ANALYSIS OF WAVELET TRANSFORM APPLIED IN FRICTIONAL COEFFICIENT SIGNAL

Efrain Pantaleón Matamoros, epantaleon@ect.ufrn.br
Gustavo Zampier dos Santos Lima, gzampier@ect.ufrn.br
Schools of Science and Technology, Federal University of Rio Grande do Norte, Lagoa Nova, Natal / RN, Brazil. 59072-900.

Abstract. *During wear testing, the friction coefficient value change due to different conditions, such as speed, load and temperature of contact. The resulting complex variations of the friction coefficient difficulties the attempts to correlate wear with the measured friction coefficient signal. From dynamics experimental pin/disk test, it has been found different types of wear mechanisms under different load conditions. In this work, one method for analysis of wear was developed using discrete wavelet transform that analyzed the friction coefficient signal. The proposed analysis attempts to correlate the frequencies of the friction coefficient with the wear rate. In addition to friction coefficient monitoring, the characterization of the specimen surface, was accomplished using the techniques of optical and scanning electron microscope.*

Keywords*: Wear, Tribology, Wavelet Transform*

1. INTRODUCTION

The study of wear of materials has been make for over 500 years since the pioneering works of Leonardo da Vinci, in which they have been developing equipment and test methods that make possible the detailed study of the role of materials and surfaces as well as other variables in the tribological system, such as the relative velocity of bodies, applied load and environment (Blau, 1997).

There are several classifications for the types of wear, but in general are presented as sliding wear, abrasive, erosive, contact fatigue, and its variants (So, 1995 and Quinn, 1962). In the '80s and '90s, the tools for image processing, combined with computational techniques, they added a great impetus to the study of microscopic wear. Works such as Abbott and Firestone (1933) helped in the understanding of the curves of wear and breakage of asperities. Already Kerridge and Lancaster (1956) discussed the stages of progression to severe metallic wear. Kragelskii *et al.* (1982) described of the other form the sliding surfaces considering to interact in terms of roughness. The idea that the friction and wear may submit a series of stages has been the focus of many studies.

According Pantaleón (2004), the transitions in wear mechanisms depend on the tribology system, more than on the characteristics of the material, which makes it complex to obtain a systematic arrangement of his study. Moreover, has been observed that there is a difficulty in predicting the occurrence of the transitions in wear mechanisms as they encompass many variables that can promote changes, both topographical and physical-chemical properties, the contact surfaces of materials. We can cite as the most important variables: the relative hardness between materials, temperature, load and speed as well as the microstructure variables, such as the nature and distribution of phases and the volume fraction of the oxide film surface.

The tribological tests show stages with different types of variations in sign of the coefficient of friction, the use of the wavelet transform is used in this work in order to help in interpreting these signs, trying to associate the characterization of wear, obtained from the pin on disc machine.

1.1. Wavelet Transform

The concept of Wavelet Transform (WT) was first formalized in the 1980s in a series of articles by Grossman and Morlet (Hubbard, 1998). In the second half of the 1980s, were defined precisely the concepts of this wavelet function and understanding clearly the nature of this type of function, allowing the construction and generation of various functions classified families of wavelets (Meyer, Mallat, 1989 and Daubechies, 1992). Much of the wavelet theory was developed independently in various fields of knowledge such as: Mathematics, Physics and Engineering. Specific contributions of these fields during the last ten years have led to a larger number of applications in various areas such as processing and image compression, turbulence, intermit series and other processes.

The wavelet transform is a mathematical tool similar to the Fourier transform, but is used to analyze non-stationary signals and extract information from the frequency variations of signals by detecting their temporal structures located (Dos Santos Lima, 2009).

In the analysis by Fourier transform, complex exponentials are used as base space. The Fourier transform represents a signal in terms of sines and cosines of different frequencies, which divides the signal into components. Similarly, the wavelet transform represents a signal in terms of wavelet basis. These wavelet basis are formed by scaled (stretching and compressing) and the shifting of a single function called the wave function.

The wavelet transform provides a combination of time and location of frequency, while the representation by a Fourier analysis only provides the frequencies space, so the wavelet method is based on wavelet function that change its position and size (Torrence *et al.* 1978). The location and the combination time and frequency are important to coding of non-stationary signals and intermittent processes such as time signals of friction coefficient showed in this work.

