sciendo

PRODUCTION ENGINEERING ARCHIVES 2021, 27(4), 257-264

PRODUCTION ENGINEERING ARCHIVES

ISSN 2353-5156 (print)
ISSN 2353-7779 (online)

Exist since 4th quarter 2013
Available online at https://pea-journal.eu

Influence of different hard-facing procedures on quality of surfaces of regenerated gears

Ružica R. Nikolić[1,*], Svetislav Marković[2], Dušan Arsić[2], Vukić Lazić[2], Branislav Hadzima[3], Robert Ulewicz[4,*]

[1] Faculty of Technical Sciences Čačak, University of Kragujevac, 32000 Čačak, Serbia
[2] Faculty of Engineering, University of Kragujevac, 34000 Kragujevac, Serbia; svetom@mts.rs (S.M.); vlazic@kg.ac.rs (V.L.)
[3] Research Center; University of Žilina, 010 26 Žilina, Slovakia; branislav.hadzima@uniza.sk
[4] Department of Production Engineering and Safety, Czestochowa University of Technology, Czestochowa, Poland
*Correspondence: ruzica.nikolic@uniza.sk (R.R.N.); robert.ulewicz@pcz.pl (R.U)

Article history
Received 19.08.2021
Accepted 26.09.2021
Available online 15.11.2021

Keywords
regeneration
hard-facing
gear
tribological properties
friction coefficient

Abstract
During the process of regeneration of machine parts, certain phenomena occur that have a significant impact on the loss of their working ability. Hereditary properties are expressed by the interdependence of geometric and physical-mechanical-metallurgical parameters of gear teeth created during the technological operations of regeneration of worn teeth by hard-facing. The influence of the type of additional material (electrodes and their combinations) on the tribological characteristics of welded gear teeth was considered, whereby the so-called hard additional materials were applied. Those are the additional materials that give the required surface hardness of the teeth without subsequent thermal or thermochemical treatment. This research did not involve the regeneration of specific worn gears removed from machine systems, but the new gears were made, which were then damaged and then regenerated by hard-facing using the shielded metal arc welding (SMAW) procedure. Thus, all the tested gears were made of the same material, belonged to one batch and were machined on the same machines with the same machining regimes. The tests were performed on samples made of 20MnCr5 steel for cementation, on a tribometer by the "block on disc" method, which was designed to simulate the operating conditions of coupled teeth of concrete gears in the exploitation conditions. Based on the conducted tribological tests, the average coefficients of friction and topography of the surfaces were determined by measuring the wear trace and it was defined which additional materials give the best tribological characteristics of the surfaces of gears regenerated by hard-facing.

DOI: 10.30657/pea.2021.27.34 JEL: L23, M11

1. Introduction

There exist various procedures for reparation of the damaged machine parts. The best procedure for regeneration of the damaged gears, according to reported investigations, is the hard-facing of the damaged/worn surfaces. To be able to apply such a procedure one must know all the mechanisms of the contact surfaces wear. The regeneration of gears by hard-facing is a complicated procedure, including numerous technological operations. Order of execution of those operations is extremely important and must be precisely defined. The comparative tribological characteristics of gears regenerated by hard-facing and the new ones are considered on appearance of small pits on the gear's surfaces, namely the phenomenon of the primary pitting on gear teeth. Another element for comparison the pitting development rate on those surfaces. Literature on gears regeneration by hard-facing is not voluminous. Authors of this article have some experience on this subject (Lazić et al., 2009; Lazić et al., 2014; Lazić et al., 2016; Arsić et al., 2016a; Arsić et al., 2016b) and have pointed to possibility of using the reparation for restoring the damaged parts of various machine systems. Based on investigated literature one can conclude that a small number of researchers were considering influence of the regeneration procedure on tribological characteristics of regenerated gears, especially from the point of view of technological inheritance (Vicen et al., 2020). Various hard-facing methods and their application in the reparation process of gears were considered in authors' own investigations (Markovic et al., 2011; Markovic et al., 2013; Markovic et al., 2021), where results of experimental metallurgical investigations of the repaired gear teeth were analyzed (Mohammed et al., 2020; Vasić et al., 2020). General conclusion is that the damaged gear teeth can be repaired by careful selection of the filler metal and welding technology (Markovic et al., 2021; Yousfi et al., 2020).

2. Literature review

(Desir, 2001) has presented the way in which the Castolin company (now Castolin Eutectic) has dealt with increasing number of failures and fractures of steel parts in the mid-seventies of the last century. The problem appeared on the cast mild steel parts in the cement industry (rotary kiln tyres, ball mill trunnions, girth gears, support rolls and press bodies – all made of the cast steel of different grades, as well as kiln exhaust ports, shells of ball mills and kilns, kiln tyres adjustment blocks, reducer housings and hydraulic containers – all made of wrought mild steel and some of the high strength low alloyed steels - HSLA). He listed the reasons for failures as surface defects, internal defects, heterogeneity of the cast material, then the adopted solutions for repair from the mechanical, chemical and metallographic aspects, as well as economic justification for such solutions on three examples (a kiln tyre, a ball mill and a girth gear).

