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Research paper

THE EFFECT OF EXPLOITATION CONDITIONS ON THE DAMAGE OF A ROLLER REDUCER TOOTHED SHAFT AND ITS REPAIR

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Abstract: *This paper describes repair method of the toothed shaft of roller reducer located in Steelworks Smederevo facility, as well as the effects of exploitation conditions that have led to damage i.e. shaft fracture. After more than 15 years of in-service exploitation the shaft fracture has occurred at the bearing position. The fracture occurred due to blocking on the roller driven by this shaft. In order to restore the working capabilities of the shaft, the repair welding procedure has been established. Additional difficulties during establishing repair procedure were caused by the fact that the base material of the shaft was unknown, so certain assumptions were made (e.g. assumption of base material). Application of repair welding has resulted in significant direct and indirect savings in comparison to the purchasing of a new shaft.*

Key words: *repair welding, roller reducer, toothed shaft, fracture*

1. INTRODUCTION

Machine parts subjected to variable load during their exploitation are often prone to failure due to fatigue. As it is known, fatigue always initiates at the location of the initial crack, wherein this process can be caused by cyclic accumulation of plastic strain at locations where there is significant stress concentration or where damages have occurred during the manufacturing process [1-5]. Fatigue occurs as a result of plastic strain during both crack initiation and propagation. One of the machine part types which are prone to fatigue damage and failure is the shaft. In addition to fatigue, the integrity of shafts is also affected by other factors such as bearings and their lubrication, etc.

Bearings are standardized machine assemblies which are made by specialized manufacturers. Installation of bearings is of great significance for the functioning of the system as a whole, as well as for achieving the predicted exploitation life of both the bearing and the shaft. Adequate installation of bearings ensures the necessary conditions for transferring of the force from the shaft to the supports, and vice versa. This enables the unconstrained deforming of the shaft, as well as the fulfilling of conditions requires to achieve the necessary gap, rotation accuracy and exploitation stability [1]. Basic destruction of a roller bearing is caused by the damaging of the surface layer, due to fatigue. In addition to the effects of surface pressure caused by loading, bearing destruction can occur due to shaft axis position deviation, damages to the cage and other parts and mostly due to lack of lubrication of the bearings and the presence of mechanical impurities or small parts which contribute to additional mechanical damaging. These bearing damages can affect the damage to the shaft, and together with the presence of initial cracks can cause shaft failure [1, 6-7].

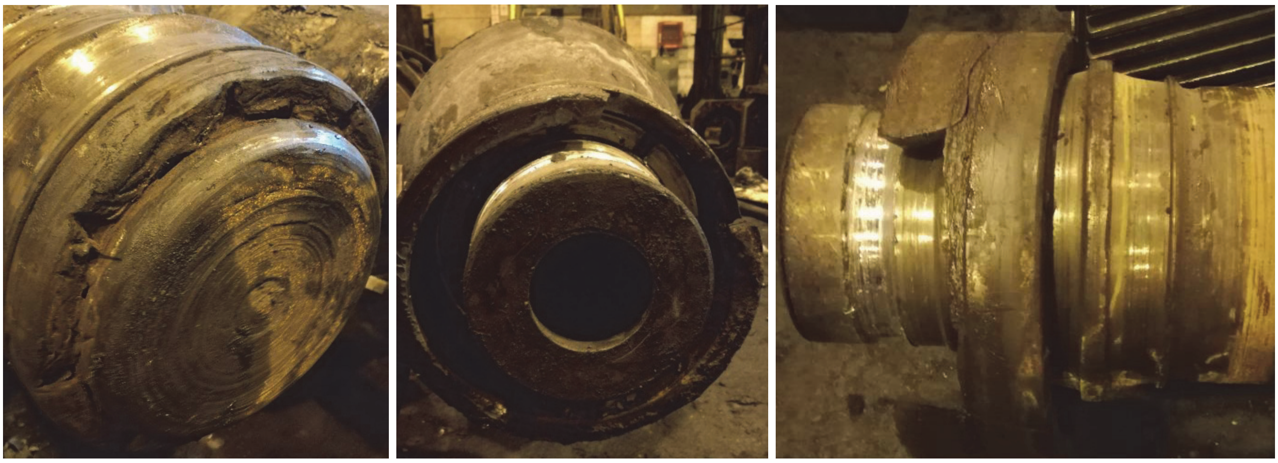

Fig.1. Some of the damages of roller bearings which can (and did) cause the failure of the toothed shaft

