

Studies of worn surfaces by relocation profilometry

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Abstract: By relocation profilometry, a series of surface profiles can be recorded from the same track on a specimen. These techniques are used for monitoring specific particular points on the surface subjected to wear processes, in a more accurate manner as comparing to those involving average statistical information for surface. The method is providing a much more significant information about the surface, in a more efficient way, assuring that the same unworn investigated surface is studied after wear test. The studied roughness digital profiles were obtained before and after the testing of rolling/sliding line contacts, characteristic for spur gears, which has been simulated on SAE sets, with a two rollers test machine. The acquisition of the relocated profiles is performed on the same generatrix of the roller, before and after wear testing. To correlate the unworn and worn profiles, a spheroconical indentation was created on the circumferential surface of the disk, in the zone of the tested roller that remain unworn during the test. Measuring changes of the profiles by relocation techniques, two methods for wear assessment are presented: linear wear estimation by simulating the profile wearing and estimation of the volume wear.

Keywords: Relocation profilometry, wear tests, worn surface.

1. Introduction

In any experiment proposing to find a relationship between surface topography and tribosystem functioning, the objective is selecting the parameter that will better characterise the tribological function being under observation.

The interesting aspects of studying the running in process are information about surface characteristics and their changes during the running in, with or without experiment, the behaviour prediction starting from the unworn zones, for the efficient monitoring of the wear process to identify the wear types [1, 2, 3, 4].

The measurements of many surface parameters before, during and after testing rise immediate problems especially for isotropic surfaces. The measuring process of every parameter on a determined surface length has a statistically limited incertitude degree. And especially the summit height measurements are susceptible to incertitude.

There are a few ways of approaching this matter. One method is to perform measurements along the investigated surface and to average them, this one being not completely satisfactory as concerning economic and technical points of view as only a small percentage of asperities may be affected during the wear process. The consequence is that this averaging process may lead to loose the significance of severe local changes of surface topography.

The other method is by using relocation profilometry techniques. By relocation profilometry, a series of surface profiles can be recorded from the same track on a specimen [5]. These ones are monitoring



specific particular points on the surface, during the experiment, in a more accurate manner as comparing to those involving average statistical information for all over the surface. The advantage of the method is that of getting a much more significant information about the surface, in a more efficient way, assuring that the initial investigated surface is repeatedly studied. For the most experiments, the individual profiles of the surface are identified and consecutively monitored during the experiments usually using digital techniques. For different stages of the experiment, the profile is investigated and the signal offered by the amplification system is digitised and stored. Thus it is possible to evaluate and calculate the changes of the surface parameters. The example presented by Stout in the paper [1] indicated the changes of some surface parameters during wear tests with a rig of cross cylinders.

This kind of information is difficult to obtain without digital methods and devices. The relocation techniques were used for experiments involving many types of laboratory systems: cross cylinders, twin rollers testing machines and bearings testing rigs.

The major problem is to obtain a suitable solution for introducing the measuring device and the testing machine in the same investigating chain. Previous research demonstrated the necessity of two stages for applying the relocation technique, these being a certain repeated and accurate positioning both in the testing machine and in the measuring device of the specimen.

The results of applying the relocation techniques in tribology are presented in [1, 5, 6, 7, 8, 9, 10, 11, 12, 13]. These techniques require either an accurate positioning of the specimen in the complex measuring instrument [2, 14]. In the study presented in [11], a Hirth Coupling (Mitsubishi Heavy Ind.) was used for positioning a specimen on the measuring device. Placement, measurement, and removal were repeated 10 times and the deviation in the profile measurement direction was calculated using cross-correlation functions. In work [4], a procedure used to relocate and take profile measurements is presented.

Different gear tooth surface profile traces taken from standard steel FZG test gears have been used in [15]. The profiles are measured by mounting the test gear on a specially manufactured relocation rig for profilometer measurement, ensuring that the same area of the tooth is assessed at each load stage.

Metrology studies using indentation system, demanding the presence of control unworn zones on the inspected surfaces, are presented in papers [4, 7, 9, 16].

2. Studying wear by profilometric methods

2.1 Wear experiments

In rolling/sliding wear tests, studies on the surface profilometry can provide useful information about load-carrying capacity and some functional proprieties concerning lubricant retention.