(Borego et al., 2006) have analyzed parameters of reparatory welding and hard-facing in order to achieve better fatigue strength of steel for manufacturing the casting molds. They used the laser-deposit welding procedure. Advantages of this process, with respect to the "traditional" welding procedures, is a smaller heat affected zone (HAZ) due to the concentrated heating action of the laser beam and smaller volume of the used filer material. The objective of authors was to obtain the better fatigue strength of the casting molds, by selecting the better filler wire materials. For the H13 steel molds the filler metal was the stainless steel, while for the P20 steel molds they tested several alloy steels.

(Li et al., 2009) tried to solve the problem of repairing the very large gear (dimension over 4 m), since there was no furnace large enough for its preheating and no conventional hard-facing procedure could be applied. They found a solution by adding a rare-earth (RE) oxide to the coating of the electrode used for hard-facing. By this new kind of electrode, the hard-facing was possible without the preheating or the post-heating of the large gear. The realized microstructure of the hard-facing metal was mainly composed of the fine acicular ferrite and refined what was ascribed to adding the RE oxide in the electrode coating. No cracks, air holes or any other defects in the binding sites between the hard-faced metal and substrate were recorded.

(Hao et al., 2011) followed in the lead of the previous research and developed new electrodes for hard-facing of medium carbon steel with six different amounts of a rare-earth (RE) oxide additions. They used the optical and scanning electron microscopy to study the microstructure, inclusion and the fractographs of the hard-faced metal. Authors also analyzed effects of the rare-earth oxide addition on the microstructure and inclusions in it. The hard-faced metal's microstructure consisted of ferrite and a small amount of pearlite and it was refined. The hard-faced metal had the smallest grain size between 5 and 10 μm, when the addition of RE oxide was 5.94 wt.%. However, with increase of the rare-earth oxide addition, the structure became coarse. The size of dimples on the fracture surface of samples has increased with increase of the RE oxide addition, as well. The fractographs of the hard-faced metal were fully brittle ones, when the RE oxide addition was larger than 8.65 wt.%. The ferrite grains' coarsening was attributed to the misfits between Ce_2O_3 and d-Fe and Ce_2O_2S and d-Fe.

(Xing et al., 2012) prepared the hard-facing alloys with different amounts of Ceria for the self-shielded flux-cored arc welding. The base material for the hard-facing deposition was the Q235 steel. The flux core powder was composed of a mineral powder (which contained the gas and slag formers, the arc stabilizer and the deoxidizers) and an alloy powder (which contained ferro-chromium, ferro-manganese, ferro-silicon, ferro-niobium and nickel powder). Authors also performed the abrasion tests of the hard-faced layers using the dry sand/rubber wheel machine, which were followed by the hardness measurements and analysis of microstructure. The results showed that the wear resistance was determined by the size and distribution of the carbides, as well as by the substrate's microstructure. The main wear mechanisms on surfaces were micro-cutting and micro-ploughing of the substrate. The Ceria addition improved the hardness and fracture toughness of the hard-faced deposited layers. That, on the other hand, caused an increase in resistance to plastic deformation and scratching of the hard-faced layers, which resulted in improving their wear resistance, as well.

(Bokuvka et al., 2013) have considered influence of the welded joint quality on safety and reliability of welded structures in operation, on examples of pipes and rails. The defects – fractures were caused by defects in the welded areas, which included pores, blow holes, slags, lack of fusion, metallic and/or nonmetallic impurities, cracks and shrink holes. Those defects could have been caused by human factor (improper preparation for and/or execution of welding), by inadequate quality or type of the base materials or filler metals, or poorly selected welding procedure. They concluded that observance of optimal rules in the chain chemical composition - microstructure - technology leads to high exploitation properties and required quality of welded components and constructions.

(Hanus and Konečny, 2014) analyzed influence of the welding process on safety of structures made of the advanced high strength steel (AHSS). They studied the martensitic 22MnB5 steel, used for automotive industry structures, to define the optimal method for evaluation of the local changes in material's elastic-plastic response and for determination of the yield strength. To realize that, authors experimentally simulated the critical layer of the heat affected zone (HAZ) and the heat loading influence was assessed, as well.

(Gualco et al., 2015) have studied the microstructural evolution and wear resistance of a nano-structured iron-based alloy, deposited by the FCAW (flux-cored arc welding) process. Two samples were prepared, with a single and two layers welded under the Ar-20CO_2 shielding, with the heat input of 3.5 kJ/mm. Authors determined the chemical composition and studied the microstructure by both optical and scanning electron microscopy and X ray diffraction. They evaluated the effect of number of layers on the microstructure and wear resistance of a nanostructured iron-based alloy, deposited by the FCAW process. The conclusion was that the wear resistance was higher for the specimen welded with two layers, which could be attributed to increased presence of ultra-hard carbides. The hardness decreased with the second layer from 920 to 800 HV, for extreme values. This decrease of hardness could be associated with the higher crystallite size.

(Ulewicz and Novy, 2016) analyzed surface fatigue properties of steel S355JR2 in the area of ultra-high cycle numbers (in the range from 6 × 1010 to 10 × 1010 cycles). The samples were coated by electrolytic coatings. Authors considered the effect of those coatings on the fatigue properties of the base material. The samples underwent the grit blasting to determine if the prescribed process parameters caused changes in the surface layers' resistance to fatigue.