Wavelets are functions of waves with finite duration and finite length with zero mean value. The wavelet analysis complete the Fourier analysis and allows, in general, a similar interpretation, but extends the Fourier analysis, adding there resolution in time. Therefore, this numerical technique is appropriate for analyzing our time signals of friction coefficient given by the system pin-disk, which represent rapid changes in frequency and intermittency in a short time interval (Pantaleón, *et al*. 2002).

The Equation (1) show of Morlet wavelet function, which consists of a plane wave modulated by a Gaussian, is given by (Farge, 1994):

$$\Psi^0(\eta) = \pi^{-\frac{1}{4}} e^{i\omega_0\eta} e^{-\frac{\eta^2}{2}} \tag{1}$$

where ω_o is a dimensionless of frequency and η is the time parameter. The Eq. (2) represent to continuos wavelet transform $W_n(s)$ of a discrete sequence of data x_n is defined as the convolution with a scaled and translated version of $\Psi^0(\eta)$ (Torrence *et al*, 1978):

$$W_n\ (s) = \sum_{n'=0}^{N-1} x_{n'} \psi^* \left[\frac{(n'-n)\delta t}{s} \right] \tag{2}$$

The symbol (*) indicate the complex conjugate. Thus we get a picture showing the amplitude versus scale (or period) and how these amplitude vary in time.

2. MEASUREMENTS OF FRICTIONAL COEFFICIENT ON PIN AND DISK EQUIPMENT.

2.1. Materials

Table 1 shows the chemical composition of materials used as a pin and disk.

The material used for the disc was AISI 1045 of ∅ 38 x 10 mm. The material was austenized to 830 ± 10 °C and austempered in a salt bath of potassium nitrate, 370 ± 5 °C, obtaining hardness Rc = 40.6 ± 0.5. The pins were steel M2 with final size of ∅3x6 mm. The heat treatment consisted of preheating at 550 ^{o}C and 850 ^{o}C to 1180 ^{o}C austenitizing and tempering at 550 ° C, salt bath, followed by three tempered at 550 ^{o}C, obtaining hardness Rc = 64.8 ± 0.4 (Pantaleón, 2004).

Table 1. Chemical composition of materials.

Materials	C(%)	S(%)	P(%)	Mn(%)	Si(%)	Cr(%)	Mo(%)	W(%)	V(%)
Pin (M2)	0,79	0,02	0,01	0,24	0,24	4,25	5.35	6,65	1,97
Disk (1045)	0,44	0,2	0,02	0,52	0,17	-	-	-	-

Figure. 1 show, microstructure constituents were observed after etching with a dilute solution of 2% nitric acid and 98% anhydrous ethanol (2% Nital) for 10 seconds. The microstructure observed in the disc material is typical of a heat treatment in salt bath at a constant temperature (isothermal process), with regions with lower and upper bainite. The microstructure observed in the material of the pins were tempered martensite with retained austenite and the carbide.

