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REPAIR WELDING OF GEAR SHAFTS OF SERVICE ROLLERS AT THE ŽELEZARA SMEDEREVO

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Abstract: *Presented in this paper are two methods for repair welding of a total of 8 gear shafts (toothed shafts) of service rollers in the "Topla valjaonica" rolling mill within Železara Smederevo. Damage that occurs in these shafts is a consequence of exploitation conditions, which lead to lateral wear of the tooth up to one half of its thickness, due to adhesion and surface fatigue. Shown in the following text are the procedures for repair welding of gear shafts, including manual arc welding (MAW procedure) and the automatic welding procedure (FCAW). In addition, the requirements that need to be fulfilled in order to successfully perform the repair welding, so that the repaired pars can be exploited again, are presented. The techno-economical analysis had confirmed the technological and economical justifiability of applying this repair welding methods, compared to purchasing of new parts.*

Key words: *repair welding, gear shaft, wear, techno-economical analysis*

1. INTRODUCTION

Material loss represents one of the main causes for applying of repair weld procedures. In the case of contact between two or more coupled machine parts, the following mechanisms of material loss can be distinguished: wear, abrasion, erosion. Damages caused by these mechanisms occur on the machine part surface. In addition to these damages, machine part damage can occur along the volume, due to material fatigue [1-4], usually caused by dynamic loads.

In order to make the proper decision about the need for repair welding and the corresponding procedure, it is necessary to develop the requirements and algorithm of the repair welding technology [5, 6]. Each technological procedure for repair welding of a machine part has its own specificities. The general algorithm for repairing of machine parts consists from a series of activities, which should be performed in the following order: disassembling, specimen cleaning, damage analysis, selection of the repair method, techno-economical analysis, development of technical documentation, development of the technological procedure, specimen preparation, repairing, tests and control, machining to the final dimensions, assembly, running in of the repaired parts.

Shafts made coupled with the gear, i.e. toothed shafts, are typically manufactured from materials used for the manufacturing of gears. These materials include cementation steel or enhanced materials, in accordance with the technical requirements. Finishing of the teeth is performed by milling or grinding, whereas other functional surfaces are always finished by grinding. In addition, shafts to which toothed elements are attached are made of high quality enhanced materials. Shaft samples are made of forgings or rolled material. The model of one such toothed shaft is shown in Figure 1.

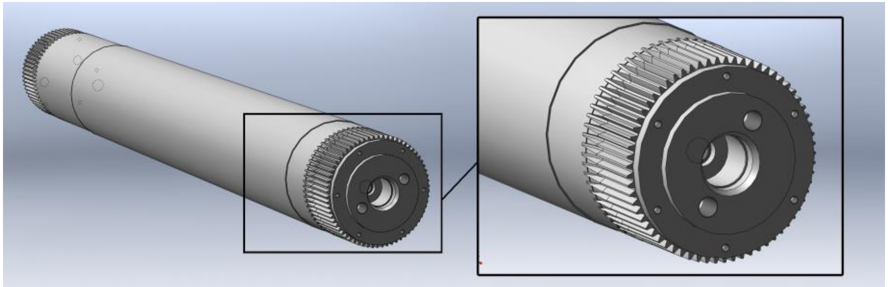

Fig.1: Model of gear shaft

Presented in this paper is the welding technology used on eight toothed shafts, i.e. the repairing of damaged teeth of driving shafts. Damage was caused by the exploitation conditions, and were reflected in form of worn teeth along the lateral profile, until one half of the thickness, due to adhesion and surface fatigue, which affects the connection between the shaft and the coupling. These gear shafts are parts of service rollers of "Topla valjaonica" rolling mill within Železara Smederevo. Železara Smederevo has 6 facilities with 2 service rollers and 2 support rollers. These driving shafts were manufactured by the German company "Siemag". During exploitation, gear shafts were subjected to variable loads and difficult working conditions at elevated temperatures. In Figure 2, the appearance of the teeth after exploitation and their damage can be seen.

