TECHNOLOGY OF REPAIR WELDING OF BOILER UNIT ASSEMBLIES WITHOUT POSTWELD HEAT TREATMENT

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The paper considers repair welding of the damaged assemblies of boiler equipment at heat electric power stations and heat power plants made from heat-resistant steels of the Cr–Mo and Cr–Mo–V systems (collectors, heating surface pipes, T-joints, steam piping elements etc.), which exhausted their life under severe service conditions (at high temperature and pressure) that caused damages in metal mainly in the form of cracks. The technology recommended for repair of such damages involves manual arc welding using the 06Kh1M type electrodes combined with the 09Kh1MF type electrodes. It includes for the use of preliminary and concurrent heating with subsequent thermal recovery of a welded joint. Welded joints made by the suggested technology have high crack resistance and required mechanical properties. Present technology successfully passed the tests in repair welding of boiler equipment assemblies.

Keywords: *repair welding, damages, heat-resistant steels, assemblies of boiler equipment, electrodes, preheating, thermal recovery, extension of life time*

Extension of life time of power equipment for HEPS and HPP with exhausted equipment service life is possible after technical diagnostics and detection of operation damages as well as investigation of metal state (structure and properties). Elements of boiler equipment (heating surface pipes, superheaters, collectors, T-joints, stem piping elements etc.) are manufactured from heat-resistant Cr–Mo or Cr–Mo–V steels. Tables 1–3 [1, 2] show the main grades of steel as for application at operating temperatures, their chemical composition and mechanical properties.

Chromium, molybdenum and vanadium are the main alloying elements of these steels. Molybdenum as one of the main elements determining the steel heat resistance is mainly in a solid solution. It reduces a diffusion mobility of atoms and rate of dislocation movement. Certain content of molybdenum allows obtaining an optimum combination of strength and ductility of steel. Participation of molybdenum in carbide formation is limited at that. Chromium and vanadium carbides are formed at its presence. Vanadium makes a positive effect on increase of long-term strength and creep strength due to formation of heat-resistant carbides. Steels of Cr–Mo system were virtually completely replaced by steels of Cr–Mo–V system in the power units with 545 °C vapor operating temperature at manufacture of boiler equipment and pipelines of domestic HEPS. At the same time the damages caused by operational, technological and structural factors [1, 3] are formed in the boiler units manufactured from indicated steels in a process of long-term operation at high temperature.

Cracks of different type are the most typical damage for the welded joints from heat-resistant steels. Welding and surfacing are the main methods of repair of the damaged parts and assemblies of boiler units. Repair of the damaged parts has specific difficulties related with the necessity of work performance under working conditions of electric power stations. Development of progressive welding technologies as the main method for repair of power equipment is, therefore, an im-

Table 1. Heat-resistant steels used for seamless pipes of collectors and steam piping elements in boiler unit manufacture

Steel grade	Standard		Limiting maximum temperature, °C
	Pipes	Steel	
12MKh	TU 14-3-610–75	GOST 20072–74	530
15KhM	TU 14-3-460–75	TU 14-3-460–75	550
12Kh1MF			570
15Kh1M1F			570

Table 2. Chemical composition of heat-resistant steels of Cr–Mo and Cr–Mo–V systems, wt.%

Steel grade	C	Si	Mn	Cr	Mo	V	Ni	Cu	S	P
							Not more			
12MKh	0.09–0.16	0.17–0.37	0.40–0.70	0.40–0.70	0.40–0.60	–	–	–	–	–
15KhM	0.11–0.16	0.17–0.37	0.40–0.70	0.80–1.10	0.40–0.55	–	–	–	–	–
12Kh1MF	0.08–0.15	0.17–0.37	0.40–0.70	0.90–1.20	0.25–0.35	0.15–0.30	0.25	0.20	0.025	0.025
15Kh1M1F	0.10–0.16	0.17–0.37	0.40–0.70	1.10–1.40	0.90–1.10	0.20–0.35	0.25	0.25	0.025	0.025

