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Fretting wear in an interference fit with a modified surface layer of the shaft

SUMMARY

Research results presented in the article pertain to fretting wear in a push-in connection. The research was carried out on an interference fit - a shaft and a sleeve. Surface layer of the examined shaft was modified through rolling and surface hardening. The analysis also adopted the research over shafts without modifications to the surface layer. At first the tear and wear tests were carried out in a fatigue machine, enabling to perform rotational bending of the sample, as a consequence of which cooperating oscillatory shifts appeared on the surface, which is a condition for the fretting wear emergence. After the tear and wear phase, there were laboratory tests carried out, the purpose of which was to determine the actual condition of the surface layer. Those examinations included macroscopic and microscopic observations carried out with an optical and scanning microscope. The research proved that elimination of the adhesion phenomenon limits development of fretting wear. Observation of samples suggests that application of surface hardening limits development of fretting wear to the greatest extent. This is caused by achievement of a high level of surface hardness. At the end, it was found out that the research results performed on the shaft-sleeve connection may be referred to a real object, which is e.g. a wheel-axis connection of a rail vehicle wheelset.

Key words: Fretting, interference fit, surface hardening, rolling, wheelset.

Introduction

Fretting is one of the processes damaging the surface layer of machinery elements. It is a phenomenon of oscillatory slippage with a low amplitude, not exceeding 150 μm, of contacting elements, the result of which is damage and wear of the surface layer. Fretting is a phenomenon characterized with a highly complex tear and wear mechanism, where the following actions overlay or appear subsequently: adhesion wear, surface fatigue, exfoliation, oxidation, abrasion of roughness tips and erosion with loose wear products[1].

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[1] S. Guzowski, *Analiza zużycia frettingowego w połączeniach wciskowych na przykładzie osi zestawów kołowych pojazdów szynowych*, „Monografia 284", Politechnika Krakowska, Kraków 2003.

A condition for presence of fretting wear is posed by contacting oscillatory shifts of the cooperating elements surfaces. Thus, the phenomenon of tear and wear may be encountered in numerous fields of science. While reviewing academic literature, we may found works related to research over fretting wear, among others, in aviation, aerospace, medicine or ropes of cable cars. An example of such works may be posed by[2]. Elements connected through pushing-in are especially exposed to tear and wear. This connection accumulates all factors that condition development of fretting wear, especially the contact force between the connected elements, and the possibility of oscillation between them, if the connection works in rotational bending conditions. Such a case may be encountered e.g. in the rail industry. An example of potential occurrence of fretting wear in rail vehicles may be a push-in connections wheel-axis, which undergoes rotational bending during exploitation. Literature also includes positions related to fretting wear studies in rail vehicles. Exemplary works, where authors concentrate on the fretting wear phenomenon in rail vehicles are[3]. Previous research results suggest that a process that initiates development of fretting wear in a push-in connection is first of all adhesion.

One manner to limit the adhesion phenomenon in a push-in connection, therefore to reduce or eliminate fretting wear, is to increase hardness of the surface layer on one of the connected elements.

Methodology of research

The research was carried out on a clamped joint – a shaft and a sleeve. The shaft applied in the research was made from C35 steel, while the sleeve from E295 material. Samples dimensions were dictated by the research stand requirements. The shaft length was 226 mm; the remaining dimensions were presented in fig. 1.

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[2] H. Carreon, *Thermoelectric detection of fretting damage in aerospace materials*, „Russian Journal of Nondestructive Testing” Nov 2014, Vol. 50 Issue 11, p. 684–692; A. Cruzado, S.B. Leen, M.A. Urchegui, X. Gómez, *Finite element simulation of fretting wear and fatigue in thin steel wires*, „International Journal of Fatigue” Oct 2013, Vol. 55, p. 7–21; E.T. Moreno, E.J. Carrasquero, Y.Y. Santana, J.G. La Barbera-Sosa, E.S. Puchi-Cabrera, M.H. Staia, *Estudio de desgaste por “fretting” de un recubrimiento tipo duplex depositado sobre una aleación de aluminio 7075-T6*, „Rev. LatinAm. Metal. Mat.” 2013,33 (2), p. 292–307; Ş. Ghimişi, *Experimental investigtion of the fretting phenomenon-dependence of numbers cycles*, „Fiabilitate si Durabilitate – Fiability & Durability”, No 2/2013 Editura “Academica Brâncuşi”, Târgu Jiu; S. Guzowski, op. cit.; Kubota Masanobu, Hirakawa Kenji, *The effect of rubber contact on the fretting fatigue strength of railway wheel tire*”, „Tribology International” Sep 2009, Vol. 42 Issue 9, p. 1389–1398; V.O. Kralya, O.H. Molyar, V.A. Trofimov, A.M. Khimko, *Defects of steel units of the high-lift devices of aircraft wings caused by fretting corrosion*”, „Materials Science” 2010, Vol. 46, No. 1, p. 108–114; Xin Li, Zhengxing Zuo, and Wenjie Qin, *Fretting fatigue mechanism of bearing cap bolted joints*”, „Review of Scientific Instruments 85”.