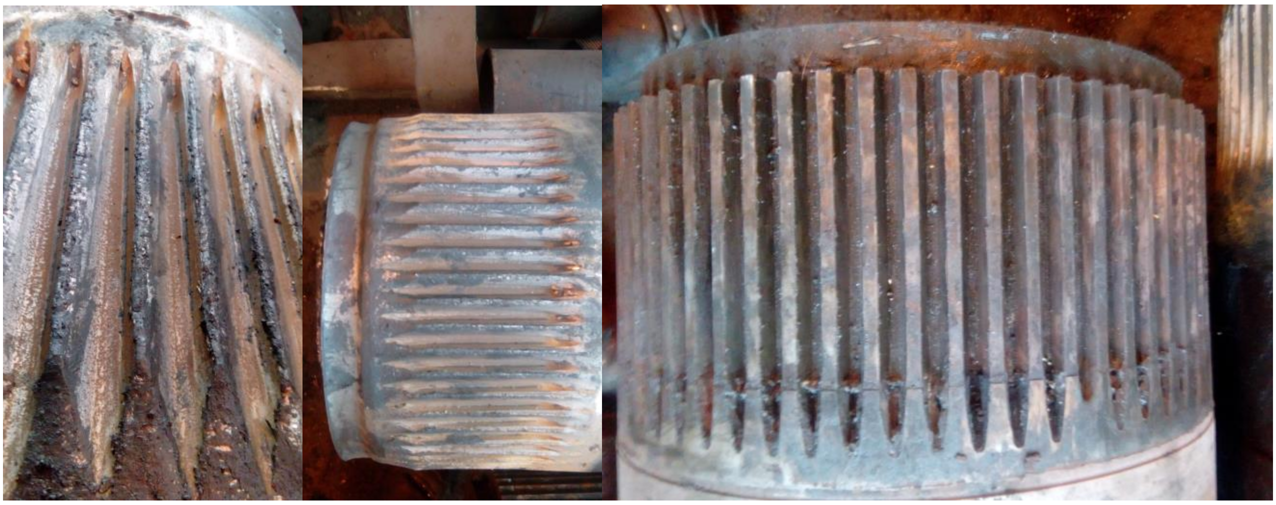

Fig.2: Appearance of some of the gear shafts in the rolling mill „Topla valjaocnica" in Steelwork Smederevo

2. BASE MATERIAL OF GEAR SHAFT

Gear shaft, which were repaired due to damage, were made of steel 42CrMo4. This is an enhancing steel used for machine parts in engines and vehicles, subjected to high levels of load, at elevated temperatures. 42CrMo4 is alloyed heat treatable steel with a typical tensile strength of 900 - 1200 N/mm². The 42CrMo4 alloy material also has high fatigue strength and good low-temperature impact toughness and low temper brittleness. The chemical composition of 42CrMo4 is given in Table 1, whereas its mechanical properties are given in Table 2.

Table 1: Chemical composition of steel 42CrMo4 [7]

Element	C	Si	Mn	Cr	Mo	P	S
Percentage [%]	0.38-0.45	Max 0.4	0.6-0.9	0.9-1.2	0.15-0.3	<0.025	<0.035

Table 2. Mechanical properties of steel 42CrMo4 [7]

Mechanical properties	Re [N/mm^2]	Rm [N/mm^2]	As %
Values	780	1000	10-14

Taking into account significant probability of residual stresses occurring after welding of parts whose thickness is greater than 30 mm, preheating and tempering after welding are required in order to remove these stresses. In addition, it is recommended to preheat in order to reduce the cooling rate, thus avoiding unwanted micro-structural changes [8-10].

3. REPAIR TECHNOLOGY FOR TOOTHED SHAFTS

During exploitation, gear shafts were subjected to variable loads and difficult working conditions at elevated temperatures. After the load analysis was performed, the development of the welding plan was initiated.

The welding plan begins by determining the reasons for repairing, and for this purpose the following activities are undertaken [5, 6, 11]:

- Selection of the repair procedure
- Calculation of the preheating temperature (if needed)
- Selection of additional materials
- Determining of the number of passes (layers)
- Determining of technological welding parameters
- Determining of the eventual need for additional heat treatment (if necessary)

3.1. Selection of the repair procedure

Repair welding was performed on eight gear shafts of service rollers. Based on the geometry and size of a gear shaft, the possibility of welding and the quality of the base material, as well as on rational welding procedures, two repair welding procedures were selected:

1) Flux core arc welding (FCAW procedure)
2) Manual arc welding using coated electrodes (MAW procedure).