(Arsić et al., 2016a) presented a voluminous techno-economic analysis of hard-facing of various machine systems. Authors analyzed costs and savings by the profitability (economic viability) method. All the analyzed machine parts were revitalized by hard-facing, what resulted not only in returning the parts into the exploitation process, but in numerous savings in time and money, as well. Evaluation and verification of quality of the applied hard-facings was performed experimentally and by monitoring the repaired parts' behavior in exploitation. The realized savings, with respect to the costs of the new parts' purchasing, were calculated by the cost effectiveness method and presented by the concrete monetary values.

(Durmus et al., 2018) investigated the wear resistance of iron-based hard-faced coatings, which were produced with Fe-Cr-C-B- and Fe-Cr-C-based filler metal wires. They applied the ball-on-disc and dry sand/rubber wheel wear tests. The iron-based hard-facing alloys were coated on the St37 steel by the arc welding, without application of a shielding gas. The reported results showed that the wear resistance is related not only to hardness and the volume fraction of hard phases, but to morphology of microstructural constituents, as well. The minimum wear loss was obtained for a sample that was coated with Fe-Cr-C-B based filler wire, reinforced with 40% FeB+60% FeCr powder. The massive carbide/boride phases and a tough matrix phase, supported by a large number of secondary carbides, provided a superior wear resistance. Existence of martensite in the substrate phase raised not only the hardness but the brittleness, as well, which negatively affected the wear resistance.

(Vicen, Bronček and Novy, 2019) investigated a reduction of the friction coefficient of bearing steel 100Cr6. Their objective was to verify the behaviour of the DLC (Diamond Like Carbon) coating in the absence of lubricant, under the dry friction conditions. Reduction of friction was realized by the CarbonX DLC coating. Authors claimed that those coatings exhibited excellent friction and mechanical properties. The coating temperature of 240°C did not affect the substrate material significantly. The substrate hardness was reduced by 4 HRC. The measured hardness of the substrate of 59 HRC meets the normative conditions for bearing steel. Authors concluded that the thin CarbonX DLC coating, formed on the surface of the quenched 100Cr6 bearing steel, significantly improved the friction properties of this steel. Reducing the friction of 100Cr6 bearing steel resulted in reduced wear and increased lifetime.

(Feng et al., 2020) considered a cause of failure of a secondary driving helical gear steel in a transmission system of an electric vehicle. The gear was made of the 20CrMnTi steel. Authors used the macroscopic fractography, microscopic metallography, inspection and analysis of hardening depth and hardness, as well as the chemical composition and nonmetallic inclusions to evaluate the gear failure mechanism. The stress distributions of the tooth flank were obtained based on ANSYS Workbench software, using static and dynamic contact finite element simulation. They concluded that the cause for the gear failure was the lower content of Ti in the steel, which caused the difference of the TiC particles and affected the hardenability during the heat treatment. The hardening layer's depth and hardness tests showed that their values at the root of the tooth were lower than the specified/required ones.

(Czuprynski, 2020) studied the metal-mineral-type abrasive wear of a wear-resistant plate, made by a tubular electrode with a metallic core and an innovative chemical composition, using the manual metal arc (MMA) hard-facing process. Properties of the new layer were compared to results of eleven wear plates, commercially available. Based on the wear resistance and surface layer hardness tests, the wear plates most suitable for use in the metal-mineral conditions were selected. The presented results confirmed the high metal-mineral abrasive wear resistance of the deposited weld metal (WM) produced by the new covered tubular electrode. The high linear relationship between an increase in the surface hardness and an increase in the mineral abrasive resistance of the wear-resistant plate's hard-faced layers was suggested, as well. Author also emphasized the fact that the mechanical properties obtained by the hard-facing could be similar to properties of the original material of a repaired part.

(Dadon et al., 2020) considered impact of the gear tooth surface quality on detection of the local faults. They used the numerical simulation of the gear tooth surface interactions to realize what were the limits of the faults' detection. A dynamic model was created to simulate vibrations of gears of various sizes and types. For verification of the simulation results, authors performed a series of experiments in the comparative conditions. Their conclusion was that the low-precision gear profile grade reduces the ability to detect faults, while the gears with high quality teeth surfaces allowed for detecting the smaller faults.

(Vicen et al., 2020) investigated the tribological properties of a nitride layer applied to a low-alloyed steel. The authors' experimental work included determination of the chemical composition and wear resistance, as well as the Rockwell, Vickers and nano-indentation tests, both of the substrate material and the deposited layer. Results show that the nitride layer possessed the better friction properties than the substrate, since its measured friction values exhibited a 10% reduction, with respect to the low-alloyed steel. This decrease in friction is attributed to a hard layer of the ε - phase, located on the surface of the sample. On the other hand, after the nitriding, an unfavorable decrease in substrate's hardness, from 63 HRC to 45 HRC, was recorded, which was caused by the nitriding temperature of 530°C. That was reflected in the higher wear rate of samples. The nitride layer applied to low-alloyed steel did not improve the samples' tribological properties significantly. On the contrary, it significantly deteriorated the quality of the substrate material due to decreased hardness. Authors concluded that applying the nitride layer does not significantly improve the tribological properties of the tested steel.