[3] C. Song, M.X. Shen, X.F. Lin, D.W. Liu, M.H. Zhu, *An investigation on rotatory bending fretting fatigue damage of railway axles*, „Fatigue Fract Engng Mater Struct” 2014, 37, p. 72–84; S. Guzowski, op. cit.; Kubota Masanobu, Hirakawa Kenji, op. cit.; J.F. Zheng, J. Luo, J.L. Mo, J.F. Peng, X.S. Jin, M.H. Zhu, *Fretting wear behaviors of a railway axle steel*, „Tribology International” May 2010, Vol. 43 Issue 5/6, p. 906–911.

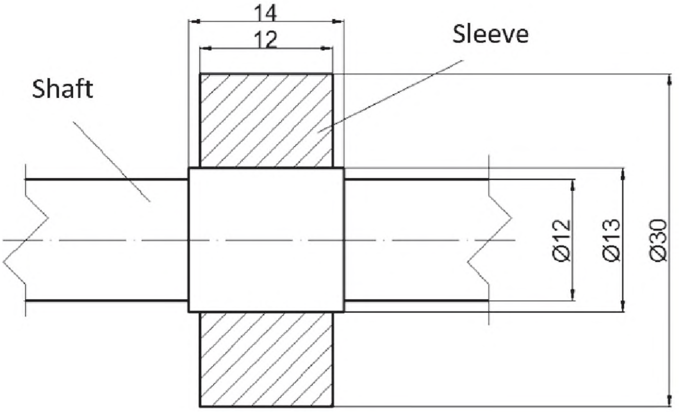


Fig. 1. Dimensions of the shaft and the sleeve

The connection between the shaft and the sleeve was made through pushing the sleeve into the shaft. Fig. 2 presents the samples near the connection.

Fig. 2. View on the sample around the push-in connection

Pushing in the sleeve on the shaft took place on a hydraulic press equipped with two independent manometers and a device registering the pushing-in force in the pushing-in function length.

Literature review and applicable calculation allowed to assume the pressure value of 0.02 mm. During the push-in process, attention needs to focused on the emerging tensions, the value of which may be exceeded what in turn may lead to permanent plastic deformation of the connected surfaces.

The tear and wear tests were carried out on a fatigue machine, the structure of which allows to adopt periodically variable load, with purse bending of the rotating sample.

The sample was loaded in such a manner as to obtain a proper distribution of the bending moment that leads to the roller bending. Therefore, the contact oscillatory shifts will occur between the connected surfaces, necessary for emergence of the fretting wear.

Fig. 3 presents a scheme of the sample load on a fatigue machine, and the resulting distribution of the rotational bending moment. Parameters of the sample's tear and wear tests were as follows:

- rotations $n = 1360\ \left[\frac{obr}{min}\right]$,
- sample load $Q = 400\ [N]$,
- number of cycles $7 \cdot 10^6$.

