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RESTORATION OF WORN HELICAL COARSE PITCH GEARS BY ELECTROSLAG CLADDING

S.M. Kozulin[1], **I.I. Lychko**[1], **S.S. Kovalchuk**[1], **G.S. Podyma**[2] and **M.V. Lazarchuk**[2]
[1]E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua
[2]National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute»
6/2 Dashavska Str., 03506, Kyiv, Ukraine. E-mail: meganom8@ukr.net

The paper presents the results of experimental studies performed with the aim of development of a high-efficient technology, equipment and special technological fixtures for restoration of worn teeth of coarse pitch helical gears by electroslag cladding (ESC). The main objectives of the work were development of the design and method of fabrication of a special water-cooled forming fixture, establishing ESC modes that guarantee fusion of the filler with the base metal, as well as sound formation of the working surfaces of clad teeth; adaptation of the assemblies of batch-produced machine A-535 UKhL4 with TShS 1000-3 power source to perform consumable-nozzle ESC by 3 mm electrode wire using AN-8 and AN-9U fused fluxes; restoration of a test-standard helical gear and evaluation of its serviceability. The level of specific heat input providing a sound teeth restoration was established; welding consumables were selected to provide the required chemical composition and service characterisitcs of the clad metal. A special shop section for restoration of the teeth of coarse pitch gears was set up at repair-mechanical plant of TPA «Bratsk TIC», where a gear wheel was restored using ESC and sent for performance tests. Operation experience showed that the restored gear wheel has good running smoothness and teeth resistance under the conditions of alternating and contact loads, arising at operation of the dedebarking drum. Teeth wear on the level of the generating circle is not more than 3–5 mm. 10 Ref., 1 Table, 8 Figures.

Keywords: restoration, helical coarse pitch gears, wear, electroslag cladding, consumable nozzle, specific heat input, forming fixture, cladding machine, heat treatment, residual deformations, performance tests

Restoration of machine parts and mechanisms prone to natural or accidental wear during operation is an important means of saving material and labor resources. Restorative cladding in many industries has become a separate branch of welding production and is widely used for the needs of the national economy [1].

It has a particular importance in repair of large-sized, weighty and expensive parts of machines and technological equipment of import production.

Currently, in the mining, metallurgical, wood-working, power and other industries, a large fleet of import production equipment is operated, in the drive mechanisms of which coarse pitch helical gears, ring gears and wheels are used, which operate in the conditions of considerable alternating loads and abrasive wear.

Most of them do not work out the regulated life as a result of a premature wear of involute and pitch profiles of teath to 60 %, and also in case of their breakdowns, arising in the course of operation that inevitably leads to downtimes of the equipment operating round the clock, and the need to purchase spare parts by import.

Manufacturing practice shows that in many cases scientifically based technology and organization of restoration of defective parts generally allow achieving the normative development of technology, and in some cases even surpassing the development of new products [1, 2].

Today in Ukraine and abroad most of these worn or damaged parts, the mass of defective elements of which does not exceed 3–5 % of their total mass, are sent to scrap, which in our opinion is absolutely irrational from technical and economical pont of view.

The existing methods of restoration of teeth of coarse pitch gears using multipass electric arc cladding with coated electrodes, applying mechanized process in a shielding gas and submerged automatic one were not widely used due to a low process efficiency, unguaranteed quality of fusion of the filler material with the base one, risk of the formation of interlayer defects in the form of nonmetallic inclusions, pores, cracks, chipping of active surfaces of teeth, etc. (Figure 1).