Table 3. Mechanical properties of pipes from heat-resistant steels at 20 °C temperature [1]

Steel grade	Heat treatment, °C	σ_t, MPa	σ_y, MPa	δ, %	ψ, %	KCU, J/cm^2
			Not more			
12MKh	Normalization at 910–930 + tempering at 670–690	≥ 410	235	21	45	60
15KhM	Same at 930–960 + 680–730	450–650	240	21	50	60
12Kh1MF	Same at 950–980 + 720–750	450–650	280	21	55	60
15Kh1M1F	Same at 1020–1050 + 730–760	500–700	320	18	50	50

portant and relevant task for extension of life and secure operation of the boiler units of HEPS [4].

Welding of heat-resistant steels of Cr–Mo–V system are as a rule performed using preliminary and concurrent heating as well as postweld heat treatment (PWHT) of the welded joints. Application of welding methods without PWHT is highly perspective considering that performance of the heat treatment of repaired parts and assemblies is not always possible under HEPS conditions. The aim of the present paper in this connection is a development of repair welding technology without PWHT providing high crack resistance and required properties of the welded joints of boiler unit assemblies.

Activities preventing formation of cold cracks in the welded joints are one of the main conditions of repair welding technology. It is well known [5, 6] that combination of three factors, i.e. formation of hardening structures in HAZ or weld metal, content of diffusible hydrogen, and level of residual welding stresses in the welded joints promotes formation of the cold cracks (delayed fracture).

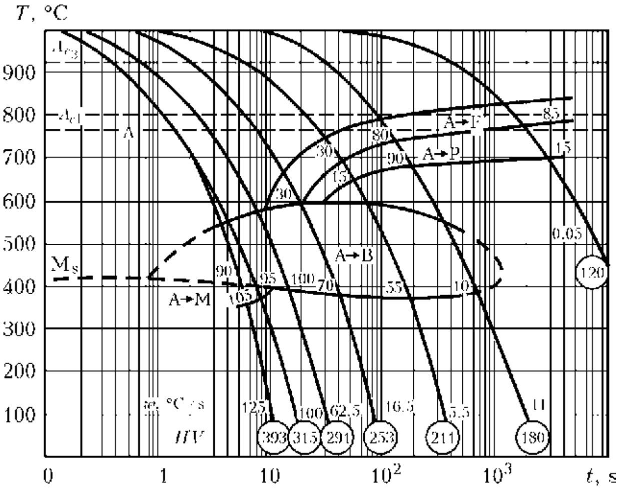

Figure 1. Thermal-kinetic diagram of austenite transformation in 12Kh1MF steel [3]

Selection of heat modes and welding conditions can provide absence of the hardening structures in the welded joint. This is achieved as a rule through application of the preliminary and concurrent heating, at which cooling rate will promote formation of HAZ metal structure stable to crack generation.

High sensitivity to cooling rates starting from austenite decay temperature (A_{c3}) is character for pearlite class heat-resistant steels. Therefore, influence of welding thermal cycle on structure and properties of widely used 12Kh1MF grade steel (Figure 1) under different welding conditions was investigated first of all. It can be seen from given diagram that austenite decay takes place in martensite area with 100 % martensite formation in 800–700 °C temperature interval at cooling rate more than 125 °C/s. Decrease of cooling rate results in formation of structures of intermediate transformation, i.e. bainite. Structure consisting of 30 % ferrite and 70 % bainite is formed already at 16.5 °C/s cooling rate. Thus, structures differing by sensitivity to delayed fracture and promoting obtaining of various mechanical properties of metal [7] can be obtained due to cooling rate regulation. Application of additional activities for regulation of process of welding zone cooling in a form of preliminary and

Table 4. Chemical composition and mechanical properties of metal of welded joints from steel of Cr–Mo–V system [3]