(Bai et al., 2020) studied the tooth interior fatigue fracture (TIFF) of the wind turbine gears, caused by the gear contact fatigue. This type of fracture appears frequently in the case-hardened wind turbine gears. Authors developed a contact fatigue model to study influence of the material properties and the design parameters on the TIFF appearance. They presented a fatigue parameters analysis to characterize the risk of the TIFF. That risk increases with increase of the external load, while an increase of the pressure and the compressive residual stress could reduce the risk of the TIFF occurring.

(Trsko et al., 2020) carried out the residual stress and microstructural analysis of welded Strenx 700 MC steel structures. High strength low alloy (HSLA) steels are carbon steels with significantly improved mechanical properties and retained good weldability. The welding process introduced changes to microstructure and residual stress state to the welded samples, causing the significant grain coarsening in the heat affected zone. The microstructural changes were accompanied by creation of the tensile residual stress field in the weld metal and heat affected zone, reaching up-to depth of 4 mm. Those stresses can cause acceleration of the fatigue cracks initiation and propagation, which, together with the coarse grains, can lead to significant decrease of the fatigue properties of a welded structure. Since the superior mechanical properties of the experimental material are mainly obtained due to the fine-grained microstructure, the material of the weld metal and in the heat affected zone did not have the same parameters as the rest of the samples. It should be noted that appearance of the tensile residual stresses after welding is quite common, however, authors warned that they have to be considered when designing a construction from the HSLA steel, since such constructions are expected to sustain the higher loading.

(Atxaga and Irrisari, 2020) have analyzed the causes of the premature failure of an engine's shaft end, made of steel C45. The keyway was damaged and previously repaired by welding. The fracture surface analysis revealed that the origin of the failure was in a corner of the repaired keyway. Due to large damage was not possible to determine if the stress level was high. Authors found several possible causes for this failure, the first being inadequate material since the carbon content was markedly lower that the minimum level established for the C45 steel and the mechanical properties of the material did not agree with those specified in the purchase order. There were some design errors noticed, as well, since the keyway had a very small fillet radius and sharp angles. What concerns the reparatory hard-facing, there were the following faults: the previous cracks were not eliminated before repairing and incorrect welding process was applied. Furthermore, the filler metal has not been really joined to the shaft, what caused the detachment of the linchpin during the metallographic cutting. In addition, the used filler metal had markedly different microstructure as compared to the steel used for manufacturing the linchpin or the shaft. This example verifies the previous conclusions that precisely following the prescribed reparatory procedure is of a vital importance for successful reparation by hard-facing of any damaged structural component.

(Suraj, 2021) discussed different methods to evaluate the wear and corrosion resistance properties of mild steels, such as EN-8, EN-9 and EN-24, by calculating their corrosion rate. He used the pin on disc apparatus for analysis of ferrous welded materials, hard-faced by the tungsten inert gas (TIG) welding process, as well as the Vickers micro hardness tester for measuring the micro hardness. Author found that EN-24 exhibited the least wear when compared to EN-8 and EN-9. Its micro hardness was higher than that of the other two materials. The hard-faced materials were more corrosion-resistant than the parent metal. The hardness of the three materials varied in accordance with their chemical compositions. By comparing wear and corrosion rates of the hard-faced and non-hard-faced surfaces, author was able to conclude that the hard-facing improved both the wear and corrosion resistant properties of the tested materials.

3. Preparation of samples for testing

For the purpose of eliminating all other influences, here were not considered actual damaged gears, pulled out of exploitation and aimed for regeneration. The new gears were manufactured of the 20MnCr5 steel for cementation and then intentionally damaged and subjected to the prescribed regeneration procedure. The base metal (BM) chemical composition is presented in Table 1. Such an approach ensured that all the tested gears were made of the same material, belonged to the same batch and were all machined by the same machining processes on the same machines.

Thus prepared gears shown in Figure 1, had the following characteristics: module m = 6 mm; number of teeth z = 43; base profile angle $\alpha = 20°$; tooth profile angle $\beta = 0°$; pitch circle diameter $d_0 = 258$ mm; profile correction $x_m = 0$; base circle diameter $d_b = 270$ mm; addendum circle diameter $d_f = 243.6$ mm; circular pitch p = 18.84 mm.

Behavior of austenite during the cooling is primarily determined by the chemical composition of steel, a simpler system for evaluating the influence of carbon and various alloying elements on the stability of austenite was developed, i.e. the concept of equivalent carbon (CE) as an indicator of metallurgical weldability of steel, (Lazić et al., 2009).