In this regard, the development of new high-efficient methods of restoring worn teeth of coarse pitch

S.M. Kozulin — https://orcid.org/0000-0002-8368-4545, I.I. Lychko — https://orcid.org/0000-0002-4977-7473,
S.S. Kovalchuk — https://orcid.org/0000-0002-1247-6917, G.S. Podyma — https://orcid.org/0000-0002-0825-3235,
M.V. Lazarchuk — https://orcid.org/0000-0001-6192-6825

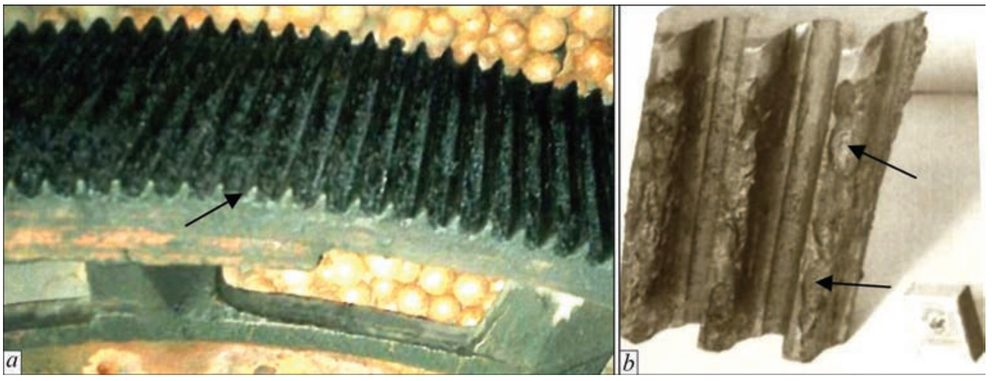

Figure 1. Typical wear of teeth of helical crown of the drive of the ore-pulverizing mill (*a*) and an example of chipping the teeth of the helical gear wheel of the drive of the debarking drum after their cladding with coated electrodes (*b*)

gears in order to extend their service life is a very important task.

Electroslag cladding (ESC) has the greatest technical possibilities for increase of efficiency and quality of repair works, which has found a wide application sized in restoration of large-sized parts of the machines which are operated in heavy, metallurgical, power, cement and in other industries [3–5]. The main advantage of ESC is the ability to perform cladding of metal layers of different profiles of almost unlimited size in one pass while providing a sufficiently high accuracy of geometric dimensions of restoration elements.

It is known about the examples of successful use of ESC in the restoration of several broken teeth (module 36) of the chevron gear of the crank press [2], as well as the teeth of the girth gear pinion (module 40) of the rotary annealing furnace, defects in which (thinning of the profile and dip of through) at the final stage of its manufacture [6]. After the completion of the restoration works by the technical control departments of the plants, the gears were recognized as serviceable and installed in the drive mechanisms, where they operated successfully until the end of the standard service life. It is also known about the experience in the use of ESC for restoration of teeth (module 20) of worn-out girth gear pinions of ball mills for coal grinding [2]. However, the information on the examples of restoration of helical coarse pitch gears by ESC is absent. The main problem of their restoration is the design features of these products, namely the helical nature of the arrangement of the surfaces of tips and troughs of the teeth [7], which significantly complicates the designing and manufacture of the forming fixture, as well as the technique of ESC.

The aim of the work is to develop high-efficient technology, equipment and special technological fixtures for restoration of worn teeth of coarse pitch helical gears using ESC.

To achieve this aim it was necessary to perform the following set of investigations of analytical and practical nature:

- development of design and method of manufacturing special water-cooled forming fixture;
- performance of laboratory experimental studies with the aim of searching modes and technics of performance of ESC providing the guaranteed fusion of filler metal with the base one, and also qualitative formation of working surfaces of deposided teeth;
- testing the technique of the starting of ESC process using the method of a «liquid start»;
- adaptation of units of the serial device A-535 UKhL4 with the power source TShS 1000-3 for performance of ESC by a fusible mouthpiece by the electrode wire of 3 mm diameter with use of fused fluxes of AN-8 and AN-9U;
- development of the design of the cladding machine and device for producing liquid flux;
- restoration of the experimental-standard helical gear ESC;
- evaluation of the fitness for service of the restored gear according to the results of operational tests.

The procedure of research works provided:

- choice of welding materials to obtain the chemical composition of the clad metal, which provides equal strength of the joints to base metal, required hardness and ductility and absence of hardening structures;
- spectral analysis of clad metal, prodution and study of cross macrosections of clad joints;
- quality control of clad joints using a portable ultrasonic flaw detector UD2-12;
- determination of hardness of the clad teeth using a portable dynamic hardness tester TEMP-2;
- development of the mode and carrying out of the general heat treatment of the restored gear;
- measurements of residual deformations of the restored gear using the caliper ShTs-III-2000-0.1 (ISO 3599–76).