The rolling/sliding line contacts, characteristic for spur gears, has been simulated on SAE sets, with a two rollers test machine [9]. An Amsler test machine was adapted for SAE test sets, adjusted and completed for a wear testing program. The test rig has been provided with a torque transducer (type T30FN200 - Hottinger Baldwin®) for measuring friction torque and rotational speed, a force transducer, temperature transducers and a data acquisition system (DMCPlus-Hottinger Baldwin®). The rollers were loaded on line contact using a hydraulic loading system (load range: 3-15 kN), at three values, producing Hertz pressure comparable to those in the studied spur gears.

For all tested pairs the running time was 10^5 cycles, corresponding to the early-stage wear, while the most significant tribolayer parameters changes occur. The tests were performed for the same rotational speed $n= 525$ rev/min. Because the rotational speed of each one of two rollers in running is the same, three different diameter combinations assure the different rolling-sliding ratio, calculated as $s=(v_1-v_2)/(v_1+v_2)$.

Lubrication was achieved by splashing and the lubricant was paraffinic mineral base-oil (AGMA lubricant no. 4 EP).

The experimental research was done taking into account the following commanding factors influencing the wear process [9]:

- relative sliding speed characterised by sliding-rolling ratio $s=(v_1-v_2)/(v_1+v_2)$: $s_1=0,225$, $s_2=0,075$ and $s_3=0$ (pure rolling);
- normal loading on the line contact, by terms of Hertz pressure: $p_1=850$ MPa, $p_2=700$ MPa, $p_3=560$ MPa;
- different materials for rollers, C 45 (similar to 1045 SAE steel grade) and 40Cr10 (similar to 5140 SAE steel grade), being two common grades of steel for high pitch spur gears, through-hardened;
- different initial microgeometry pairs: roller 1 and roller 2 both turned or roller 1 turned and roller 2 grinded.

Based on relocation technique, there were done complex profilometry analysis of surfaces using statistical roughness parameters and Abbott-Firrestone curve, allowing to establish interdependent evaluation and characterisation of values and evolution of both some specific wear process parameters and tribolayer parameters.

2.2 Data acquisition equipment

The acquisition of the digital profiles was performed by the help of the profilometer Surtronic3+, widely used in tribological studies involving surface geometry evaluation and was processed with Talyprof (equipment and software Taylor Hobson®).

Some of the expert functions of the software were used for the studies. Figure 1 presents Talyprof screens, with “Compute area of the hole” feature, for the unworn profile (a) and for the worn profile (b), respectively.

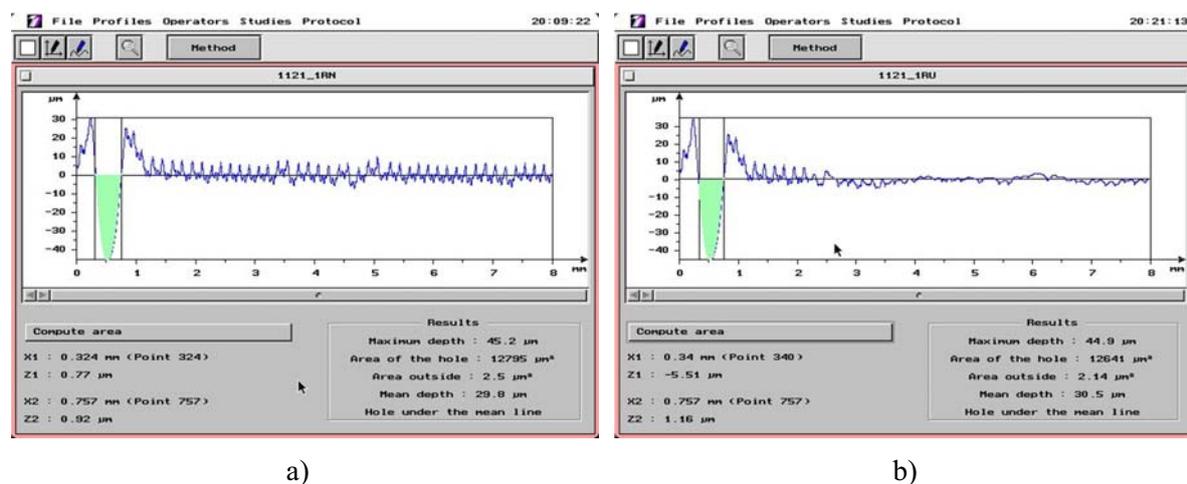


Figure 1. Talyprof screens, with “Compute area of the hole” feature:
a) unworn profile; b) worn profile.