Seven of the shafts were repaired using the EPP procedure, and one was repaired using the E procedure.

3.2. Selection of additional materials

The chemical composition and mechanical properties of the electrode used for manual arc welding differs from the one used in the FCAW procedure. Based on the map shown in Figure 3, the selection of additional materials for repair welding is made. This selection is made in accordance with the percentage of carbon and other alloying elements, as well as in accordance with damage mechanisms.

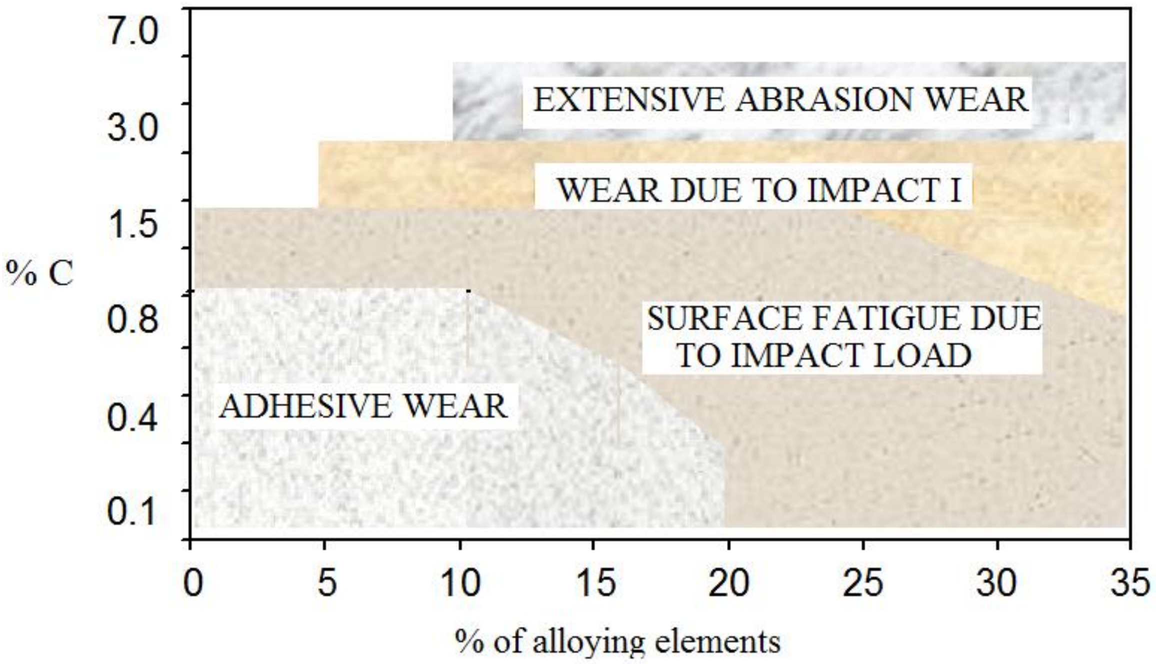

Fig.3: Map of iron based hard repair welding [5]

Taking into account the selected repair procedures, base material quality, geometry and dimensions of the welded surface, geometry after machining, as well as the conditions under which the toothed shaft is working, the following additional materials for each procedure were selected:

1) For the flux core arc welding (FCAW), the WLDC 3 ∅ 3,2 mm wire was used, along with the universal Weldclad powder. WLDC 3 wires are used for general purposes and are characterized by exceptional wear resistance at higher temperatures [12].
2) For manual arc welding (E), the following two electrodes were used:

- Electrode Piva 29/9 R ∅ 3.25 mm for the applying of the intermediate layer. This is an austenite-ferrite rutile electrode, used for welding of appropriate types of corrosion resistant steels and steel moulds, and for welding of heterogeneous steels, hard manganese steels and steels with poor weldability. It is suitable for repair welding and welding of intermediate layers [13].
- Electrode Piva 430 B R ∅ 5 mm for the finishing layers. This is a coated base electrode, used for repair welding of worn elements such as gears, axles, crushers, shafts and other machine elements [13]. Welded layers are characterized by high wear resistance and can be machined. Welded layers are pure, without porosity and material toughness is high at low temperatures as well. Hydrogen content in the welded layer is less than m1/100g of metal.