In the manufacture of special technological equipment, the most critical and time-consuming units are devices that provide reliable maintenance of slag and metal pools, necessary geometric parameters of the restored teeth and high-quality formation of external (operating) surfaces of the clad metal. The design of the forming device is influenced by geometric parameters of the teeth and the nature of their restoration, namely: single cases of ESC of individual broken teeth or recladding of all worn teeth, use of stationary installation or temporary applications for repair in site conditions, etc.

For restoration of worn teeth of the drive helical gears of a debarking drum (tooth module is 18, number of teeth is 88, inclination angle of teeth is 15°, external diameter is 1676 mm, weight is 1250 kg, material is steel SIS 1650, manufacturer — Vaplan Company, Sweden), the design of a forming device was developed. The device consists of water-cooled mold, bottom plate, inlet and outlet technological tabs. The mold represents an all-copper product, in which cavities are formed that exactly repeat the original profile of the teeth and have a desired inclination from the vertical. To cool the working surfaces in the body of the mold the holes were drilled for water flow. The design of the mold allows using one of the cavities as a crown, mounting it on previously clad teeth. This allows reducing the pitch error of restored teeth. Technological tabs are designed to provide the guaranteed fusion of filler metal with the edge, which is clad in the initial area, as well as bringing the slag pool and shrinkage cavity outside the clad edge at the completion of cladding the tooth. To provide a reliable start of cladding process using the method of «liquid start» [3], a water-cooled bottom plate is used, in the body of which the grooves are present, that serve as channels for transporting liquid flux into the working cavity [8]. Filling of liquid flux is carried out in a siphon way, using the funnel made of heat-resistant steel.

Taking into account the helical (deployable helicoid) nature of the location of the surfaces of the tips and troughs of the teeth in helical gears [5], at the stage of the process of the mold manufacturing there were some difficulties. For manufacture of the developed design it was necessary to use a unique gear milling or coordinate boring machine. Due to the fact that such machines are not always available as they are available only in large machine-building plants, an alternative method of mold manufacturing was proposed, which is as follows. A rectangular box was made of rolled steel, which was mounted and fixed on the sector of a helical wheel with unworn teeth. On the inner surface of the mold a refractory coating was deposited. The required amount of copper scrap was melted in an induction furnace and after heating the mold to 200 °C, the molten copper was poured. To eliminate pores and cracks, molten copper was deoxidized with phosphorous copper MF9. Small surface cavities were clad using coated electrodes ANTs-3M. Then, in the casting holes were drilled for the flow of cooling water and fittings were welded-in for its supply and drainage. After testing the cooling system at a water pressure of 5 atm the mold was admitted to be fit for operation.

Testing of the ESC modes providing the guaranteed fusion of filler metal with the base one and quality formation of working surfaces of the clad teeth was carried out by a number of experimental cladding on full-scale specimens.

The parameters of the ESC mode were calculated taking into account the previously obtained dependences for the restoration of the teeth of modules 22 and higher [9]. For an approximate calculation of the required specific input energy of ESC (E_w) the efficiency factor of the process (η) was experimentally determined. Taken into account the fact that the width of the cladding edge amounts to not more than 45 % from the perimeter of the working profile of the mold, heat losses from the radiation of the slag pool were decided to be neglected. The amount of heat removed by the cooling water in the walls of the mold was determined using the known equation (1), measuring the flow of water and its temperature at the inlet and outlet of the mold:

$$Q_w = G_w(T - T_0), \qquad (1)$$

where G_w is the water consumption, g/s; T_0 and T is the temperature of the water at the inlet and outlet of the mold, respectively, °C.