Table 1. Chemical composition of samples' steel

Steel notation according to different standards						
ISO DIS 683/11	DIN		GOST	USA		SRPS (JUS)
	17007	17006		AISI/SAE	UNS	
≈ 20MnCr5	1.7147	20MnCr5	18HGT	4820	G48200	Č4321

Alloying elements, %					
C	Si	Mn	P_{max}	S_{max}	Cr
0.17-0.22	0.15-0.40	1.1-1.4	0.035	0.035	1.0-1.3

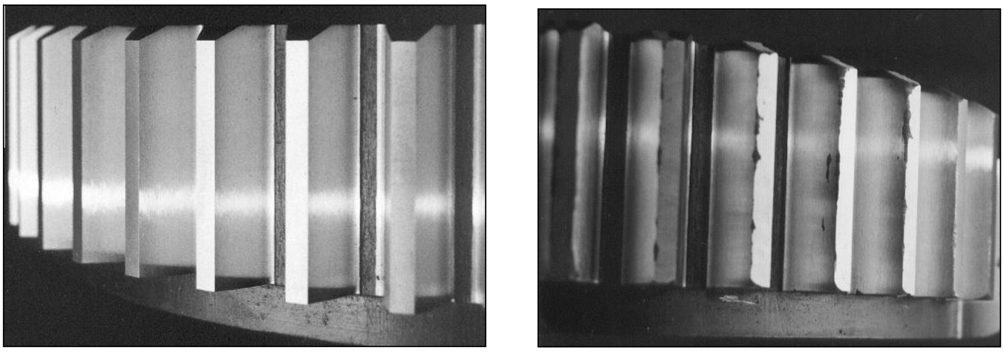

Fig. 1. Newly manufactured gear (left) and regenerated gear (right)

Behavior of austenite during the cooling is primarily determined by the chemical composition of steel, a simpler system for evaluating the influence of carbon and various alloying elements on the stability of austenite was developed, i.e. the concept of equivalent carbon (CE) as an indicator of metallurgical weldability of steel, (Lazić et al., 2009).

The most frequently used expression for weldability estimate is recommended by the International Institute of Welding (IIW). For the tested steel the CE value was within limits 0.55 – 0.71%, which is higher than the limit value (0.45%), so it is considered that the 20MnCr5 steel is sensitive to appearance of cracks and application of preheating, prior to hard-facing, is necessary. The preheating temperature can be approximately determined according to Seferian formula, (Markovic et al., 2021):

$$T_p = 350 \cdot \sqrt{C_E - 0.25} \quad (1)$$

which gives the range of the T_p values from 191°C to 237°C.

The adopted value for these tests was 230°C to compensate for the heat losses that usually appear due to transporting the gears from the furnace to the welding stand prior to commencing the hard-facing.

The 20MnCr5 steel for cementation (according to all the criteria and other methods for weldability estimates) belongs to conditionally weldable materials. That imposes application of preheating the gear prior to hard-facing, as well as selecting the adequate welding technology and the hard-facing parameters, including application of the post-welding heat treatment to reduce the level of residual stresses. The notation of the applied filler metals (FM), their sizes (diameter, *D*) and current intensity (J) are given in Table 2, while the chemical composition and the most important mechanical properties are given in Table 3.

Table 2. Notation and sizes of the used filler metals and applied current intensity

Notation			Manufacturer	D (mm)	I (A)
DIN	**AWS**	**DIN855**			
E-6-UM-55G	/	EDur 600	Jesenice[1]	2.50	70
/	/	Castolin 2	Castolin Eutectic[2]	3.25	92
E-6-60-UM	/	UTP 670	UTP[3]	3.25	90
E18.8Mn6B20+	E307 - 15	Inox 18/8/6	Jesenice[1]	2.50	90

[1] Slovenia; [2] Switzerland; [3] Germany.

Table 3. Chemical composition and mechanical properties of the applied filler metals

No.	C	Si	Mn	Cr	Ni	Mo	Other	Hardness		R_m	R_{p02}
	%							HV	HRC	[MPa]	
1	0.5	2	/	9.5					54		
2			+	+		+			57-62		
3	0.4	0.85	0.8	9.7		0.6	1.5% V	> 600			
4	0.12		7.0	19.0	9.0					590-690	> 350

4. Tribological investigations

Universal and special control-measuring devices were used for control of the geometrical measures of samples. The tooth profile, the tooth flanks directions and radial deviation were checked on involute-meter "Kligelnberg". Quality of the regenerated surfaces was determined by the comparative method; the controlled surface was compared to corresponding standard with medium arithmetic profile deviation Ra. The surface hardness was measured on the "Leitz Wetzlar" device by the Rockwell method (HRC).

The characteristic parameters values, obtained by measurements, are presented in Table 4.

To select the optimal filler metal for hard-facing the working surfaces of gears the model tests were performed on a tribometer by the "block-on-disc" method (Arsić et al., 2016b). The average values of the friction coefficients were determined based on those tests, results of which are presented in Table 5 and in Figures 2 to 4. The tested samples surface topography was determined by measuring the wear traces on a universal microscope UIM-21.