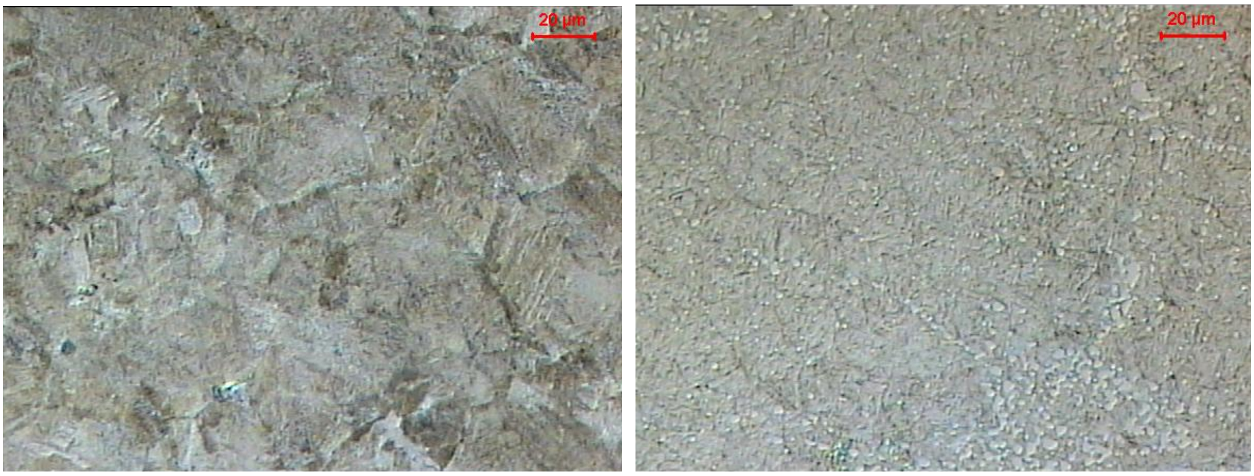

Figure 1. a) Disk: bainitic microstructure b) Pin: martensite microstructure with presence of carbides. 500x, etched with Nital 2%. (Pantaleón, 2004).

2.2. Tribology test

The wear tests were divided into two phases, the first stage is characterized mating surfaces in contact with a load of 15 N for 30 minutes at a constant speed of 756 rpm with a pin and sliding track on the disc with a radius 10 mm. The preparation of the surface of the discs was done with the process of polishing with diamond pastes of 6 microns and 3 microns. This first phase aimed to minimize the effect of conformation of surfaces that occurs during the initial test and which is called "runing-in.

The second step of the trials lasted 3 hours, where the load varied over time and the disc rotation was kept constant (756 rpm). In this step, the track of sliding pin on the disk was moved to 13.5 mm. There were three replicates of experiments in which varied the load end of the second stage of testing between 0 and 120 N, to evaluate the influence of the rate of load application. The test equipment as a result provides the signals of the friction force, coefficient of friction, load, sliding distance during of test the pin on the disk.

Figure 2, shows the equipment used during the wear tests. The wear tests were kind of pin-on-disc, model TE-67 equipment, manufacturing PLINT & PARTNERS LTD (Phenomena Surface Laboratory at São Paulo University).

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Figure 2. Pin disk test machine.

3. RESULTS AND DISCUSSION

Figure 3 shows the curves of the coefficient of friction as a function of time, characterized by varying the load from 20 to 120 N. Looking at the graphs, can note that the friction coefficient has an irregular fluctuation amplitude and high in the early 4500 second, for different tests, and from that moment, the magnitude of the coefficient of friction tends to vary in a range more narrow. This fact may be related to the transition from one stage of several wear to a stable stage of wear.

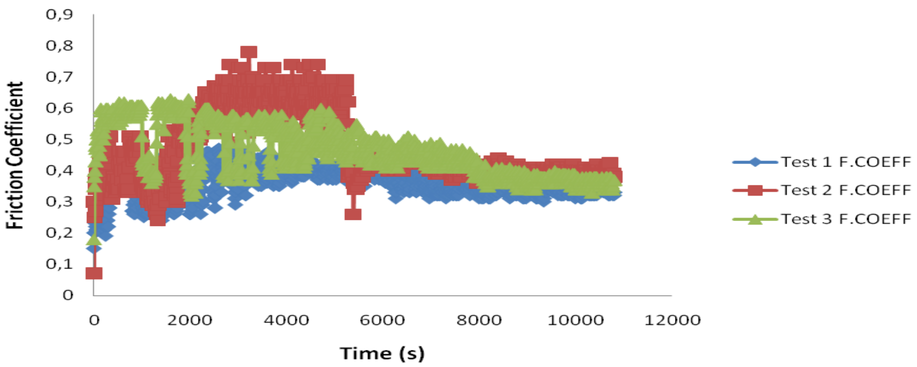
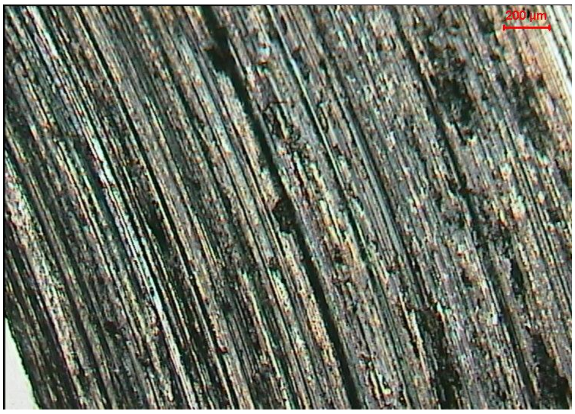
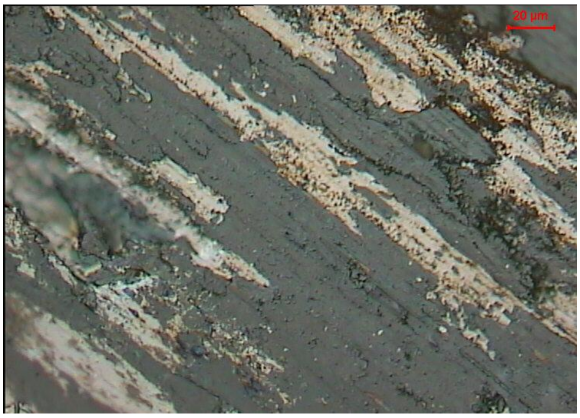