Measurements showed that the amount of heat extracted by the cooling system of the mold is 19.8 kJ/s, and the heat released in the slag-metal pool is 30.6 kJ/s. Therefore, the value of the efficiency value of the process was taken as $\eta = 0.35$. Such a small value of η, in contrast to the experience of ESC of coarse teeth can be explained by a significantly larger area of the clad surface of the profile relative to the size of the base metal (tooth root). The specific input energy of the process E_w was determined from the expression (2):

$$E_w = \frac{IU\eta}{2.3V_c m}, \qquad (2)$$

where I is the cladding current, A; U is the cladding voltage; η is the efficiency factor of the process; V_c is the cladding speed, cm/s; m is the tooth module, cm.

The calculated value of E_w for ESC of teeth of the module 18 (tooth height is 40.5 mm) amounted to 117.3 kJ/cm^2. However, the process of cladding on the calculated E_w including the vertical position of the working cavity of the mold, was characterized by an insufficient constancy. In addition, defects were

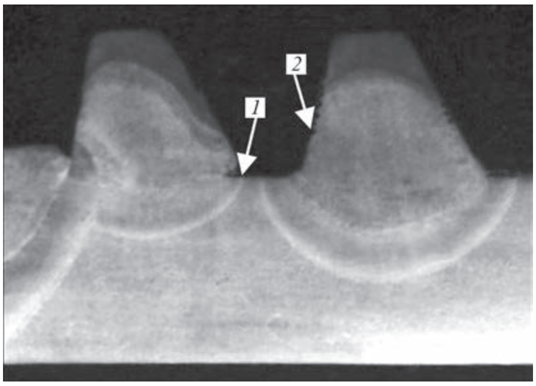

Figure 2. Cross macrosection of teeth (module 18) with defects (shown by arrows): *1* — nonfusion in the transition curve; *2* — corrugations on the working surface of the tooth

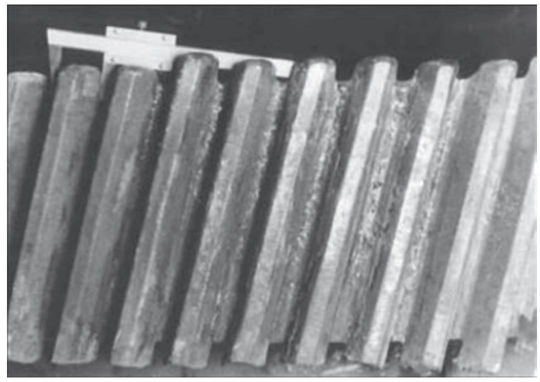

Figure 3. Appearance of clad teeth

detected in the form of nonfusion in the transitional dumbbells of teeth roots, as well as corrugations on the clad surface (Figure 2).

The mentioned problems of insufficient stability of the electroslag process and the quality of the clad metal are caused by a relatively small size of the cladding zone, including significant dimensions of the cooled forming surface (for the canonical electroslag process). Increasing the stability of the process and eliminating the mentioned defects was carried out by correcting the parameters of the mode and a significant reduction in heat removal in the walls of the mold. It was established that at E_w = 123 kJ/cm^2 and depth of a slag pool of 30–35 mm, a satisfactory quality of fusion of the clad metal with the base one and the formation of an external surface of teeth is provided. In this case, performing the ECS with a deviation from the vertical does not affect the quality of the alloy and the formation of the clad metal (admissible deviation is 15°) [10]. However, in the process of ESC, a periodic appearance of arc discharge between the mouthpiece and the walls of the mold was observed, which can lead to a violation of the stability of the process. Therefore, the flux AN-8 was replaced by AN-9U, which has a reduced content of SiO_2, which facilitates an increase in the temperature of the beginning of its boiling and improves the stability of ESC [9]. The flux AN-9U allows providing a long-term ESC process at a higher voltage, which is necessary to guarantee a reliable fusion of the filler metal with the base and a high-quality formation of the clad metal. A lower viscosity of the flux AN-9U (achieved by increasing the content of CaF_2, as well as the introduction of ZrO_2) as compared to the flux AN-8 allows obtaining a thinner skull crust [9], which is necessary to increase the accuracy of geometric parameters of the restored profiles. To reduce the level of heat removal in the working cavity of the mold from its cooling system excluded a part of the channels for the flow of water.