Electrode Piva 430 B and wire WLDC 3 are located in the adhesion resistant area, according to the map shown in figure 3, which partially corresponds to the requirements of the welded layer on the shaft. These electrodes are commercially available, economical and completely meet the welded layer requirements. Commercial designations, electrode manufacturers, chemical composition and mechanical properties of pure weld metal for the electrodes available on the market are presented in table 3 [12, 13].

Table 3: Electrodes used for repair welding procedure: chemical composition and mechanical characteristics

No.	Commercial designation	Manufacturer	Chemical composition %					Mechanical properties		
			C	Mn	Si	Cr	Ni	Re [MPa]	Rm [Mpa]	Hardness
1	PIVA 430 B	FEP Plužine	0.15	1.3	0.7	1.2	/			280-330 HB
2	PIVA 29/9 R	FEP Plužine	0.15	1.2	/	29.0	9.0	500	740-840	230-270 HB
3	WLDC 3	Weldclad	0.12	1.0	0.6	12.2	2.5			33-48 HRC

Before use, these electrodes were dried for two hours at a temperature of 300°C, and were then stored at a temperature of 150°C. On site, the electrodes are kept in accessory driers (quivers).

3.3. Repairing of the toothed shaft

After the additional materials have been selected, the repair welding of damaged gear shafts took place. In the following section of the paper, the activity flow during the repairing is presented, for both procedures.

The first step is the removal of worn-out teeth on one, as well as on both sides (depending on the damage) of the shaft, by machining. Shown in Figure 4 are the shaft dimension before and after preparation, i.e. machining. In this way, the damaged parts of the shaft (teeth) were removed, until the shaft diameter of ∅ 380 mm was achieved. In addition, machining also removed the material along the length until the non-damaged part of the shaft is reached.

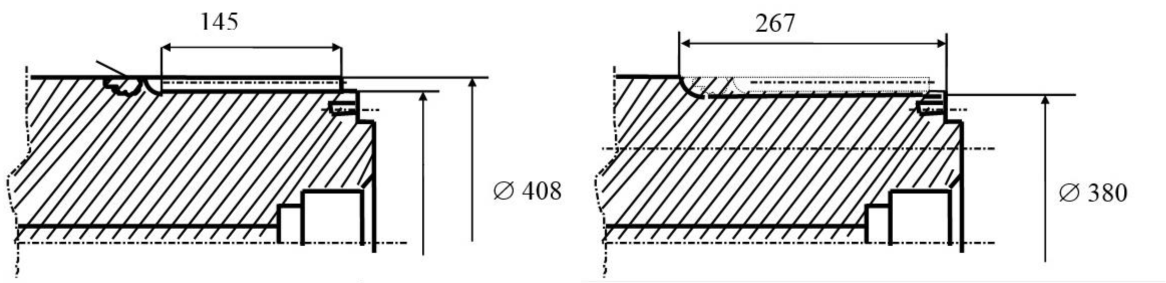

Fig.4: Left) Shaft dimensions before, and Right) after repair welding preparations

The next step involved the testing of the prepared surface for repair welding via magneto-flux in order to detect cracks and other defects which can affect the bond between the parent material and the welded layer.
Taking into account the workpiece thickness, as well as the properties of the base material, heat treatment of the welded joint represents the key position for the successful repairing of the gear shaft. Prior to welding, the shaft is locally preheated to a minimum of 200 mm to the left/right of the welding location to temperatures of 300 ±10oC. Preheating temperature was determined according to the Seferian procedure [14, 15].

Repair welding in accordance with the selected procedure and the corresponding additional material (in the case of repair welding using the MAW procedure, a puffer layer is first applied, using the Piva 29/9 R electrode, whereas welding continues with the use of Piva 430 B electrode). In order to overcome the differences in the mechanical properties, an intermediate layer made of a "softer" material is applied, which is common practice in engineering [6, 16, 17]. Parameters of the repair welding process are given in table 4.