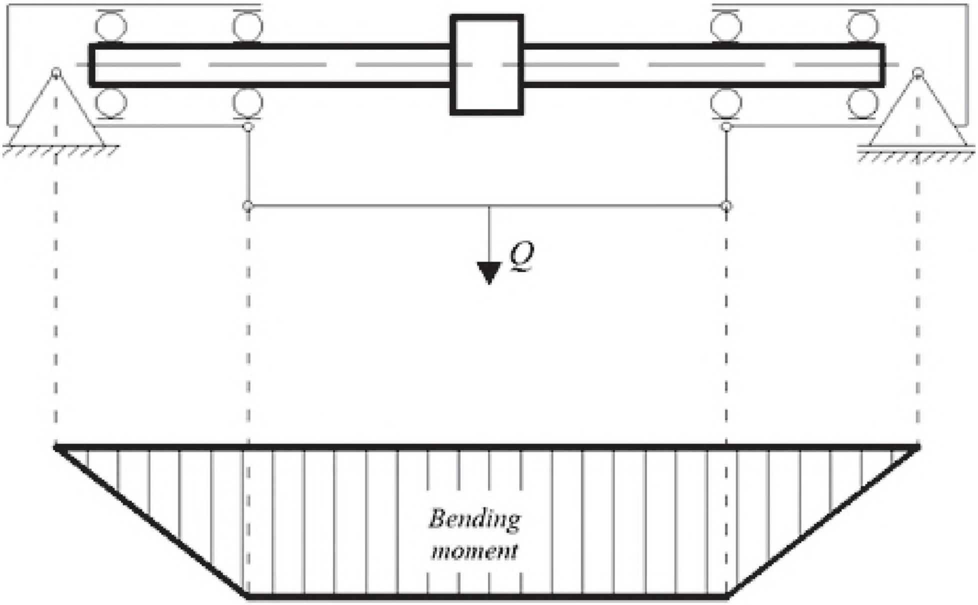


Fig. 3. Scheme of sample load on the fatigue machine

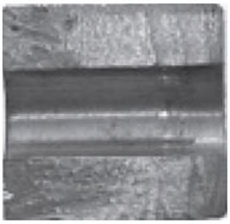
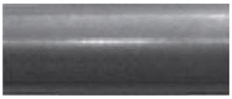
Distribution of regular tensions on the shaft surface for the load values mentioned above did not cause any plastic deformations. Maximum value of tensions of the examined connections, determined with the finite elements method in the ANSYS software, is 70 MPa.

The tear and wear research was applied in case of samples, where modification of the shaft's surface layer included surface rolling and hardening. For comparison purposes, the examination was also carried out on samples without finishing processing for the shaft's top layer.

The processing methods of the top surface mentioned above were selected because of easiness to implement a given technology, relatively short processing time and low costs.

After completion of the tear and wear examinations, the laboratory tests were carried out, including macro- and microscopic observations. A detailed scope of that research is presented in table 1.

Table 1. The scope of laboratory tests of the samples after the tear and wear examinations

Sample	Test	Observation	Section	Device	Sample appearance
tshaf	micrographic	surface	not pickled	metallographic microscope	
			pickled		
			not pickled	scanning microscope	
connection between a shaft and a sleeve		connection surface	not pickled	metallographic microscope	
			pickled		
			not pickled	scanning microscope	
sleeve	macrographic	surface	—	camera	
shaft			—	camera	

Characteristics of technological processes

Rolling processing is carried out mainly in order to generate specific physical qualities of material in the top surface of an item, to render it resistant towards such exploitation factors as: fatigue, abrasive wear, corrosion, etc. A characteristic feature of the top surface after rolling processing is its sphere structure, occurring especially visibly in case of steel with ferrite-perlite structure. There are four main spheres that may be differentiated in the top surface: fragmentations, plastic deformations, elastic deflections, tensile residual stresses. Fig. 6b presents micro-structure of the researched sample after rolling.

The rolling process applied to the wheel seat in the examined samples took place with an especially prepared device installed in a turning lathe. The rolling process scheme is presented in fig. 4.

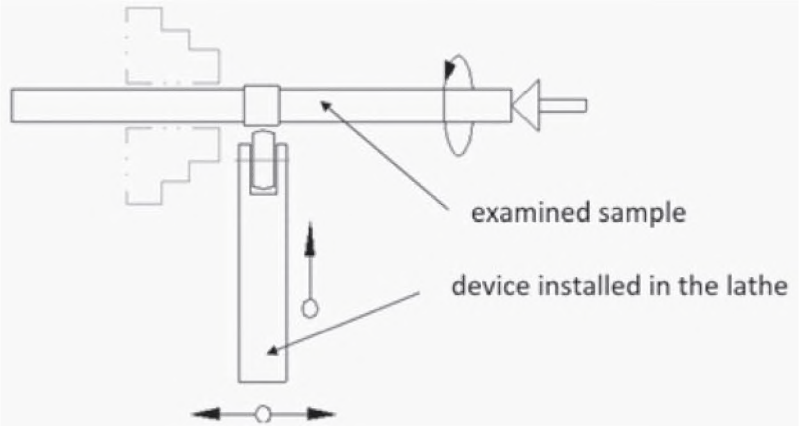


Fig. 4. The sample rolling process scheme

Surface hardening is applied in case of various parts of machinery, among others, shafts, gear wheels, wheelsets axes of cars, related to numerous advantages brought by this method of the top layer processing. An increase in the fatigue limit of hardened samples results from advantageous distribution of internal tensions, characterized by small residual tensile stresses within the non-hardened zone.