Table 4. Parameters of geometrical and kinematical accuracy of the controlled gears

Controlled parameter	**Required values**	**Gears hard-faced by**		
		INOX 18/8/6 and EDur 600	**Castolin 2**	**UTP 600**
Base circle diameter d_b (mm)	$270_{-0.5}$	269.82	269.77	269.77
Measure over 5 teeth W_5 (mm)	83.32	83.12	83.18	83.11
Tooth profile tolerance T_{ev} (μm)	16	11	15	13
Tooth flank line deviation T_β (μm)	15	10	14	12
Radial tooth deviation T_r (μm)	78	33	60	52
Tooth surface machining quality	N7	N7 R_a =1.60 μm	N7 R_a =1.60 μm	N7 R_a =1.60 μm
Surface hardness (HRC)	55 - 58	56.4	56.2	55.8

Table 5. The friction coefficients and the wear trace widths for samples hard-faced by different filler metals

Disc		**Block**	**Friction coefficient**	**Wear trace width (mm)**
Material	Hardness (HRC)	Filler metal		
20MnCr5 steel	55 - 58	INOX 18/8/6 and EDur 600	0.064	0.960
		Castolin 2	0.115	1.028
		UTP 600	0.090	0.955

From analysis of the tribological tests one can conclude that out of the tested filler metals the best results, i.e. the lowest values of the friction, are obtained for samples hard-faced by the combination of the filler metals INOX 18/8/6 and EDur 600, while the worst results are obtained for the Castolin 2 filler metal

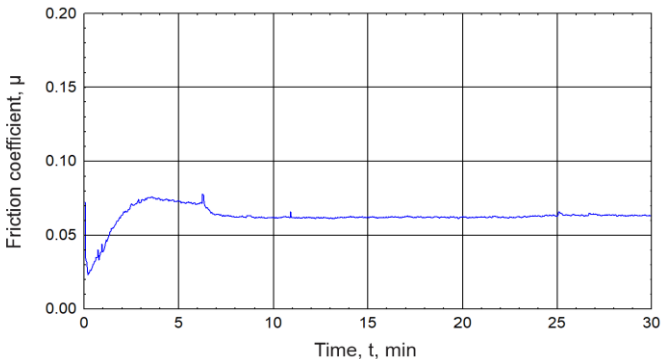

Fig. 2. Friction coefficient variation with time of the sample hard-faced by combination of the filler metals INOX 18/8/6 and EDur 600

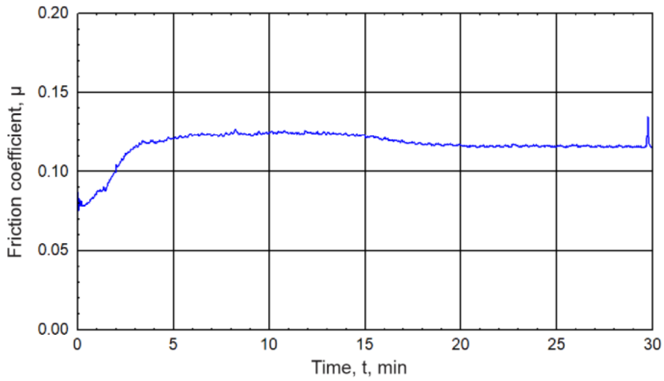

Fig. 3. Friction coefficient variation with time of the sample hard-faced by the Castolin 2 filler metal

From analysis of the tribological tests one can conclude that out of the tested filler metals the best results, i.e. the lowest values of the friction, are obtained for samples hard-faced by the combination of the filler metals INOX 18/8/6 and EDur 600, while the worst results are obtained for the Castolin 2 filler metal.

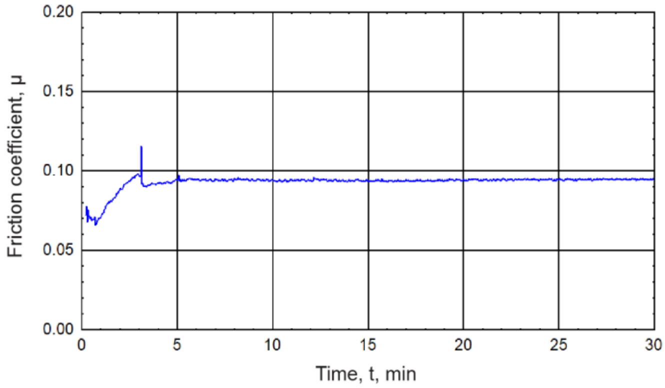

Fig. 4. Friction coefficient variation with time of the sample hard-faced by the UTOP 6570 filler metal

5. Conclusions

With carefully selected and well organized preparation for hard-facing of the damaged gears, selection of adequate filler metal(s) and welding procedures and strictly respecting the prescribed operation procedures, it is possible to realize the successful reparation and to obtain the working surfaces of the regenerated gears that possess improved mechanical characteristics.

Analysis of results obtained by testing the regenerated gears' surfaces provided for the following conclusions:

- Geometrical characteristics, prescribed tolerances and deviations, as well as the quality of the regenerated gears' surfaces, completely comply with prescribed and standardized values.
- What concerns the tribological characteristics, the best results, i.e. the lowest friction coefficient and the smallest width of the wear trace, were achieved when the base metal was hard-faced with the combination of filler metals INOX 18/8/6 and EDur 600, while the worst results were exhibited for the Castolin 2 filler metal.