Electrode grade (type)	Chemical composition, wt.%						
	C	Si	Mn	S	P	Mo	Cr
				Not more			
TML-5 (E-06Kh1M) (for welding of root passes)	Requirements according to normative documents (weld metal)						
	0.065	0.025–0.40	0.5–0.7	0.025	0.025	0.45–0.60	0.55–0.80
	Actual values (weld metal)						
	0.044^{**}–0.05^{***}	0.25–0.34	0.56–0.70	0.017–0.021	0.021–0.020	0.51–0.50	0.69–0.72
TML-3U (09Kh1MF) (for groove filling)	Requirements according to normative documents (weld metal)						
	0.08–0.12	0.15–0.40	0.5–0.9	0.025	0.030	0.4–0.6	0.80–1.25
	Actual values (weld metal)						
	0.09	0.30	0.8	0.016	0.025	0.51	1.10

Table 4 (cont.)

Electrode grade (type)	Mechanical properties at 20 °C, not less				
	σ_t, MPa	σ_y, MPa	δ_5, %	ψ, %	*KCU*, J/cm^2
TML-5 (E-06Kh1M) (for welding of root passes)	Requirements according to normative documents (weld metal)				
	550	350	18	60	88
	Actual values (weld metal)				
	580	430	20	69	130^{****}
	Requirements according to normative documents (welded joint)				
	500	–	–	40	–
	Actual values (welded joint)*				
	490	–	16	–	78.5
TML-3U (09Kh1MF) (for groove filling)	Actual values (weld metal)				
	569	481	17	40	160

*Fracture place — base metal (12Kh1MF) at 6–8 mm from the fusion line. **Diameter of electrodes — 3.0 mm. ***Diameter of electrodes — 4.0 mm. ****61 J/cm^2 at −20 °C, 40 J/cm^2 at −40 °C.

concurrent heating or usage of welding providing autoheating of the joint allows, therefore, formation of metal structure resistant to crack generation.

Application of welding consumables providing chemical composition and weld metal structure close to the base metal [8] is necessary for obtaining of the required properties of the welded joints from heat-resistant steels in repair of elements of power equipment operating under temperature above 540 °C. Thus, TML-5 electrodes of E-06Kh1M type (GOST 9467–75) [8–12] were recommended and implemented for repair welding of cast parts of turbine case equipment from steels of Cr–Mo and Cr–Mo–V systems without PWHT. Table 4 shows chemical composition and mechanical properties of metal deposited using TML-5 grade electrodes. These electrodes provide high crack resistance and optimum combination of strength and ductile characteristics of the deposited metal of welded joints from Cr–Mo steels. Therefore, they are also useful for welding of root welds and facing of edges, and electrodes of TML-3U grade (09Kh1MF type) are used for further groove filling in repair welding of the joints from steels of Cr–Mo–V system.

Investigations on Implant method (method of inserts) [13] were carried out for evaluation of Cr–Mo–V system steel resistance to cold crack formation and determination of the necessary preheating temperature in repair welding using TML-3U electrodes. The maximum (critical) stresses in the samples before fracture start were the criterion of welded joint crack resistance. Significant attention at that was also dedicated to investigation of effect of postweld heating (recovery) on crack resistance of the welded joints.

Influence of the conditions of recovery performance on diffusible hydrogen content $[H]_{dif}$ in the deposited metal was preliminary studied.

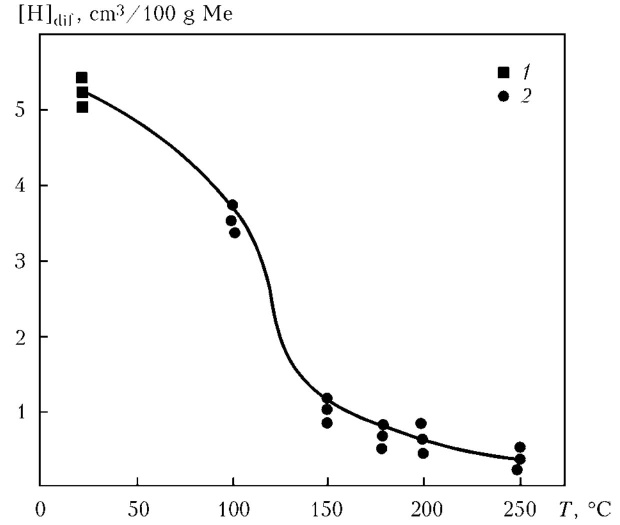

Figure 2. Dependence of content of diffusible hydrogen in deposited metal on heating temperature without recovery (*1*) and at 10 min recovery (*2*)