Table 4: Welding parameters

Manual arc welding (MAW procedure)		**Flux core arc welding (FCAW procedure)**	
Electrode diameter	5 mm	Wire diameter	3.2 mm
Welding currency	190 - 230 A	Powder - granulation (Tyler)	8 x 48
Welding arc length	4 - 5 mm	Current type and amperage	(+) do 800 A
Electrode angle relative to the application line	70 - 80^{o}		

Temperature during the repair welding was locally maintained within the range between 280 °C and 300 °C, for its full duration.
The welding process lasted until the removed material was filled (i.e. until the pre-treatment shaft diameter was achieved), with added 3 mm along the generatrix for machining - tooth manufacturing. Welding was performed until a shaft diameter of ∅ 415 mm was achieved.
After welding, the repaired shaft is tempered in order to reduce residual stresses. The shaft is heated locally to a temperature of 620 °C/h at the rate of 50 °C/h and this temperature is maintain for a period of 3 hours. After 3h, the shaft is subjected to controlled cooling at the rate of 50 °C/h, until the temperature of 150 °C is reached, and at this point the machine is turned off and heat isolation is removed. After that, cooling continues at room temperature.
For the purpose of welded layer quality control, hardness was measured for both cases of repairing (MAW and FCAW procedures). Measured hardness of surfaces welded by the E procedure after heat treatment ranged from 280 to 310 HB, which entirely corresponds to the hardness of the tooth surface before repairing. The hardness of the welded layer on one of the shafts welded using the FCAW procedure is slightly higher and ranged from 320 to 340 HB.

3.4. Techno-economic analysis

Repair welding of working parts can help in achieving significant savings. All repaired shafts from the "Topla valjaonica" rolling mill have been in exploitation for over two years and there are still no signs of damage. The costs of repairing a single shaft, including the manufacturing of all necessary tools were around 1.500 €. The price of manufacturing a new shaft is around 25.000 €. Savings achieved with the use of repair welding in this case was around 200.000 € for all eight shafts, compared to the purchase of new ones. It should be mentioned, that due to their dimensions, delivering and assembling of new shafts would require several months, whereas repair welding can be performed in one week. Production downtime of several month in this facility would cause considerably higher financial losses. Thus it can be concluded that the indirect savings achieved by the use of repair welding is significantly higher than the aforementioned amount.
The conceptual solution for repair welding of machine parts was developed within the Železara Smederevo. A detailed techno-economic analysis determined that a bit over 800.000 € could be saved on an annual level, i.e. that repair welding of spare parts would make up 53% of the price of new parts. Costs mentioned previously also include the purchasing of necessary equipment, adaptation of the industrial hall, additional materials, etc.

4. DISCUSSION AND CONCLUSION

The problem of repair welding cannot and should not be observed purely as compensation of lost dimensions. Significant issues in repair welding occur within the domain of working parts dimension preservation. Enhancing the work surfaces quality is a particular technological problem whose solving needs to include extensive material science, the metallurgical nature of both base and added materials, which are dictated by the requirements which the applied welded layer must meet. In the example presented here, providing of a high quality weld in the case of toothed shaft repair welding requires the controlling of the following:

- preparation of the shaft for welding
- electrode drying process
- preheating and tempering temperatures
- the repair procedure itself, including the work done by welders or operators.

A high quality welded layer can be expected only in the case that all these elements are in accordance with the prescribed technology. After repair welding, the welded surface is machined, and after that, it needs to be examined in detail, using a non-destructive test method. It should also be noted that repairing of a single machine part cannot be performed an unlimited number of times. Practice had shown that a machine part can be repaired up to 3 or 4 times, thus it would be useful to introduce records about the repair history of any given machine parts, as a form of its "passport", which would contain information about its previous repairs.
In the example presented in this paper, both repair welding procedures that were performed (manual arc welding - MAW procedure, and flux core arc welding - FCAW procedure) were determined as favorable solutions for compensation of materials lost due to wear. Of all the requirements that need to be fulfilled, the most important ones are related to the absence of cracks and notches from the welded layer. In the case defects are detected after the repairing was completed (insufficiently welded surface for the MAW procedure and surface cracks for both procedures), these defects are removed by grinding the surface, or grooving in the case of significant depth of defects, followed by repeated welding in accordance with the technology.
All eight of the repaired shafts were put into back into exploitation and have been working for over two years, still showing no signs of damage, which confirms the justifiability of this technical solution for repairing. Direct financial savings achieved by applying repair welding, compared to the purchase of new shafts can be seen from these examples. Techno-economical analysis had determined that the total amount of around 200.000 € was saved, for all eight shafts, whereas the indirect saving were even greater.

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