2.3 Methodology for studying the surface microgeometry based on the relocation technique

The authors used the relocation technique for evaluating rough profile, before and after a wear testing, without any intermediary investigation.

After 10^5 running cycles (rotations), the inspected roller (figure 3) has been designed with a larger width as compared to its mating roller. Two unworn zones, l_1 and l_2 , border the worn zone (b_2), this one being the zone having contact with the mating roller, during the test.

The acquisition of the relocated profile is done on length $l_r=8$ mm and include the spheroconical indentation AC. The indentation is manufactured in the zone of the tested roller that will remain unworn during the test, using the indenter involved in measuring hardness in the HRC scale. The accurate positioning of the stylus is due to the AC indentation and to the V prismatic guide. The acquisition of the relocated profiles is performed on the same generatrix of the roller, both before and after wear testing. Figure 2 presents a profile with spheroconical indentation, used in relocation technique, represented with equal scales for both axes.

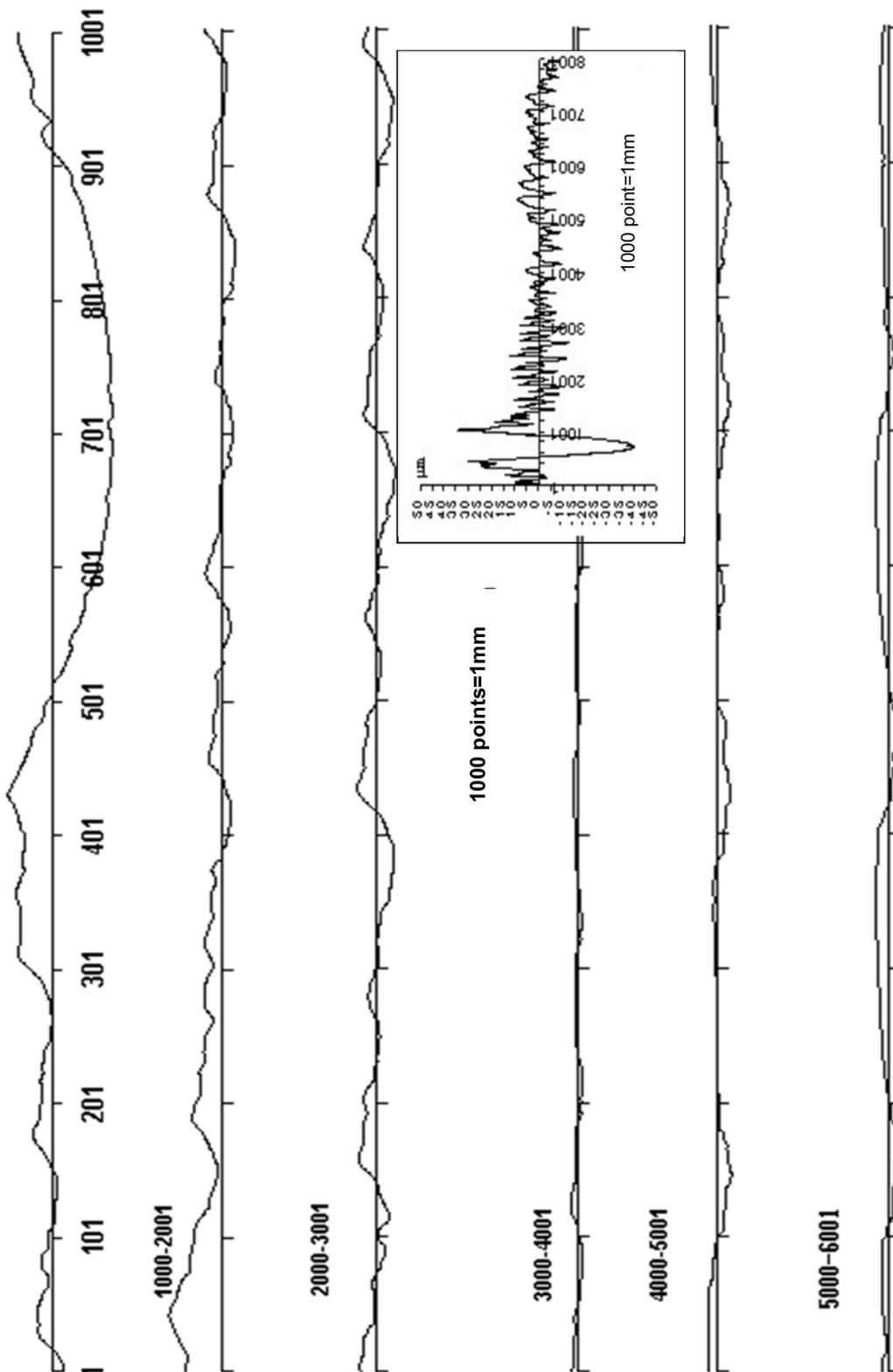


Figure 2. Profile with indentation, used in relocation technique, with equal scales for both axes. The profile is presented in 6 data sets (indentation between points 440÷1060). Regular presentation of the profile is shown in the detail box.

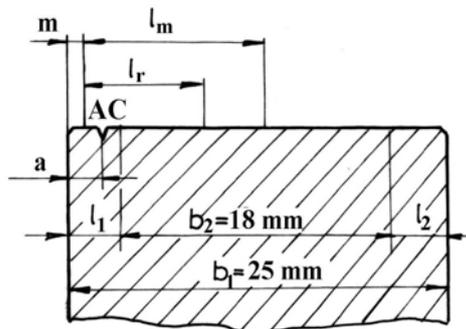


Figure 3. Indentation location on the roller, in order to apply the relocation technique.

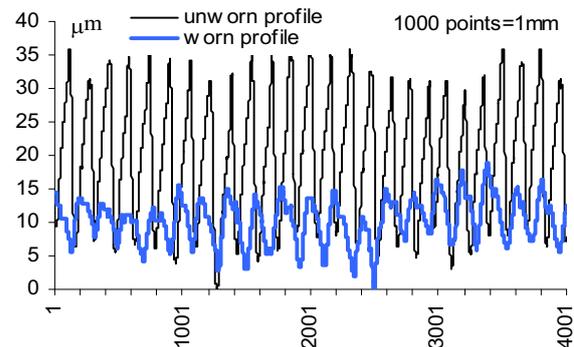


Figure 4. Unworn profile (U) and worn relocated profile (W), on the same generatrix of the roller.

The relocation of the device stylus on the worn surface was done on the same generatrix that was used for the acquisition of the unworn profile, in a transverse direction to the witness indentation. In order to achieve the relocation of the stylus, there were used two study operators of the Talyprof software: “Hole