Considering that its content in the metal deposited using standard TML-3U electrodes has relatively low level (1.5–2.5 $cm^3/100$ g of metal based on alcohol test), evaluation of recovery effect on $[H]_{dif}$ content of initial higher concentration makes an interest. Pilot electrodes TML-3U were manufactured in this connection. Muscovite was specially included in their coating that provided increased concentration of the diffusible hydrogen. Concentration of $[H]_{dif}$ in the deposited metal made 5.3 $cm^3/100$ g of metal according to alcohol test after baking of the electrodes at 400 °C during 1.5 h. Holding of these samples of the deposited metal for 10 min at different recovery temperatures significantly reduces content of the diffusible hydrogen (Figure 2). $[H]_{dif} = 0.5$ $cm^3/100$ g in thermal recovery at 250 °C that promotes increase of crack resistance of the welded joints.

Heating of pilot joint using electric resistance heater was performed after sample-to-plate welding in testing on insert method for evaluation of recovery effect on crack resistance. Temperature was controlled using chromel-alumel thermocouples in welded-in condition. The samples were hold under load for 24 h. The investigations were performed by stages. Firstly, the joints welded without preheating was tested for evaluation of the level of critical stresses, exceeding of which results in development of delayed fracture. Further a cycle of testing were performed with application of thermal recovery under conditions of load stress, which exceeded the critical one, in order to confirm efficiency of present procedure and determine the parameters of recovery mode necessary for delayed fracture resistance to be provided.

Figure 3 shows results of testing of the welded joints without preheating and further thermal recovery. Investigations performed allowed determining that critical level of stresses makes approximately 150 MPa. The result of study of effect of the postweld recovery showed that the load stress of 200 MPa from a supercritical area does not lead to development of fractures as a result of weakened influence of hydrogen factor (see Figure 2). Therefore, further investigations were performed with load corresponding to 400 MPa stress for fracture initiation. Such a load promotes a fracture. Generalizing dependence was build based on given data (Figure 4) which determines correspondence between the temperature and recovery duration necessary for providing delayed fracture resistance. Present dependence can be a basis for selection of thermal recovery mode.

Thus, obtained results verify high efficiency of the postweld recovery for providing delayed fracture resistance of the welded joints. No phase transformations are observed at that, and favorable conditions are developed in order to remove diffusible hydrogen from the zone of welding [14, 15].

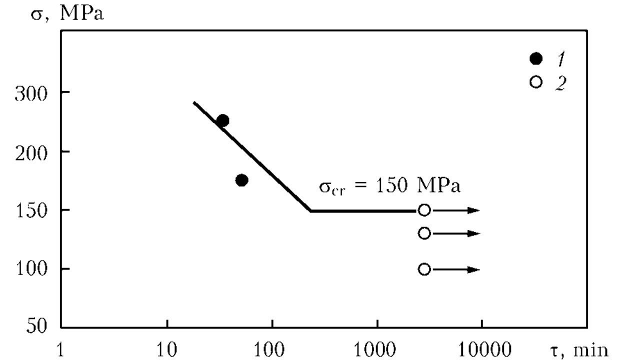

Figure 3. Effect of stresses on tendency of welded joints from 12Kh1MF steel to delayed fracture (*1*), and welded joints without fracture (*2*)