Top layer of the examined samples was hardened with an induction method. The samples were heated through induced current, by varying magnetic field. The heating time was 90 second. After hardening, the samples were stress relived in the temperature of about 380°C. The process took one hour. Fig. 5 presents the sample induction hardening process.

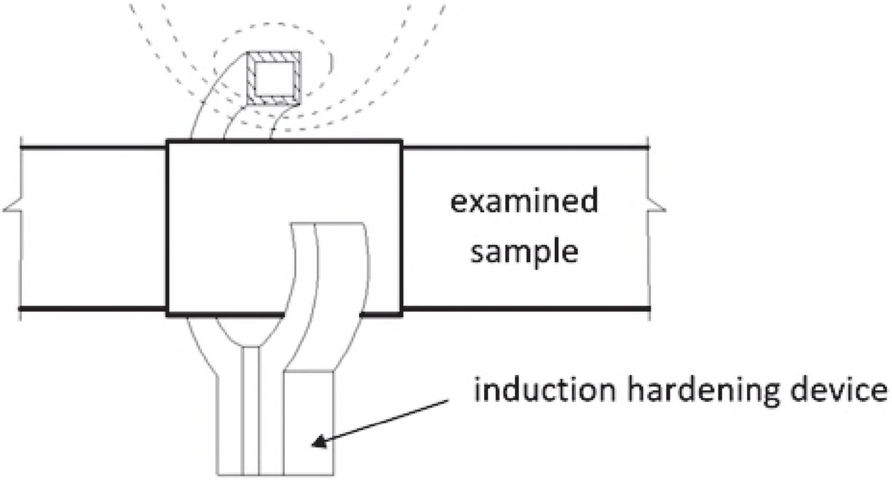


Fig. 5. The sample induction hardening scheme

The top layer after surface hardening has a martensitic structure. A gradual increase in the residual austenite amount lying between the martensite needles. Fig. 6 c presents micro-structure of the top surface after induction hardening.

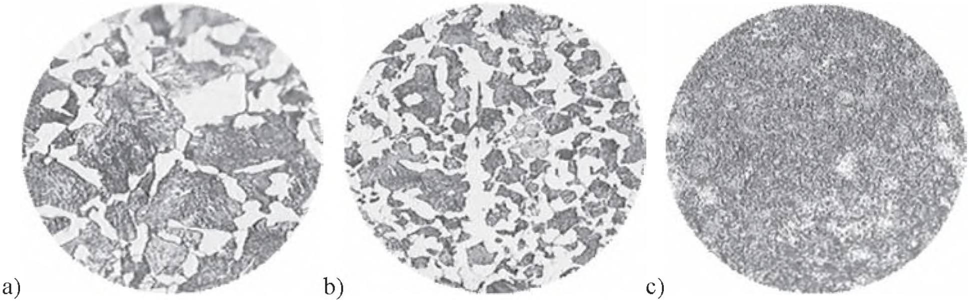


Fig. 6 Microstructure of the top layer, pickled with nital, surf. 200X: a) only milled shaft, b) rolled shaft, c) surface hardened shaft

Characteristics of the top layer of samples accepted for examinations are presented in table 2. The lowest roughness value was achieved for rolled shafts. It caused by "smoothening" of the surface during preparation of the sample.

Table 2. Measurement of hardness, roughness and push-in force for samples that underwent tear and wear tests

Surface type	**Hardness [HB]**	**Roughness Ra [μm]**	**Maximum force of pushing the sleeve into the shaft [kN]**
Only milled	170	1,86	8,6
Rolled	193	0,34	10,2
Surface hardened	>600	1,79	8,0
Sleeve surface (ground)	163	0,30	—

Laboratory tests results

Purpose of the laboratory tests was to determine the actual condition of the surface layer around the connection between the sleeve and the shaft, after the tear and wear tests for each proposed variant for finishing the shaft top surface.

At first, the macroscopic examination over the shaft surface was carried out on the spot of fretting wear. The results of observations are presented in Fig. 7.