After taking these measures and correcting the parameters of the mode, it was possible to provide satisfactory stability of the ESC process, good quality of fusion and formation of the clad metal (Figure 3).

The choice of electrode consumables (cladding wire, plates and channels of the fusible nozzle) was carried out taking into account the technological strength of the joint, high impact toughness and sufficient hardness of the clad metal. Since steel SIS 1650 (analogue is steel 45 DSTU 7809:2015), from which a gear wheel is made, belongs to the hard-to-weld class. To avoid the appearance of hot cracks, it was proposed to reduce the carbon content in the clad metal, as well as preliminary and acompanying heating of a gear wheel (150–300 °C). Preservation of the required mechanical properties of the clad metal was achieved by alloying it by adding chromium (about 1%) and silicon (more than 0.8–1.0 %). The table shows the chemical compositions of the base and clad metals.

The hardness of the base metal was *HV* 190–207, and the hardness of the clad metal was *HV* 220–240, which confirmed the correctness of the chosen method.

To provide a reliable start of the ESC process and shorten the cladding time at a large number of teeth, requiring restoration, it was proposed to use the method of a «liquid start» [2]. For this purpose, a design

Chemical composition of base and clad metal

Steel grade	Mass fraction of elements, %								
	C	Si	Mn	Ni	P	S	Cr	Cu	As
SIS 1650	0.42–0.50	0.15–0.40	0.68–0.90	–	0.03	0.03–0.05	–	–	–
45 DSTU 7809:2015	0.42–0.50	0.17–0.37	0.50–0.80	0	Up to 0.0 Up to 0.335	Up to 0.04	Up to 0.25	Up to 0.30	Up to 0.08
Clad metal	0.23	1.09	0.85	0.13	0.022	0.023	0.98	–	–

was developed and a separate autonomous device was manufactured for melting the flux and maintaining it for a long time in the liquid state (Figure 4).

The required dose of a liquid slag was poured through the siphon funnel of the forming device, after which the feed of welded wire was switched, providing a stable start of the ESC process. After the start of the ESC of each tooth, the current and voltage on the flux melting device (Figure 4) were reduced by 30–40 % (regular mode), constantly maintaining the flux in the molten state. The use of such a device allowed not only reducing the time of cladding, assembly and preparatory works, but also saving the cost of the flux by remelting its hardened pieces, selected from the siphon funnel and the water-cooled bottom plate. The efficiency of restoration of worn gear wheels depends on a number of technical factors: the level of mechanization of preparatory and adjusting operations, the standard size of restored teeth, and also quantity of simultaneously clad teeth, etc. When using multielectrode devices, it is possible to perform cladding of four or more teeth simultaneously.

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To realize the technology of restorative repair on the basis of the serial device A-535 UKhL4 with the power source TShS 1000-3, a specialized installation

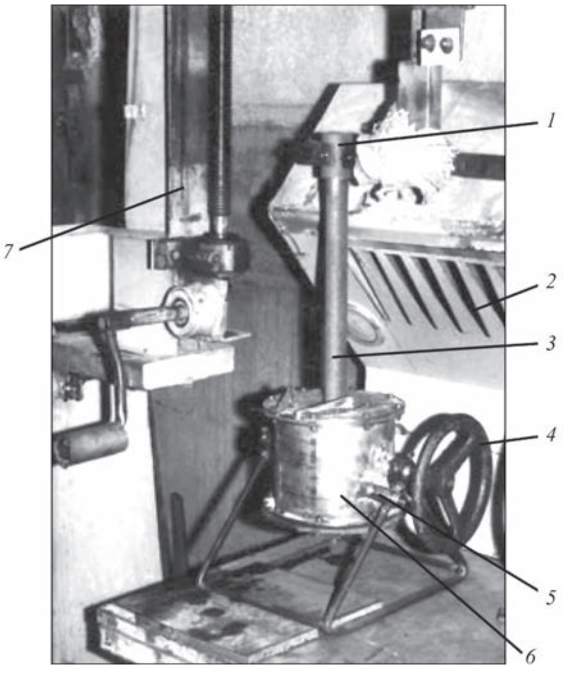

Figure 4. Device for melting welded flux: *1* — electrode holder: *2* — fume exhaust system; *3* — graphite electrode; *4* — steering wheel; *5* — stopper; *6* — lined crucible; *7* — mechanism for electrode movement

for ESC of teeth of helical coarse pitch gears was developed (Figure 5). In the presence of the welding machine, the installation can be formed from the completing mechanisms and the fixture which is more or less available, or it is possible to produce at each industrial enterprise.