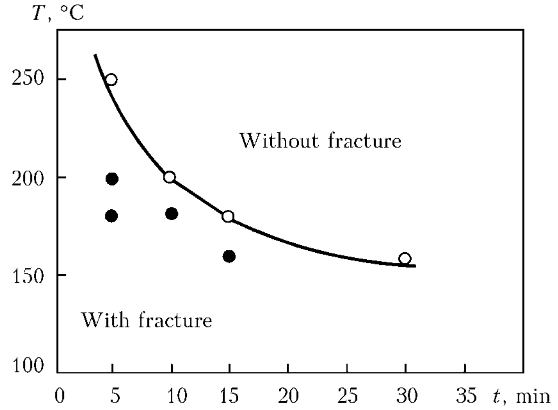

Figure 4. Influence of temperature and duration of thermal recovery on tendency of welded joints from 12Kh1MF steel to delayed fracture in load stress σ = 400 MPa

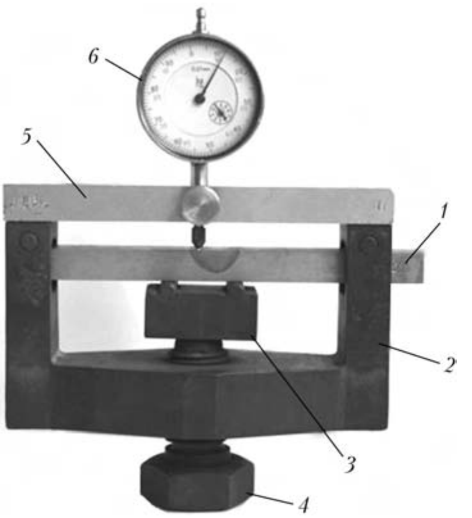

Figure 5. Scheme of device for loading of sample in relaxation tests: *1* — sample; *2* — welded base; *3* — support; *4* — loading screw; *5* — removable plate for indicator fastening; *6* — indicator

Since the level of residual welding stresses is one of the constituent factors determining welded joint cracking resistance, the investigations of influence of temperature of postweld heating (recovery and heat treatment) on a level of stress relaxation were performed. The investigations were carried out in accordance with a procedure proposed by OJSC «I.I. Polzunov SPA TsKT» [16]. The sample of the welded joint from 12Kh1MF steel of 12 × 14 × 210 mm size was set over a support of special device manufactured from heat-resistant nickel alloy, and load was applied up to obtaining specified stress in area of pure bending (Figure 5). The stress was measured depending on bending deflection *f* using an indicator being fastened over a removable plate. After loading and measurement of elastic bending deflection the device together with loaded sample was put in a furnace heated to specified temperature for defined time. The samples were cooled up to ambient temperature after holding in the furnace, and bending deflection *f* was repeatedly measured on them. Plastic strains in the samples and relaxation of the stresses depending on time of holding in the furnace at specified temperature and load were calculated on bending deflection differences. Figures 6 and 7 show the results of the investigations.

It was determined that thermal recovery of the studied samples independent on time of holding at 250–350 °C makes no influence on relaxation of the stresses. However, stress drop can be reduced up to 150 MPa level in the welded joint at operating temperature 545 °C. Such a tendency of the welded joints from steels of Cr–Mo–V system to relaxation at operating temperature provides a real possibility to apply only thermal recovery in a case when performance of postweld high-temperature tempering (730–750 °C) is difficult.

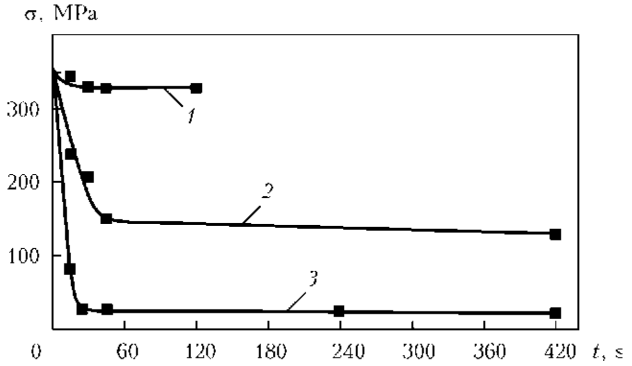

Figure 6. Dependence of stress relaxation in the welded joint samples on holding time and temperature of 250 (*1*), 545 (*2*) and 750 (*3*) °C

Further operation of the boiler unit at 545 °C operating temperature promotes significant relieve of the residual welding stresses. However, relaxation of the residual stresses at operating temperature is significantly lower than after high-temperature tempering (see Figure 6). Therefore, repaired assemblies of the boiler units without postweld high-temperature tempering can operate with limited life. Decision about further operation is made after performance of routine examination and technical diagnostics.