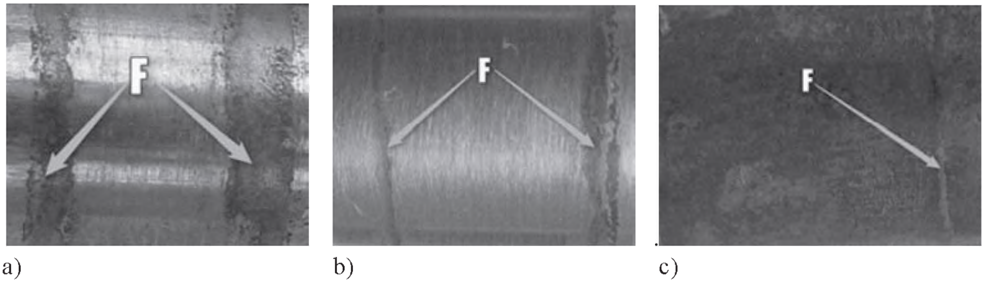
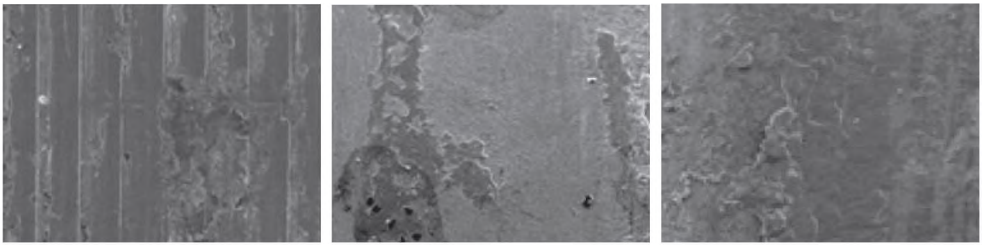


Fig. 7 Shaft surface after the tear and wear test, surf. about 10X, letter F marks the spot of fretting wear: a) only milled shaft, b) roller shaft, c) surface hardened shaft

Macrographic observations over the shaft' wheel seat proves that the fretting wear is present only on the edges of the connection, on both sides, with an exception of a surface hardened shaft. In this case, the fretting use marks are observed only on one side. In each case, the fretting wear is present in a form of a ring embracing the whole perimeter of the shaft's wheel seat. The most intense wear is observed in case of an only shaft wheel seat. The observed wear is characterized with brown color, typical for atmospheric corrosion of iron. A probable cause of such a phenomenon is contact of the damaged area with oxygen, because of a gap created between the shaft and sleeve surfaces, as a result of sample bending. Presence of oxygen is also confirmed by examinations of chemical composition in the spot of wear. Results of those examinations are presented in fig. 11. They prove that dominating elements are oxygen – 30% and iron – 33%, creating iron oxides.

Afterwards, the microscopic examination over the shafts surface was carried out on the spot of fretting wear. The results of observations performed on a scanning microscope are presented in Fig. 8.



a) b) c)

Fig. 8. Wear images on the shaft surface, surf. 100x: a) only milled shaft, b) rolled shaft, c) surface hardened shaft

The surface observations suggested that fretting wear occurs mainly in a form of build-ups that are distributed randomly within the wear area, which undergo plastic deformations and oxidation. Their source may be adhesion phenomenon. What is more, we can observe local abrasions and micro-pittings, which may result from the process of micro-cutting during shifts of consumption products.

During the microscopic observations of the connection surface between the shaft and the sleeve of sample pickled in some spots, a direct connection of the surfaces could be observed, and a gap between the connected surfaces, filled with consumption products. There is also a plastic deformation observed in case of the sleeve's top layer (fig. 9). Plastic deformation of the sleeve's top layer and local damages appeared most probably while pushing the sleeve into the shaft, and were caused by a great difference in hardness of the connected surfaces. In case of the shaft wheelbase, with similar surface roughness, what could contribute to emergence of the adhesion phenomenon.