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Presented in this paper is the case of damaging and repairing of a toothed shaft in the Železara Smederevo. The shaft is a part of the roller used for flattening of a hot-rolled strip. The flattening roller used for straightening of the hot-rolled strip, prior to its cutting, is driven by a reducer consisting of 11 gear shafts. After 16 years of exploitation, fracture of one of the toothed shafts occurred, directly in front of the bearing with a diameter of ∅120 mm. It was determined that the shaft failure occurred due to the blockage of the roll which drives this particular toothed shaft. Some of the damage of the roll and bearing failure can be seen in figure 1. Such damages can affect the failure of other reducer elements, as was the case here.

One 3D model of the toothed shaft used in this facility, wherein the fracture occurred, is shown in figure 2, with a clearly marked fracture location. The shaft was then repaired, since the manufacturing of a new part would result in downtime considerably longer than expected.

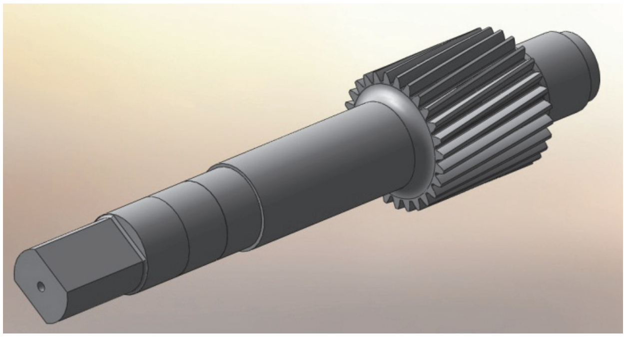

Fig.2. 3D model of a toothed shaft where fracture occurred

2. SUGGESTED PROCEDURE OF REPAIRING

Prior to repairing, it was determined that there was no shaft documentation, thus the base material of shaft was unknown. This resulted in the question about what kind of material should be used as a replacement for broken part which should be welded to the main part i.e. shaft. There was a need to repair the shaft immediately in order to avoid significant downtimes in cutting and delivering of hot-rolled strips. It was assumed that the parent material of the shaft was steel 42CrMo4 (Č4732 according to old JUS designations), based on the shaft geometry and similarity to other gear/shaft parts used for the same purposes. It should be noted that the material of the toothed shaft was determined after one year.

It was suggested that the fracture location on the gear side should be realigned and prepared for the welding, with "V" groove and 60° groove angle. In addition, an "attachment" (aforementioned replacement for broken part), which should be welded to the main part, which would then be machined to its designed dimensions (the ones taken from the broken part) needed to be made, using a material similar to the parent one. As it has been said, a "V" groove was prepared, with an M48 thread, whose length was 50 mm. The "attachment" material that was supposed to be welded with the thread due to the shape of the part was steel 30CrMoV9 (Č4734 according to old JUS designations), which was not heat treated.

3. ASSUMED PARENT MATERIAL OF TOOTHED SHAFT AND THE REPLACEMENT

Steel 42CrMo4 was assumed as the toothed shaft parent material, whereas the replacement of broken part used for welding was made of steel 30CrMoV9. As previously mentioned, the assumption about the parent material was made based on the shape of the part and its similarity to other gear/shafts used for the same purpose. The chemical composition of the assumed steel, 42CrMoV9, is shown in table 1, whereas its mechanical properties are given in table 2. The chemical composition and mechanical properties of steel 30CrMoV9 are shown in tables 3 and 4.

Table 1. Chemical composition of steel 42CrMo4 [8]

Element	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**
Percentage [%]	0.38	0.4	0.6	< 0.035	< 0.035	1.2	0.15

Table 2. Mechanical properties of 42CrMo4 [8]

Property	**Value**
Yield stress, $R_{p0,2}$	≥ 550 MPa
Tensile stress, R_m	≥ 800-950 MPa
Elongation, A	≥ 13%
Impact, Kv/Ku	≥ 35 J

Table 3. Chemical composition of steel 30CrMoV9 [8]

Element	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**
Percentage [%]	0.26	0.4	0.4	< 0.035	< 0.035	2.3	0.6

Table 4. Mechanical properties of 30CrMoV9 [8]

Property	**Value**
Yield stress, $R_{p0,2}$	≥ 700 MPa
Tensile stress, R_m	≥ 900 MPa
Elongation, A	≥ 12%
Impact, Kv/Ku	≥ 35 J