under the mean line” and “Compute area of the hole”. Many successive tries make possible to obtain relocated worn profiles, characterised by very close values of these two operators as compared to those characterising the unworn profiles (U), meaning a difference of at most $\pm 2\%$ (for the profile presented in figure 1, this difference is only a percentage of 1,22%).

From the final right parts of the profiles (figure 1), the unworn profile (U) and the worn relocated profile (W) were extracted, their length being $l_n = 4\text{ mm}$, beginning at the same distance from the AC indentation (figure 4). For these two profiles, there were calculated two parameters usually used for studying wear by profilometric methods: worn area $\Delta S = S_u - S_w$ and the variation of the actual profile length $\Delta L_0 = L_{0u} - L_{0w}$ (Note; the parameter Actual profile length, L_0 , describes how a real profile differs from a flat line is to determine how long the real profile is, compared to the horizontal evaluation length).

3. Wear evaluation by analysing relocated profiles

The shape and the dimensions of the rollers used for testing wear, allow obtaining the digital profiles by the help of the relocation technique. Based on these profiles, there are proposed two methods for wear evaluation.

3.1 Linear wear estimation by simulating the profile wearing

In order to estimate the linear wear, h , of the tribolayer, a truncation of the digital profile of the unworn surface was done using one of the operators available with Talyprof soft. The simulation criteria demand the simulated profile to have a value of roughness parameter R_q very close to the actual worn profile, meaning a difference of $\pm 3\%$ between the simulated profile and the actual worn one. Figure 5 presents an example with the three profiles involved in the estimation of linear wear: the unworn profile, the actual worn profile and the worn profile obtained by simulation (as a truncated profile). The high difference, h , is considered as linear wear.