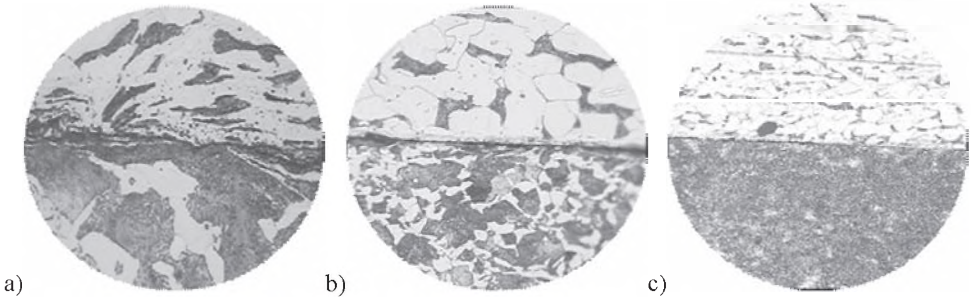


Fig. 9. Surface image of the connection between the shaft and the sleeve, pickled with nital, surf. 500X: a) only milled shaft, b) rolled shaft, c) surface hardened shaft

Alternate presence of the surfaces connection and the gap filled with consumption products confirms observations carried out on a scanning microscope, the exemplary results of which are presented in fig. 10.

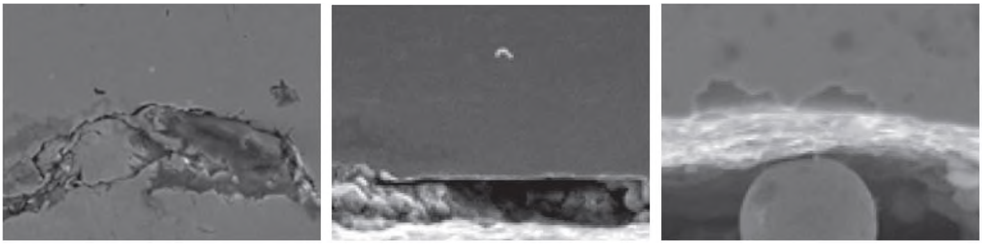


Fig. 10 Exemplary surface images of the connection between the shaft and the sleeve, observed on the scanning microscope

According to the observed laboratory tests results, the following mechanism of fretting wear occurrence in the push-in connection may be proposed. During the push-in process, micro-irregularities on the top surface with lower hardness are cut. The third substance generated in this manner fills in the micro-irregularities of the connected surfaces. Further part of the push-in process includes plastic deformations to the surface with irregularities tips cut to a smaller extent. Tear and wear examinations are accompanied by relative contact shifts between the surfaces of the connected elements. This contributes to removal of the third substance from the connection zone, and to creation of adhesive coupling in the sports of actual connection of the joined elements. Under influence of the oscillatory contact shifts, the emerged couplings are broken, thus creating gaps and build-ups on the shaft and sleeve surface, called consumption products.

A similar mechanism of fretting wear in the push-in connection of the wheel and axis is proposed by the author of the work[4].

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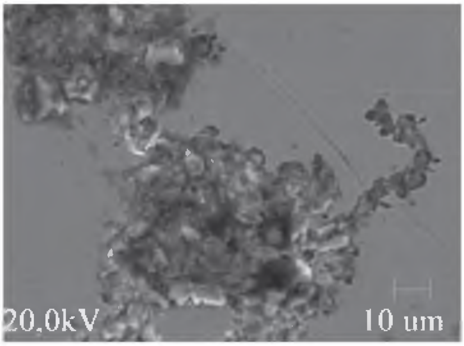
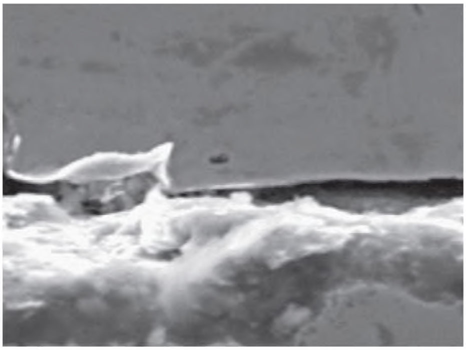
[4] S. Guzowski, op. cit.

a)


Elt.	Intensity (c/s)	Conc	Units	
C	8,25	20,154	wt.%	
O	72,03	30,168	wt.%	
Na	5,54	0,706	wt.%	
Mg	29,24	2,310	wt.%	
Al	18,19	1,139	wt.%	
Si	71,43	3,615	wt.%	
P	4,29	0,214	wt.%	
S	151,66	7,049	wt.%	
Ca	25,88	1,184	wt.%	
Fe	399,11	33,462	wt.%	
		100,000	wt.%	Total

b)


Elt.	Intensity (c/s)	Conc	Units	
C	41,06	39,936	wt.%	
O	54,14	21,472	wt.%	
Fe	577,78	38,592	wt.%	
		100,000	wt.%	Total

Fig. 11 Chemical composition a) at the spot of fretting wear on the shaft surface, b) consumption products

Conclusions and summary

Purpose of the tear and wear tests was to determine the influence of modifications to the shaft surface layer on the spot and reach of fretting wear in a push-in connection between a shaft and a sleeve.