4. REPAIR WELDING TECHNOLOGY

4.1. Weldability of assumed 42CrMo4 and 30 CrMoV9 steels

Carbon equivalent of 30CrMoV9 steel, according to Seferian method [9-13], is 1.19, which indicates poor weldability, whereas the determined HCS value of 5.9 indicates significant vulnerability to hot cracks. Preheating temperature recommended for this material is 250°C. Steel 42CrMo4 has limited weldability, and its recommended preheating temperature is 200-300°C. The upper limit should not be exceeded because of risk of deterioration of the chrome layer. Adopted preheating temperature for both parts (base and the attachment) was 250°C in this case.

4.2. Groove preparation

The appearance of the "V" groove, i.e. the grooving of the base part and the attachment, is shown in figure 3. Also shown in the figure is the thread M48. The diameter of the attachment that was necessary to weld was ∅125 mm. After welding, welded replacement will be reduced to its designed dimensions. The base part of the toothed shaft in figure 3 is denoted by number 1, whereas the part that needs to be welded (the replacement) is denoted by 2. Figure 4 shows the machined parts of broken shaft.

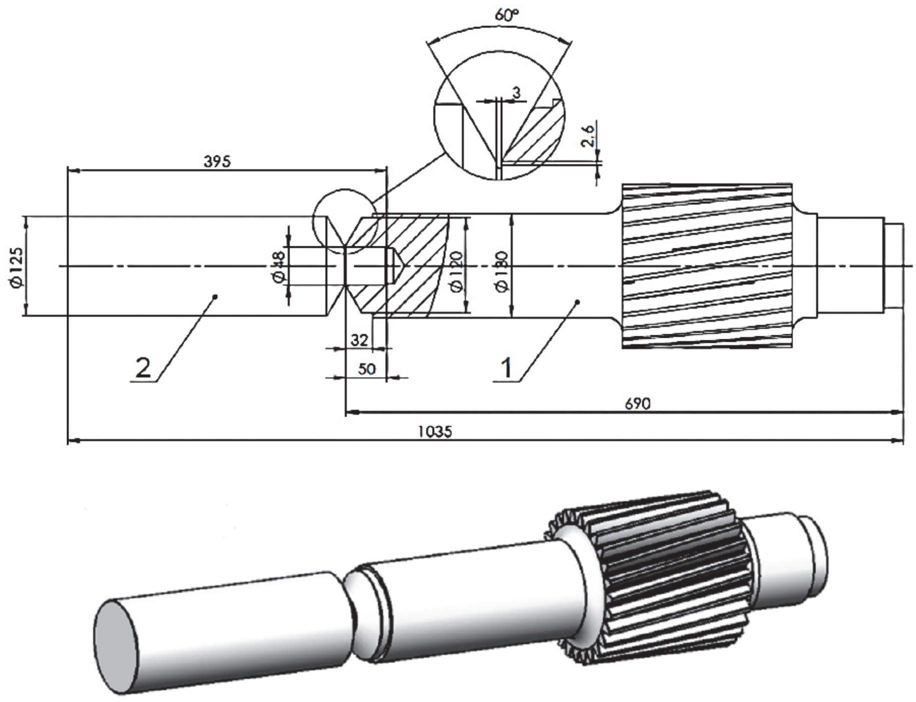

Fig.3. The "V" groove: 1) denotes the base part of the shaft 2) denotes the "attachment" that needs to be welded

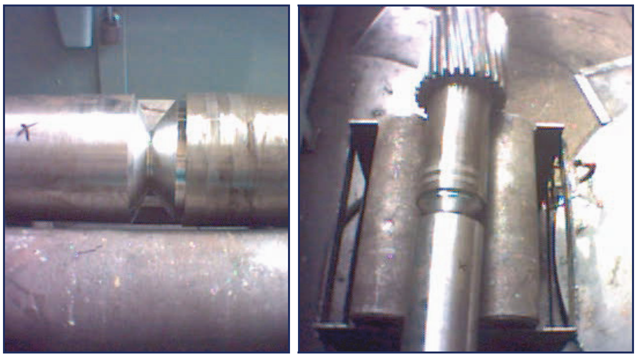

Fig.4. Appearance of machined parts of broken shaft

Fracture was located immediately in front of the bearing, which represented an advantage, since the weld could be formed in the zone beneath the bearing. At this location (where the bearing was), the shaft was subject only to torsion, and no bending. By calculating the elastic section modulus at the smallest branch (figure 5), it was determined that there was no need to weld the full ∅120 cross-section and that a "ring" can be formed instead, in order to make an overhang in the attachment and a hole in the gear, for the purpose of "centering".