The results of performed investigations allowed considering a question about the possibility of repair without PWHT during welding-up of the damages in parts of boiler units at the place of operation. Collector of heater from 12Kh1MF steel with outer diameter 273 mm and wall thickness 36 mm was taken as an object of repair using proposed welding technology. Damage in a form of circular crack was formed as a result of stress raiser action (in the corner of root in a backing ring) and propagated along the weld and coarse-grain HAZ up to appearance on the surface. Preliminary evaluation of the proposed technology was carried out in order to take a

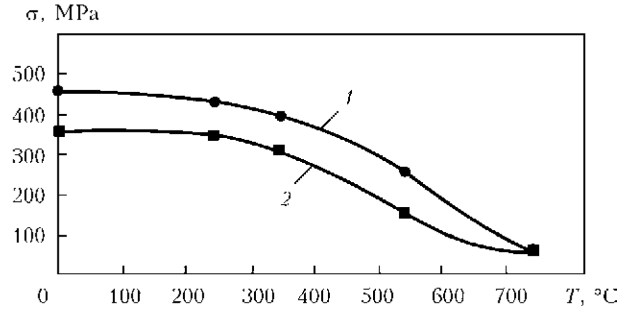

Figure 7. Dependence of stress relaxation on temperature in short-time loading ($\sigma = 0.8\sigma_y$) (*1*) and 60 min thermal recovery at $\sigma = 0.8\sigma_y$ (*2*)

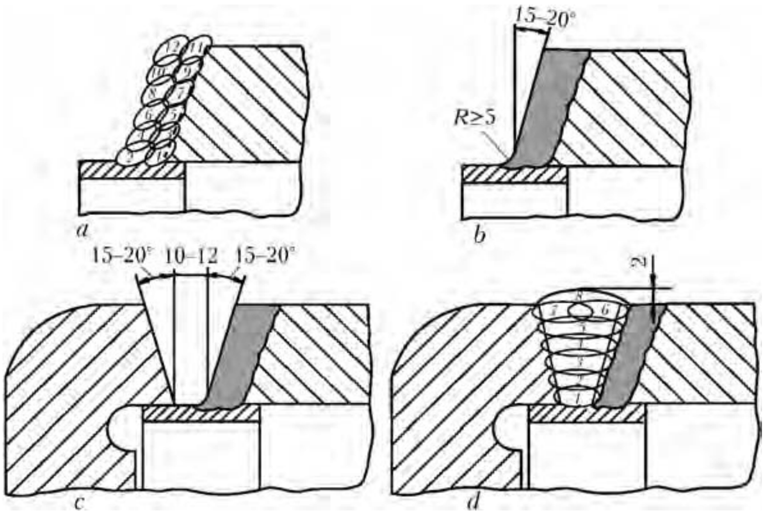

Figure 8. Scheme of order of collector repair performance: *a* — preliminary multilayer surfacing of collector end by circular beads with their successive performance; *b* — shape of groove after machining preliminary deposit; *c* — assembly for welding of bottom to collector joint; *d* — filling the groove by multilayer welding

technical decision about possibility of performance of repair welding without PWHT. Evaluation tests [17] were carried out on collector model with actual wall thickness. Magnetic particle testing of crack absence was carried out after machining end of the collector for preliminary surfacing of edge. The backing ring was tacked to the end edge from an outside with 250–300 °C preheating. Preliminary double layer surfacing of collector end (Figure 8, *a*) was carried out with 250–300 °C preheating by multilayer method using circular beads 4–5 mm thick and 15–20 mm width applying E-06Kh1M (TML-5) type electrodes. Electrodes of 3 mm diameter (I_w = 90–110 A) were used for the first layer, and electrodes of 4 mm diameter (I_w = 120–160 A) for the second one. After that the deposit surface was treated by an abrasive tool up to obtaining of the necessary size and shape of the edge (Figure 8, *b*) with quality evaluation using visual, ultrasonic and magnetic testing methods and hardness measurement. Than assembly of collector to bottom joint (Figure 8, *c*) over backing ring was carried out.

