroheterogeneity may be formed on the boundary between the new and «old» deposited metal (Figure 7, *b*), which also can influence the fatigue life of a specimen.

Table 4. Results of fatigue tests of specimens of the third series

Number of specimen	Maximum cycle stresses, MPa	Cyclic life before the initiation of a 10–12 mm crack, cycles	Cyclic life after repair surfacing, cycles	Total cyclic life, cycles
11	500	285600	256400	542000
12	500	333300	144900	478200
13	500	283100	448200	731300

Generalization of results. Comparison of the data obtained for the specimens of 40Kh steel, deposited without a sublayer [10], with sublayers of a low-carbon steel 08kp [11] and a low-alloy 12Kh1MF steel, indicates that the specimens, deposited with a sublayer with a more ductile low-carbon steel 08kp, have the longest life both before as well as after repair surfacing. This can be explained by several factors. First, this is associated with a higher ultimate and yield strength of 12Kh1MF steel as compared to steel 08kp and, at the same time, a lower relative elongation (see Table 1), which led to the formation of higher levels of residual tensile stresses in the deposited metal (see Figures 5, 6). Secondly, the reason for the negative impact on the fatigue life of 12Kh1MF material may be chemical or structural heterogeneities, formed in the transition zones base–sublayer–working layer [5, 15, 16].

It is obvious that during repair surfacing, when only a metal area around the fatigue crack is removed, the difficulties in providing a uniform chemical and macrostructural state are added as a result of violation of the initial order of deposition and the structure of deposited beads. In addition, in multilayer surfacing with the use of medium- and high-carbon electrode materials, because of the repeated heatings, in the zones of adjacent beads overlapping, an additional formation of carbides may occur, which depletes the surrounding matrix and leads to the formation of chemical and structural heterogeneity. These areas may become the sources of crack initiation in the conditions of mechanical cyclic load, and therefore, the abovementioned factors need to be taken into account when developing techniques and technology of both production and especially repair surfacing.

Conclusions

1. The technology of production and repair surfacing of specimens from carbon 40Kh steel were developed, which are deposited by the flux-cored wire PP-Np-25Kh5FMS with a sublayer of a low-alloy 12Kh1MF steel. It was found by nondestructive ultrasonic method of stress measurements, that the maximum longitudinal residual tensile stresses reach the values of 220–240 MPa. After performing the repair surfacing, the maximum residual tensile stresses σ_x are decreased to 60 MPa. At the same time in other sections of the specimen, the levels of residual tensile stresses remain almost unchanged.

2. In the deposited metal (in a wear-resistant layer and in a low-alloy steel sublayer), a fatigue crack propagates unstable. Thus, in the range of CIF being 45–60 MPa√m, when a crack propagated in the metal of a wear-resistant layer, its rate constantly changed in the range of 10^{-8}–10^{-7} m/cycle. With the further propagation in the metal of the sublayer, the growth rate of a fatigue crack rises by an order to $2\cdot10^{-7}$–$2\cdot10^{-6}$ m/cycle in the range of CIF being 60–100 MPa√m. In the base metal, a crack steadily propagated with an ever-increasing rate of $6\cdot10^{-7}$ to $7\cdot10^{-6}$ m/cycle until the fracture of the specimen at the values of CIF being 160–180 MPa√m, which corresponds to the established KDFF of 40Kh steel.

3. It was found that the cyclic life of the specimens from carbon 40Kh steel, deposited with a flux-cored wire PP-Np-25Kh5FMS with a low-alloy 12Kh1MF steel sublayer is 2–3 times lower than the cyclic life of the specimens, deposited without a sublayer. Thus, the cyclic life of the specimens without a sublayer at the levels of maximum stresses of 500 MPa, is in the range of 561–1420 thou cycles of stress changes, and the cyclic life of defect-free specimens with a sublayer of 12Kh1MF is 346–716 thou cycles.

4. It is shown that realization of repair surfacing according to the scheme of removal and a subsequent surfacing of only areas of metal with fatigue cracks allow restoring cyclic life to the level of the initial state, i.e., increase the overall life twice. In this case, the fracture of restored specimens occurred far from the place of repair surfacing.