Acknowledgements

This research was partially financially supported by the project "Innovative Solutions for Propulsion, Power and Safety Components of Transport Vehicles" ITMS 313011V334 of the Operational Program Integrated Infrastructure 2014 – 2020 and co-funded by the European Regional Development Fund and project TR35024 financed by the Ministry of education, science and technological development of Republic of Serbia.

Note: *The shorter version of this article was presented at the 15th International Conference "Quality, Production, Improvement – QPI 2021", 14-16.06.2021. Poland.*

References

Arsić, D., Lazić, V., Nikolić, R., Mutavžić, M., Sedmak, A., Hadzima, B., 2016a. Possibility for realizing savings by application of the hard-facing as the revitalization technology of various machine parts, in Technical aspects of materials quality. Eds. Pietraszek, J., Klimecka-Tatar, D., Managers of Quality and Production Association, Czestochowa, Poland, Chapter 8, 111-144.

Arsić, D., Lazić, V., Mitrović, S., Džunić, D., Aleksandrović, S., Djordjević, M., Nedeljković, B., 2016b. Tribological Behavior of Four Types of Filler Metals for Hard Facing Under Dry Conditions. Industrial Lubrication and Tribology, 68(6), 729-736, DOI: 10.1108/ILT-10-2015-0156

Atxaga, G., Irisarri, A.M., 2010. Failure analysis of the end of a shaft of an engine. Engineering Failure Analysis, 17(4), 714-721, DOI: 10.1016/j.engfailanal.2009.08.010

Bai, H., Zhu, C., Zhou, Y., Chen, X., Feng, H., Ye, W., 2020. Study on Tooth Interior Fatigue Fracture Failure of Wind Turbine Gears. Metals, 10(11), 1497, DOI: 10.3390/met10111497

Borrego, L.P., Pires, J.T., Costa, J.M., Ferreira, J.M., 2009. Mould steels repaired by laser welding. Engineering Failure Analysis, 16(2), 596-607, DOI: 10.1016/j.engfailanal.2008.02.010

Czuprynski, A., 2020. Comparison of properties of hardfaced layers made by a metal-core-covered tubular electrode with a special chemical composition. Materials, 13, 5445, DOI: 10.3390/ma13235445

Dadon, I., Koren, N., Klein, R., Lipsett, M.G., Bortman, J., 2020. Impact of gear tooth surface quality on detection of local faults. Engineering Failure Analysis, 108, 104291, DOI: 10.1016/j.engfailanal.2019.104291

Desir, J.L., 2001. Examples of Repair Welding of Heavy Machinery Subject to Breakage due to Low Frequency Alternating Stresses. Engineering Failure Analysis, 8(5), 423-434, DOI: 10.1016/S1350-6307(00)00046-7

Durmuş, H., Çömez, N., Gül, C., Yurddaşkal, M., Yurddaşkal, M., 2018. Wear performance of Fe-Cr-C-B hardfacing coatings: Dry sand/rubber wheel test and ball-on-disc test. International Journal of Refractory Metals and Hard Materials, 77, 37-43, DOI: 10.1016/j.ijrmhm.2018.07.006

EN 14700:2014: Welding consumables — Welding consumables for hard-facing.

EN 1599:1997: Welding consumables — Covered electrodes for manual arc welding of creep-resisting steels - Classification.

Feng W., Feng Z., Mao L., 2020. Failure analysis of a secondary driving helical gear in transmission of electric vehicle. Engineering Failure Analysis, 117, 104934, DOI: 10.1016/j.engfailanal.2020.104934

Gualco, A., Marini, C., Svoboda, H., Surian, E., 2015. Wear resistance of Fe-based nanostructured hardfacing. Procedia Material Science, 8, 934-943, DOI: 10.1016/j.mspro.2015.04.154

Hao, F., Liao, B., Li, D., Liu, L., Dan, T., Ren, X., Yang, Q., 2011. Effects of rare earth oxide on hardfacing metal microstructure of medium carbon steel and its refinement mechanism. Journal of Rare Earths, 29(6), 609-613, DOI: 10.1016/S1002-0721(10)60507-8

Lazić, V., Sedmak, A., Aleksandrović, S., Milosavljević, D., Čukić, R., Grabulov, V., 2009. Reparation of damaged mallet for hammer forging by hard facing and weld cladding. Tehnički vjesnik - Technical Gazette, 16(4), 107-113, https://hrcak.srce.hr/45753

Lazić, V., Čukić, R., Aleksandrović, S., Milosavljević, D., Arsić, D., Nedeljković, B., 2014. Techno-economic justification of reparatory hard facing of various working parts of mechanical systems. Tribology in Industry, 36(3), 287-292, http://www.tribology.fink.rs/journals/2008/2008-1-2/1.pdf

Lazić, V., Arsić, D., Nikolić, R., Mutavdžić, M., Meško, J., 2016. Reparation by Hard Facing of the Damaged Secondary Stone Crusher. Manufacturing Technology, 16(2), 375-380, https://www.journalmt.com/artkey/mft-201602-0012_reparation-by-hard-facing-of-the-damaged-secondary-stone-crushers.php