3.2 Estimation of volume wear

Using Visual Basic applications, the worn volume could be calculated by the help of the two digital profiles, the unworn (U) one and the worn one (W) (obtained by relocation technique, figure 4). The following areas were calculated, S_u and S_w , both being limited downside by the reference line, characterising the maximum depth (on the basic length $l = 4\text{ mm}$) and upside by the line characterising the highest peak for the unworn and worn profile, respectively. The difference $\Delta S = S_u - S_w$ was

calculated and also a specific worn area as $\Delta s = \Delta S/l$. The authors considered Δs as a mean value characterising the whole contact length ($b_2 = 18$ mm) and the roller circumference (taking into account the nominal value of the roller diameter, D). The specific mass of the worn material was also calculated, $\Delta m = \Delta s \cdot \pi D \cdot \rho$, with steel density $\rho = 7.9 \text{ kg/dm}^3$.

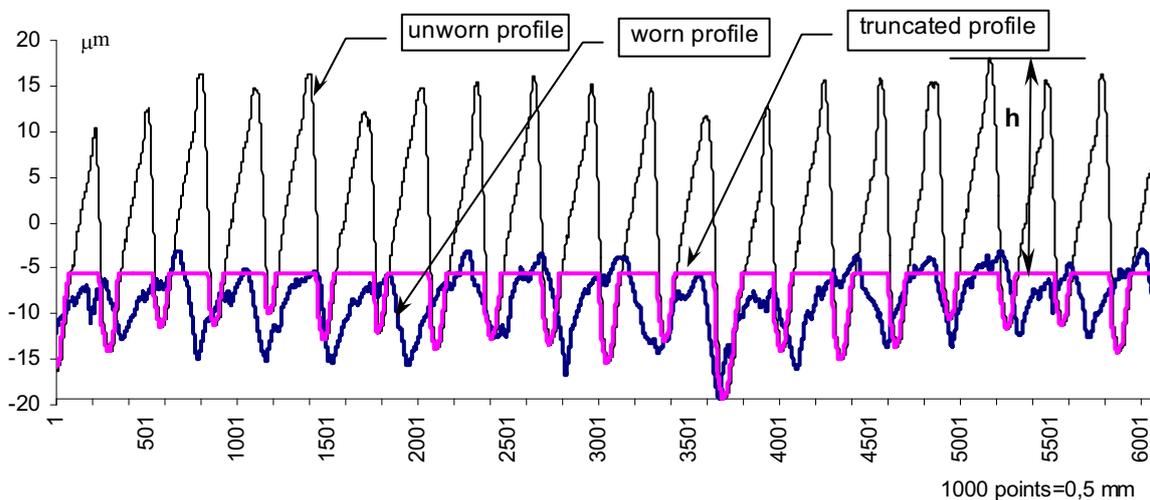


Figure 5. The profiles taken into consideration when estimating linear wear.

3.3 Discussions

Both methods presented at §3, may be applied only in the case of measurements performed using relocation techniques. Another condition for using these profilometric methods for wear evaluation, is that of having under study a wear process dominated by abrasive wear and characterised by an amount of material loss within the limit of the asperities' maximum height, R_y . This condition is necessary because calculations are based on the fact that a part of the voids patterns, initially noticed on the unworn profile, are still kept on the worn one. There is why these methods are useful in studies of microwearing process and for running in process, and only if the wear process does not have as consequence the completely taking-off of the initial microgeometry of the superficial layer.

The profilometric methods may be applied for studying wear processes characterised by a linear wear greater than maximum height of the profile only if the measured profiles contain witness (unworn) zones, bounding the wear trace (figure 6).

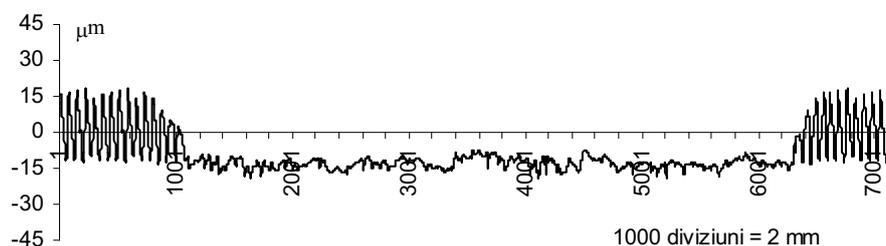


Figure 6. Worn profile having unworn bounding extremities.