1. Du Toit, M., Van Niekerk, J. (2010) Improving the life of continuous casting rolls through submerged arc cladding with nitrogen-alloyed martensitic stainless steel. *Welding in the World*, 54(**11–12**), 342–349. Doi:10.1007/bf03266748
2. Jhavar, S., Paul, C.P., Jain, N.K. (2013) Causes of failure and repairing options for dies and molds: A Review. *Engineering Failure Analysis*, **34**, 519–535. DOI: https://doi.org/10.1016/j.engfailanal.2013.09.006
3. Ahn, D.-G. (2013) Hardfacing technologies for improvement of wear characteristics of hot working tools: A Review. *Int. J. of Precision Engineering and Manufacturing*, 14(**7**), 1271–1283. Doi:10.1007/s12541-013-0174-z
4. Zhang, J., Zhou, J., Tao, Y. et al. (2015) The microstructure and properties change of dies manufactured by bimetal-gradient-layer surfacing technology. *The Int. J. Adv. Manuf. Technol*., **80**, 1807–1814 (2015). DOI: https://doi.org/10.1007/s00170-015-7170-7
5. Gao, F., Zhou, J., Zhou, J. et al. (2017) Microstructure and properties of surfacing layers of dies manufactured by bimetal-gradient-layer surfacing technology before and after service. *The Int. J. Adv. Manuf. Technol*., **88**, 1289–1297. DOI: https://doi.org/10.1007/s00170-016-8679-0
6. Vundru, C., Paul, S., Singh, R., Yan, W. (2018) Numerical analysis of multi-layered laser cladding for die repair applications to determine residual stresses and hardness. *Procedia Manufacturing*, **26**, 952–961. DOI: https://doi.org/10.1016/j.promfg.2018.07.122
7. Ryabtsev, I.A., Senchenkov, I.K. (2013) *Theory and practice of surfacing works*. Kiev, Ekotekhnologiya [in Russian].
8. Rjabcev, I.A., Senchenkov, I.K., Turyk, Je.V. (2015) *Surfacing. Materials, technologies, mathematical modeling*. Gliwice, Wydawnictwo politechniki slaskiej [in Russian].
9. Babinets, A.A., Ryabtsev, I.A. (2016) Fatigue life of multilayer hard-faced specimens. *Welding Int*., 30(**4**), 305–309. DOI: https://doi.org/10.1080/01431161.2015.1058004
10. Ryabtsev, I.O., Knysh, V.V., Babinets, A.A. et al. (2020) Fatigue life of specimens after wear-resistant, manufacturing and repair surfacing. *The Paton Welding J*., **9**, 19–25. DOI: https://doi.org/10.37434/tpwj2020.09.03
11. Ryabtsev, I.O., Knysh, V.V., Babinets, A.A., Solovej, S.O. (2021) Fatigue life of steel 40Kh specimens after wear-resistant surfacing with a sublayer of low-carbon steel. *Ibid*., **3**, 2–8. DOI: https://doi.org/10.37434/tpwj2021.03.01
12. Oberg, E. et al. (1996) *Machinery's Handbook* (25th Ed.), Industrial Press Inc.
13. Murakami, Yu. (1990) *Reference book on stress intensity efficients*. In: 2 Vol. Moscow, Mir [in Russian].
14. (2004) *Device for control of mechanical stresses and strains in solid media*. Pat. UA 71637 C2 [in Ukrainian].
15. Kaierle, S., Overmeyer, L., Alfred, I. et al. (2017) Single-crystal turbine blade tip repair by laser cladding and remelting. CIRP *J. Manufact. Sci. and Technol*., **19**, 196–199. DOI: https://doi.org/10.1016/j.cirpj.2017.04.001
16. Kim, D.-Y., Kim, D., Kang, M., Kim, Y.-M. (2017) Improvement of fatigue strength of lap fillet joints by using tandem MAG welding in a 590-MPa-grade galvannealed steel sheet. *The Int. J. Adv. Manuf. Technol*., 93(**9–12**), 4379–4387. DOI: https://doi.org/10.1007/s00170-017-0828-6.

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SEPTEMBER 1, 1939 Beginning of the Second World War. Preparation to it significantly effected application of electric welding in production of all types of arms. Germany in order to circumvent peace agreement started using welded joints in the defense industry. Series of technologies, such a underwater welding, received a large development in this time. During the first years of the war volume of welding engineering in America increased more than three times due to manual electric arc welding and submerged arc welding.