The gear wheel *1*, prepared to restoration, is fixed on the faceplate of the welded manipulator *2*. On the rail column *10* of the machine, a suspension mecha-

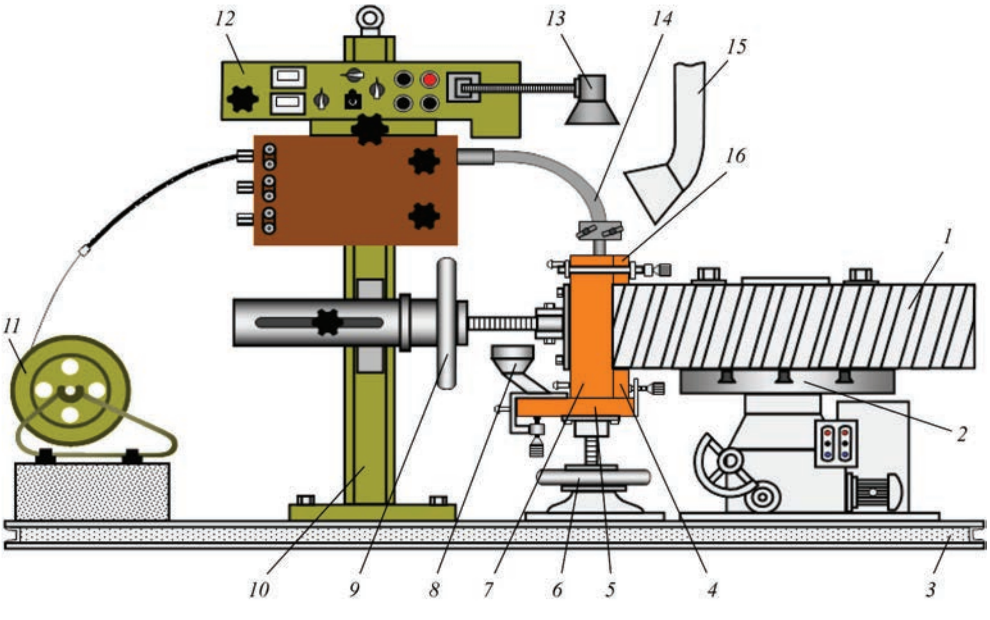

Figure 5. Scheme of installation for restoration of teeth of helical coarse pitch gear wheels by electroslag cladding: *1* — restored gear wheel; *2* — welded manipulator M1; *3* — floor plates; *4* — input technological strap; *5*—– water-cooled bottom plate; *6* — device for movement and fixation of bottom plate; *7* — mold; *8* — siphon funnel; *9* — mechanism for suspension and movement of the mold; *10* — rail column; *11* — coil with electrode wire; *12* — machine A-535; *13* — lamp of illumination of cladding zone; *14* — special nozzle; *15* — fume exhaust system; *16* — initial technological strap

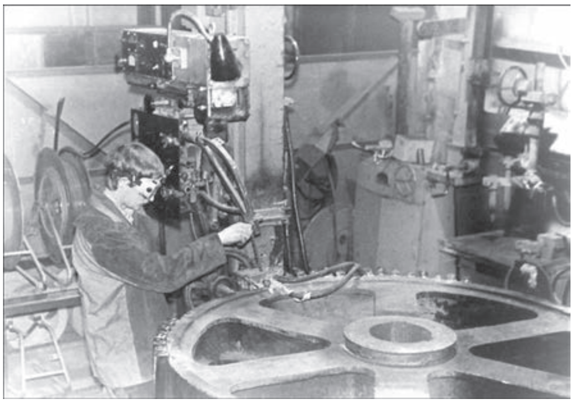

Figure 6. Fragment of ESC of teeth (m = 18, z = 88, β = 15 °) of the drive wheel of the debarking drum