Li, D., Yang, Y., Liu, L., Zhang, J., Yang, Q., 2009. Effects of RE oxide on the microstructure of hardfacing metal of the large gear. Material Science and Engineering A, 509, 94-97, DOI: 10.1016/j.msea.2009.02.018

Markovic, S., Milovic, Lj., Marinkovic, A., Lazovic, T., 2011. Tribological aspect of selecting filler metal for repair surfacing of gears by hardfacing. Structural Integrity and Life, 11(2), 127-130, http://divk.inovacionicentar.rs/ivk/ivk11/127-130-IVK2-2011-SM-LM-AM-TL.pdf

Marković, S., Arsić, D., Nikolić, R., Lazić, V., Hadzima, B., Milovanović, V., Dwornicka, R., Ulewicz, R., 2021. Exploitation characteristics of teeth flanks of gears regenerated by three hard-facing procedures. Materials, 14(15), paper no. 4203, DOI: 10.3390/ma14154203

Marković, S., Arsić, D., Nikolić, R.R., Lazić, V., Ratković, N., Hadzima, B., Szmidla, J., Ulewicz, R., 2021. Analysis of the Welding Type and Filler Metal Influence on Performance of a Regenerated Gear. Materials, 14(6), 1496, DOI: 10.3390/ma14061496

Mohammed, O.D., Rantatalo, M., 2020. Gear Fault Models and Dynamics-Based Modelling for Gear Fault Detection - A Review. Engineering Failure Analysis, 117, 104798, DOI: 10.1016/j.engfailanal.2020.104798

Suraj, R., 2021. Hardfacing and its effect on wear and corrosion performance of various ferrous welded mild steels. Materials Today: Proceedings, 42, 842-850, DOI: 10.1016/j.matpr.2020.11.592
Tomić, R., 2019. Influence of Tribological Pairs on Structural and Material Damage. Structural Integrity and Life, 19 (1), 58-66, http://divk.inovacionicentar.rs/ivk/ivk19/058-IVK1-2019-RT.pdf
Trško, L., Lago, J., Jambor, M., Nový, F., Bokůvka, O., Florková, Z., 2020. Microstructure and residual stress analysis of Strenx 700 MC welded joint. Production Engineering Archives, 6, 41-44, DOI: 10.30657/pea.2020.26.09
Ulewicz, R., Novy, F.R., 2016. The influence of the surface condition on the fatigue properties of structural steel. Journal of Balkan Tribological Association, 22, 1147-1155, https://scibulcom.net/en/article/39wnZZhcN-DoMsJzVTXq8
Vasić, M., Stojanović, B., Blagojević, M., 2020. Fault Analysis of Gearboxes in Open Pit Mine. Applied Engineering Letters, 5(2), 50-61, DOI: 10. 18485/-aeletters.2020.5.2.3
Vicen, M., Bokuvka, O., Nikolić, R., Brónček, J., 2020. Tribological behavior of low-alloyed steel after nitriding. Production Engineering Archives, 26(3), 78-83, DOI: 10.30657/pea.2020.26.16
Vicen, M., Brónček, J., Nový, F., 2019. Investigation of tribological properties of CarbonX coating deposited on 100Cr6 steel. Production Engineering Archives, 25, 52-55, DOI: 10.30657/pea.2019.25.10
Xing, S., Yu, S., Deng, Y., Dai, M., Yu, L., 2012. Effect of Cerium on abrasive wear behaviour of hardfacing alloy. Journal of Rare Earths, 30, 69-73, DOI: 10.1016/S1002-0721(10)60641-2
Yousfi, B.E., Soualhi, A., Medjaher, K., Guillet, F., 2020. New Approach for Gear Mesh Stiffness Evaluation Of Spur Gears With Surface Defects. Engineering Failure Analysis, 116, 104740, DOI: 10.1016/j.engfailanal.2020.104740

不同硬面加工工艺对再生齿轮表面质量的影响

關鍵詞
再生
硬着头皮
齿轮
摩擦学特性
摩擦系数

摘要
在机器零件的再过程中，会出现某些现象，对其工作能力的丧失产生重大影响。遗传特性通过在通过硬面修复磨损齿的技术操作过程中产生的齿轮齿的几何参数和物理-机械-冶金参数的相互依赖性来表达。考虑了附加材料类型（电极及其组合）对焊接轮齿摩擦学特性的影响，因此应用了所谓的硬附加材料。这些是无需后续热处理或热化学处理即可提供所需的牙齿表面硬度的附加材料。这项研究不涉及从机器系统中移除的特定磨损齿轮的再生，而是制造新齿轮，然后将其损坏，然后使用保护金属电弧焊 (SMAW) 程序通过硬面进行再生。因此，所有测试的齿轮均由相同的材料制成，属于一个批次，并在相同的机器上以相同的加工方式进行加工。试验是在由 20MnCr5 钢制成的用于胶结的样品上进行的，在摩擦计上通过“块盘”方法进行，该方法旨在模拟混凝土齿轮在开采条件下的耦合齿的运行条件。基于所进行的摩擦学测试，通过测量磨损痕迹确定了表面的平均摩擦系数和形貌，并定义了哪些附加材料可提供通过硬面再生的齿轮表面的最佳摩擦学特性。