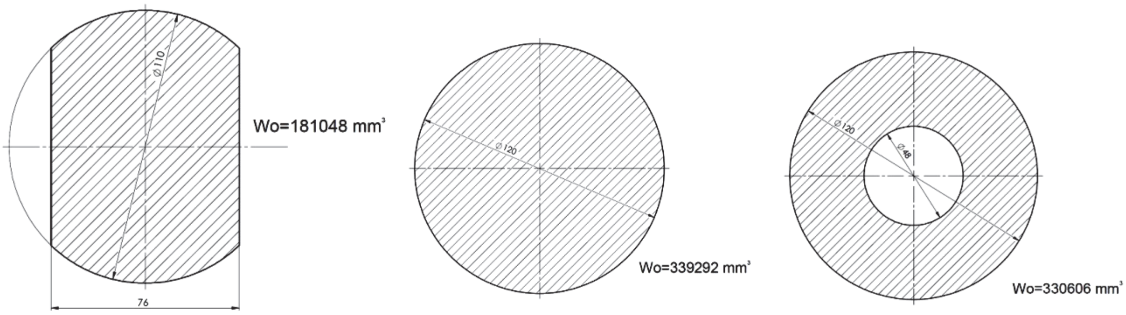

Fig.5. Elastic section modulus of the shaft (smallest cross-section, full cross-section- fracture location, weld cross-section)

It can be seen that the elastic section modulus of the welded cross-section is equal to 97.4% of the full shaft cross-section, thus the stress is 2.6% higher, which is negligible.

4.3. Welding of base part and replacement

Manual arc welding (MAW) was selected as the welding technique. Weld root was performed using electrode PIVA 29/9 R with a diameter of ∅3.25 mm, whereas electrode PIVA 350 B (∅4.0 mm) was used for weld filling. Root pass was done in 2 layers. The chemical composition and mechanical properties of clean welds made with both electrodes are shown in table 5.

Electrode PIVA 29/9 R 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 [14].

Electrode PIVA 350 B is a basic molybdenum-alloyed electrode used for welding of steels and parts which work at temperatures above 500°C, non-alloyed steels with yield strength up to 640 MPa and fine-grain steels. In the case of welding of parts thicker than 20 mm, made of steel with carbon content above 0.2%, it is recommended to preheat them to a temperature of 200°C [14].

Table 5. Electrodes used for repair welding procedure: chemical composition and mechanical characteristics [14]

Commercial designation	Manufacturer	Chemical composition [%]						Mechanical properties of pure weld	
		C	Mn	Si	Cr	Ni	Mo	Re [MPa]	Rm [MPa]
PIVA 29/9 R	FEP Plužine	0.15	1.2	/	29.0	9.0	/	500	740-840
PIVA 350 B	FEP Plužine	0.08	0.95	0.45	/	/	0.5	460-530	570-640

After the groove was prepared, and immediately before welding of these two parts, the toothed base part was locally preheated using a burner, whereas the replacement for broken part was preheated in a chamber furnace. Welding was performed by two welders in order to speed up the process as much as possible and to prevent rapid cooling during the welding. The temperature during the process did not drop below 220°C (it was controlled every 15 minutes using a non-contact thermometer). After the welding, the gear shaft was placed in a metal container and covered with sand.

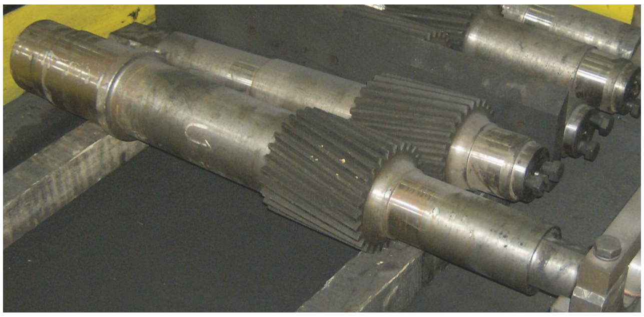

Fig.6. Toothed shaft after the repair welding of the broken part

After 4 hours, its temperature was around 70°C, and it was roughly machined on a lathe. Hardness of the weld and the adjacent area was around 210 HB, which is acceptable when compared to the measured parent material hardness of 180 HB, since there is no significant difference. After the welding activities have been completed, visual, penetrant and ultrasound controls were fully performed. No defects were detected. Figure 6 shows the shafts after the repair welding.