nism *9* of the mold *7* is installed, by means of which the latter has the ability to move to the cladding zone and clamp to a product with a necessary force. The water-cooled bottom plate *5* is fixed on the device *6*, by means of which its movement and clamping to the lower end of the mold and the input process strap *4* are performed. In order to use the wire machine *13* to perform ESC using consumable nozzle, a special mouthpiece is provided: a reliable fastening of an inexhaustible part of consumable nozzles, electrode wire feed and welding current supply. For additional illumination of a cladding zone during assembly operations on the control panel of the device the lamp *13* was installed. For preliminary and accompanying heating of the restored gear wheels three air-propane torches were mounted.

This project of machine was used during the organization of a specialized area for the restoration of teeth of coarse pitch gears and wheel gears of debarking drums at one of the repair and mechanical plants (JSC Bratsky LPK)*. Before the start of the repair works, the worn teeth were removed mechanically, leaving a part of the unworn teeth roots, which were subjected to input (100 %) ultrasonic quality testing

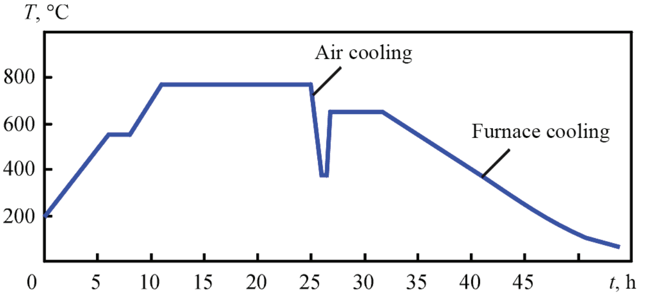

Figure 7. Heat treatment mode of the renewed gear wheel

of the metal. The main attention was paid to the detection of fatigue cracks [2, 10]. After that, the workpiece was mounted on the welded manipulator and by means of rotating the faceplate, it was preheated to 180–250 °C with air-propane torches. In order to reduce the residual deformations, the teeth cladding, was performed in a scattered way, i.e. in diametrically located sectors of the wheel (Figure 6).

Reduction of the shrinkage cavity and the size of the discard head in the original pocket 16 (Figure 5) was carried out applying the method of infeed [6]. The duration of cladding of one tooth was 22–24 min, and assembly and preparatory operations between claddings lasted 15–25 min. In the process of performing cladding, the accompanying heating of the gear wheel rim was carried out. Upon completion of ESC of all teeth, the gear wheel was subjected to general heat treatment according to the mode — normalization plus high tempering (Figure 7). Heat treatment was carried out in the electric furnace with a rolled out bottom plate. Figure 8 shows the appearance of the restored gear wheel: after heat treatment (*a*) mounted in the rotation drive of the debarking drum (*b*) after mechanical treatment of the clad teeth.

The first restored gear wheel was mounted in the sawing and debarking shop of OJSC «Bratsktselluloza» in the drive of the first section of the debarking drum No.3 (Figure 8, *b*) for the continuous operation