Figure 3. Friction coefficient signal.

Figure 4a shows the severe wear observed on the surfaces in the stage of running. Figure 4b presents the findings observed with optical microscope the surface of the disk and pin test load of 120 N, where it is noticed that the oxide layers are dispersed on the surface of contact. This has revealed that the layers form in localized regions in contact, where conditions are more favorable for oxidation, ie where the contact temperature, and the terms of the material, provide the nucleation and growth of oxide (Pantaleón, 2004).



(a)



(b)

Figure 4. Stage of wear. (a) Abrasive wear (running- in) . (b) Oxidative wear.

Figure 5. showed the time evolution of friction coefficient (the same as Fig. 3 (green)) and the instant of time taken to show the evolution of superficial pin/disk structure, around 2300 s and 10000 s, respectively Fig. 4(a) and Fig. 4(b). Fig. 5 show the scalogram from time evolution of friction coefficient. Moreover, with wavelet analysis, we can be see the time evolution of the frequency and intensity of the coefficient of friction. In Fig. 5 we see a transient from modulated dynamics (from 3500 s to 4500 s) to a steady state signals.

We can observe the appearance of modes with energy more intense given around 20 Hz, 30 Hz and 40 Hz , in the time interval between 0 s to 3000 s. Furthermore, we observed a transient interval to reach the steady state. It is noticed that the frequency of the friction coefficient is constant from a certain point (after 3000 s). And in the early 3000 s a amplitude variation shows decreasing values. These facts indicate that after the early 3000s the wear mechanisms operating in the contact provides more constant relationship with the fractional contributions to wear.