4. Conclusions

Studying the microgeometry changes of a surface bearing a wearing process suppose to evaluate different roughness parameters and waviness, based on digital profiles, volume wear evaluation by the help of the wear trace and so on.

Making the average of many profile measurements on the same surface may lead to loose the significance of some severe local changes of the topography. The *relocation techniques* of the stylus

are more accurate as the roughness has been inspected on the same generatrix of the roller, before and after wear testing.

Quantitative evaluation of microwear cannot be made using the gravimetric method or other general measuring methods such as the dimensional method. It can be made by measuring changes of profiles. The wear study using profilometric methods impose the establishment of a methodology for analysing the surface microgeometry based on relocation technique, this one being recommended by the specialists particularly for tribological process research. There was also proposed a methodology for simulating a worn profile in order to evaluate variation of the wear rate for long time tests.

References

1. Stout K. J., Kin, T. G. and Whitehouse D. J., Analytical techniques in surface topography and their application to a running-in experiment, *Wear*, **43**, 99-115, 1997.
2. Bryant M. J., Running-in and residual stress: finite element contact analysis of as measured rough surfaces and comparison with experiment (Doctoral dissertation, Cardiff University, UK), 2013.
3. Sukumaran J., Vision assisted tribography of rolling-sliding contact of polymer-steel pairs (Doctoral dissertation, Ghent University), 2014.
4. Weeks I., An experimental investigation into the mixed lubrication of steel surfaces (Doctoral dissertation, Cardiff University), 2014.
5. Williamson J. B. P. and Hunt R. T., Relocation profilometry, *J Phys E Sci Instrum.*, **1** (7), 749-752, 1968.
6. Snidle R. W., Alanou M. P., Evans H. P., Krantz T. L., Surface fatigue lives of case-carburized gears with an improved surface finish, *J Tribol-T Asme*, **123** (4), 709-716, 2001.
7. Newman P. T., Radcliffe S. J. and Skinner J., The accuracy of profilometric wear volume measurement on the rough LC1B-coated surfaces of an articulating joint, *Surface Topography* **2**, 59-77, 1989.
8. Raharijaona, F. et al., Determination de parametres rugosimetriques fonctionnels-Application au cas du frottement multipasse sur acier et aluminium en geometrie cylindre/cylindre, *JIFT 97, Journ. Inter. Francophones de Tribologie*, "Tribologie et Precision", 51-52, 1997.
9. Rîpă M., Studiul pe tribomodel al tribostratului in procesul de uzură specific roților dințate [Study of the tribolayer for wear process characterising gears in rolling/sliding wear tests]. Ph.D. Thesis, Dunărea de Jos University of Galați, 2002.
10. Roizard, X. et al., Action d' un decapage chimique sur la topographie de surface d'un substrat composite en vue d'ameliorer l'adherence d'un revetement metallique, *JIFT 97, Journ. Inter. Francophones de Tribologie*, "Tribologie et Precision", 57-60, 1997.
11. Sasajima K., Naoi K., Tsukada T., A software-based relocation technique for surface asperity profiles and its application to calculate volume changes in running-in wear, *Wear*, **240** (1-2), 152-163, 2000.
12. Yetim A. F., Kovacı H., Aslan M., Çelik A., The effect of magnetic field on the wear properties of a ferromagnetic steel. *Wear*, **301** (1), 636-640, 2013.
13. Jeng Y. R., Impact of plateaued surfaces on tribological performance. *Tribol T*, **39** (2), 354-361, 1996.
14. Gee M. G., Nunn J. W. Gant A. J., Relocation profilometry of worn coated surfaces, National Physical Laboratory, 2014, available at <http://www.npl.co.uk/upload/pdf/10787%20-%20M%20Gee.pdf> (23.04.2017).

15. Snidle R. W., Hopkinson N. A., Hughes T. G., Tao J., Elastohydrodynamic lubrication analysis of gear tooth surfaces from micropitting tests, *J Tribol-T Asme*, **125** (2), 267-274, 2003.
16. Balcon M., Marinello F., Carmignato S., Savio E., Wear analysis through surface relocation. *Journal of Physics: Conf. Series*, 311 (1), 012020, IOP Publishing, 2011.