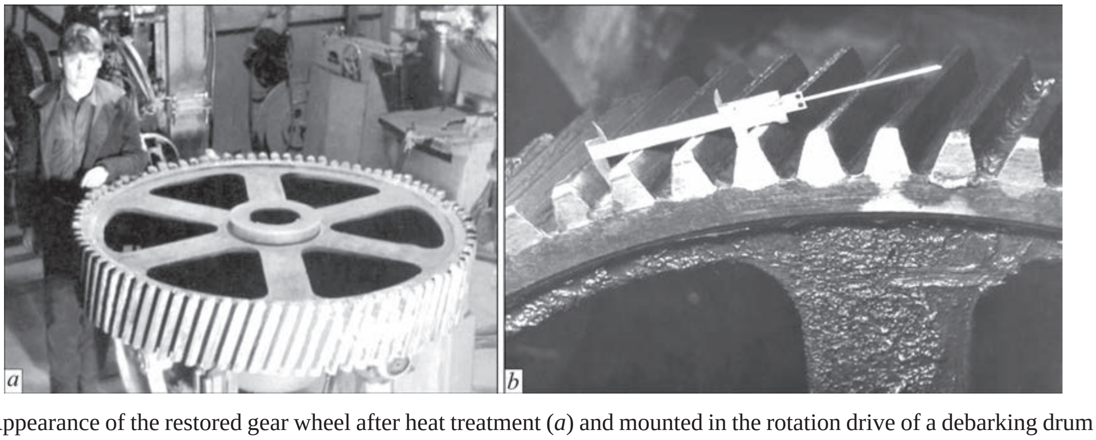

Figure 8. Appearance of the restored gear wheel after heat treatment (*a*) and mounted in the rotation drive of a debarking drum (*b*) after mechanical treatment of the clad teeth (*b*)

*In the work participated: G.M. Lapyga, A.I. Imshenetskyi, V.Ya. Tsybulenko, V.G. Tyukalov, A.P. Bordovskyi, A.M. Belezov et al.

at the working loading of the drum. The rotation speed of the drum is 5 rpm and of the restored gear wheel it is 22 rpm. The analysis of three-year operation showed that the restored gear wheel has good smoothness and stability of the teeth in the conditions of alternating and contact loads arising during the operation of the drum. The working surface of the clad teeth is smooth, without burrs. Fractures or local tooth chipping were not detected. The wear of teeth at the level of the generating circle is not more than 3–5 mm. Measurements of residual deformations of the restored gear wheel revealed that the ellipse around the diameter of the troughs is not more than 0.5–0.8 mm, and the taper around the generatrix with an outer diameter of 1676 mm is not more than 2.4–2.6 mm.

Conclusions

1. High-efficient technology, equipment and special technological fixture for restoration of worn teeth of coarse pitch helical gears by ESC were developed.

2. The service life of the repaired gear wheel exceeds the actual service life of the new gear wheels until they are completely worn out, as well as restored ones with the use of electric arc cladding methods.

3. The organized area has a certain versatility, as other repair works can be performed on it, such as electroslag cladding of rotating bodies, electroslag welding of destroyed products with a thickness of 40–350 mm, electroslag remelting of wastes of a cutting tool, etc.

4. Application of the developed technology allows prolonging service life of coarse expensive gear wheels and accordingly reducing purchases of these products by import.

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JUNE 24, 1924 The English experimental all-welded self-propelled barge «Fullagar» with a length of 46 m and a displacement of 398 tons slammed into the rocks, but, despite deformation of the bottom, it remained afloat. The vessel was designed by J.S. Goodwin. He took into account all the features of welding, including welding stresses, which were reduced due to holes in gussets and floors. The hull of the vessel was assembled according to the old method: by bolts, which were removed after welding, and the holes were rewelded. The commission came to the conclusion that a riveted vessel with such damages would have sunk, and the mark «experimental» was removed. Namely this event was widely publicized and made welding to be a popular technology in shipbuilding.

JUNE 25, 1919 The first flight of the aircraft «Junkers F-13» took place. That was the first in the world all-metal transport aircraft, designed in Germany at the end of the World War I. Among the several options, a scheme of a monoplane with a low wing was adopted for the further development. This scheme has become a classic one for the most subsequent airliners. The design of «Junkers F-13» was based on welded duralumin pipes, covered with corrugated duralumin lining. This created a very strong structure. The plane was easy in maintenance and could be equipped with wheels, skis or floats for landing on the water. The airliner was on service in all the continents and in all the climatic zones.

JUNE 28, 1935 One of the patents for welding of «Pullman-Standard Car Manufacturing» (USA) was registered. Back in 1929, the company received quite satisfied results in arc welding of thin armor plates, and in 1931 an all-welded armored vehicle was designed and manufactured there. In February of 1933, the first armored train left the workshop of the same company.

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