5. DISCUSSION AND CONCLUSIONS

It is well known that repair welding can restore the work functionality of a machine part. Such was the case here, as well. Repairing of the toothed shaft, by means of welding an attachment to the location of the broken part, and machining of this attachment to adequate dimensions restored the functionality of the shaft. The complete repair process was performed within 24 hours. After the welding activities, control and machining of the toothed shaft were completed, it was re-installed into the hot-rolled sheet roller reducer. After few years of exploitation, this reducer was inspected, and the inspection is shown in the figure 7. Repaired shaft is still in exploitation.

It took an entire year to determine that the parent material of the shaft was Japanese steel SNC 22. The chemical composition of this steel is shown in table 5. Based on the fact that the repair procedure was successful and that the shaft is still in exploitation, it can be concluded that the assessment of the parent material based on hardness measuring and part similarities was adequate.

As is known, gear shafts are made of enhancement steels or cementation steels, and steel SNC 22 belongs to this category, like the assumed steel 42CrMo4.

Manufacturing a new shaft from forgings takes 50-60 days, whereas manufacturing of a toothed shaft with a diameter of ∅210 mm, including the heat treatment of teeth takes at least 30 days. Machine part repairs can achieve financial savings, both directly, by comparing the costs of a new and a repaired part, and indirectly, by reducing the downtime which could otherwise negatively affect the number of manufactured hot-rolled sheets, further sales, etc. The price of a new shaft is 2700 Euros, whereas the total cost of the repair procedure is negligible compared to it. The shaft is still in exploitation and shows no signs of defects, as determined by regular inspections.

In order to reduce the possibility of failure of shafts in this reducer, it is suggested to lubricate the bearings in a more adequate way in order to reduce their jamming. Bearing failures can affect fracture of both the shaft and other parts of the installation (indirectly). Lubrication should be in accordance with manufacturer recommendations involving specific types of bearings, as well as the exploitation conditions to which the shaft and bearings are subjected. Additionally, it is recommended to regularly examine the reducer assembly, i.e. to perform inspections and controls more frequently.

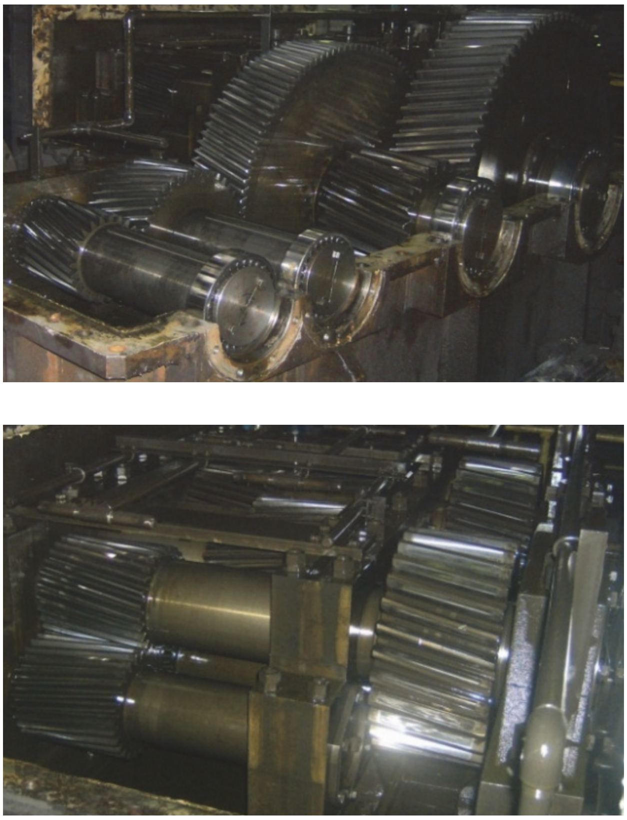

Fig.7. Roller reducers used for flattening of hot-rolled strips during the inspection in 2017

Table 6. Chemical composition of steel SNC22 [8]

Element	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**
Percentage [%]	0.12	0.15	0.35	< 0.03	< 0.03	2.3	3

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