Macrographic observations of the shafts surface after the tear and wear tests prove that fretting wear is present in case of all examined surfaces. Its size and reach depend on the type of the applied finishing. A factor that will decide in this case about intensity of the fretting ware development is roughness and hardness of the connected surfaces. Shaft with only milled surface are characterized with the highest value of roughness, but the smallest hardness of surface. Thus the area covered by the wear is the greatest, and present in a form of a ring, 5-10 mm wide on both sides of the sample. Shafts with rolled surfaces are characterized with a greater surface hardness when compared to milled shaft, but the lowest surface roughness caused by smoothing. In this case the fretting wear is observed as well, in a form of a ring on both sides of the shaft, but width of the wear ring is 2–5 mm. Shafts with induction hardened surface are characterized with the greatest level of hardness, thus the fretting wear is present only on one side of the shaft, in a form of a ring with maximum width of 1.5 mm.

Analysis of images from the scanning microscope, related to surfaces after the tear and wear examinations, present a similar character of fretting damages in case of all examined samples. A dominating type of damage are build-ups of materials emerging on the studies surfaces, which afterwards are deformed plastically and oxidized. What is more, spot abrasions and micro-pittings are observed. Furthermore, the scanning images prove that hardness and roughness of the connected elements surfaces exert crucial influence on intensity of the fretting wear. Surface damages in a form of build-ups and micro-pittings may results from the adhesion phenomenon. Local abrasion results most probably from the micro-cutting processes.

Microscopic images of the connection surface between the shaft and the sleeve confirm that the push-in process is accompanied by surface irregularities cuts, creating third substances, shifting during the exploitation process (fig. 10) under influence of oscillatory static shifts.

Results of examinations presented in the work refer to the push-in connection, shaft-sleeve. However, if adequate similarity is maintained, regarding, among others, the applied materials, dimensions proportions, load as well as the push-in force, the results may be related to an actual object. An example of an actual object may be posed here by a push-in connection wheel-axis of a rail vehicle wheelset. As the fretting damages may cause fatigue tear, they need to be eliminated e.g. through application of additional finishing to the connected surfaces. It is especially related to the wheelset mentioned above, as its technical condition exerts direct influence on travel safety.

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STRESZCZENIE

Sławomir Kowalski

Zużycie frettingowe w połączeniu wtłaczanym z modyfikowaną warstwą wierzchnią wałka

Zaprezentowane w artykule wyniki badań dotyczą zużycia frettingowego w połączeniu wtłaczanym. Badania przeprowadzono na połączeniu wtłaczanym wałek–tulejka. Warstwę wierzchnia badanych wałków poddano modyfikacji poprzez rolkowanie i hartowanie powierzchniowe. W analizie wykorzystano również badania wałków bez modyfikacji warstwy wierzchniej. W pierwszej kolejności wykonano badania zużyciowe na maszynie zmęczeniowej umożliwiającej uzyskanie obciążenia próbki w warunkach obrotowego zginania, a w konsekwencji pojawienie się oscylacyjnych przemieszczeń współpracujących powierzchni, co jest warunkiem wystąpienia zużycia frettingowego. Po badaniach zużyciowych przeprowadzono badania laboratoryjne, których celem było określenie stanu warstwy wierzchniej. W ramach tych badań przeprowadzono obserwacje makroskopowe oraz mikroskopowe przy użyciu mikroskopu optycznego i skaningowego. Badania wykazały, że wyeliminowanie zjawiska adhezji ogranicza rozwój zużycia frettingowego. Z obserwacji próbek wynika, że zastosowanie hartowania powierzchniowego znacząco przyczyniło się do ograniczenia rozwoju zużycia frettingowego. Spowodowane to jest uzyskaniem dużej twardości powierzchni. Na zakończenie stwierdzono, że wyniki badań przeprowadzone na połączeniu wałek–tulejka można odnieść do obiektu rzeczywistego, jakim jest np. połączenie koło–oś zestawu kołowego pojazdu szynowego.

Słowa kluczowe: fretting, połączenie wtłaczane, hartowanie powierzchniowe, rolkowanie, zestaw kołowy.

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