Preheating in the collector to bottom assembly and welding made 250–300 °C. The first two root welds were made using TML-5 electrodes of 3 mm diameter (I_w = 90–120 A). They allow obtaining more ductile deposited metal due to low content of carbon and chromium as well as absence of vanadium. This prevents possibility of lamellar tearing formation in the weld root and provides high crack resistance of the welded joints. TML-3U 4 mm electrodes (I_w = 130–180 A) were used for further groove filling (Figure 8, *d*). Complete thermal recovery of the welded joint at 250 °C during 2.5 h was performed immediately after welding for evacuation of diffusible hydrogen and increase of crack resistance. Slow cooling of zone of repair welding up to 50–70 °C was carried out after thermal recovery by means of wrapping of the repair place by asbestos cloth. Then outer surface of the circular weld was mechanically treated up to obtaining of the joint of required shape (see Figure 8, *d*). Non-destructive quality testing was the final stage. Visual and ultrasonic testing, and surface etching with 15 % solution of nitric acid were used for detection of surface defects in evaluation of repair quality. Performed testing of quality of evaluated joint showed no defects in the welded joint.

Investigations of the mechanical properties showed that tensile strength of the welded joint was in the limits of 490–560 MPa in tensile testing of the samples, and impact toughness of the deposited metal made 120–160 J/cm^2 that corresponds to the requirements to the base metal of this steel (σ_t = 440–588 MPa and $a_n \geq 98$ J/cm^2).

Carried out metallographic investigations of marco- and microstructure determined no defects in the weld metal and HAZ. Hardness of the weld metal makes *HB* 180 at allowable values of reduction of medium hardness up to *HB* 140 and increase not more than *HB* 270 for 12Kh1MF steel.

Thus, positive results were obtained after performed evaluation tests of repair welding of collector from 12Kh1MF steel using developed technology. This allowed making the technical decision and recommending the proposed technology of repair welding for the collector from 12Kh1MF steel.

CONCLUSIONS

1. Technology of repair welding of standard heat-resistant steel 12Kh1MF being widely used in manufacture of the boiler units of HEPS and HPP was developed and its weldability was investigated.

2. Preliminary and concurrent heating together with postweld low-temperature recovery can be used for repair of damaged assemblies and parts of the boiler units from heat-resistant steels in acting HEPS and HPP in the case when performance of high-temperature tempering is impossible. Further running at operating temperature 545 °C promotes reduction of the residual welding stresses (up to the level of around 150 MPa) that allows extending resource of the repaired boiler unit for limited period up to the next examination.

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MODERN METHODS OF SURFACING THE TOOLS OF AGRICULTURAL TILLERS AND HARVESTERS

(Review)

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It is shown that application of induction surfacing is the most promising for flat parts of agricultural machinery with wall (BM) thickness of 2.0–6.0 mm and deposited metal (DM) thickness of 0.8–2.0 mm. In this case, minimum mixing of BM and DM, minimum equipment cost, possibility of mechanization and automation are provided.

Keywords: *surfacing processes, electric contact strengthening, agricultural machinery tools, thin parts, induction surfacing, automation*

Thin flat parts are widely applied in agriculture as tools of tilling and harvesting machinery, namely: plough shares, cultivator hoes, skim plough discs, shredder knives, etc. which operate under the conditions of abrasive wear and considerable static and dynamic loads. These parts should have high strength and wear resistance [1–4]. However, during operation the metal continuously contacts the soil and plants that, in its turn, leads to blade blunting. To ensure the cutting properties, the tools should sharpen themselves during operation. Bimetal (two-layer) working parts are the most suitable for these conditions. Their strength is ensured by base material from which the tool is made, and wear resistance and self-sharpening are provided by