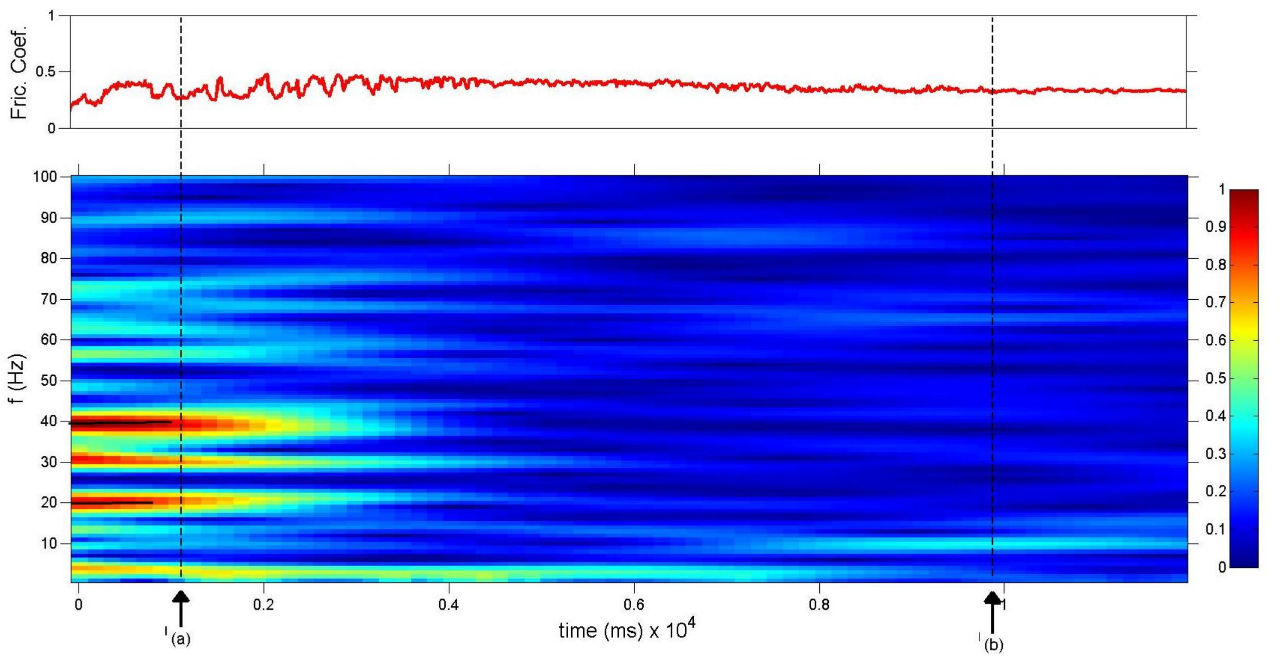


Figure 5. Scalograma of signal of friction coefficient.

4. CONCLUSION

This method used in this work was sensitive to variations in the behavior of the coefficient of friction and the information extracted by Wavelet Transform showing of the changes that reveal the mechanisms of wear characterized by the presence of waves with frequencies of different intensities. The mechanism of running-in is characterized by frequency range (20 and 40 Hz) high intensity and oxidative wear is associated with absence of waves of high intensity in specific range (45 to 100Hz).

Wavelet transform proved a useful and robust mathematical tool for time-series analysis with non-stationary signals in filtering tribological profile, with information of the coefficient of friction, providing a powerful base in the detection of wear mechanisms by changing frequency.

The wavelet filters effectively preserve the signature of the signal, despite its transient and stationary characteristics. In fact, even with a strong steady signal can be analyzed and filtered with good results using the wavelet transform.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Abbott, E. J. E., Firestone, F. A., 1933, “Specifying surface quality”, Mechanical Engineering, pp. 559-569.

Blau. P.J., 1997. “Fifty Year of Research on the Wear of Meta”. Tribology International, Vol.30, No.5, pp. 328-331.

Daubechies, I., 1992, “Ten Lectures on Wavelets. Society for Industrial and Applied Mathematics”, Philadelaphia, Pennsylvania.

Dos Santos Lima, G. Z., (2009), "Análise da turbulência do Plasma no Tokamak TCABR" , Tese de Doutoramento, Instituto de Física da Universidade de São Paulo.

Farge, M., 1992 “Wavelet transforms and their applications to turbulence”, Annu. Rev. Fluid, Mech, No.24, pp.395

Hubbard, B.B., 1998, “The world according to wavelets. The story of a mathematical technique in the making”, A. K. Peters Ltd, 2 ed., pp.286.

Kerridge, M. E., Lancaster, J. K., 1956, “Stages in progress of severe metallic wear”, Proceedings of Royal Society, pp. 236-250.

Kragelskii, I. V., Dobychin, M. N. and Kombalov, V. S., 1982, “Friction and Wear Calculation Methods”, Pergamon Press Oxford, U.K., pp.297-316.

Mallat, S. A., 1989, “Theory for multiresolution signal decomposition: wavelet representation”, IEEE Trans. Pattern Anal. Mach. Intellig., no.11, pp. 674-693.

Meyer, Y., 1989, “Wavelets and Applications”, Proceedings of the International Conference, Marseille, France, May, pp.105-110.

Pantaleón, E., Bernardes, F.G., Tanaka, D.K., Bichone, R., 2002. "Wear mechanisms in a test pin / disc and its correlation with standard deviations and averages of the coefficient of friction", Proceedings of the 57th Annual Congress of ABM International, pp. 2001- 2010.

Pantaleón, E., 2004, "Modelo de Desgaste Oxidativo Baseado em Parâmetros Termodinâmico", Teses de Doutoramento, Escola Politécnica da Universidade de São Paulo. pp. 83-96.

Quinn, T.F.J., 1962. "Role of oxidation in the mild wear of steel". J. Applied Physics. No.13, pp 33-37.

So. H., 1995, "The mechanism of oxidational wear", Wear, Vol.184, pp.161-167.

Torrence, C. and Compo, G.P., 1978, "A practical guide to wavelet analysis", Bulletin of the American Meteorological Society, Vol.79, No.1, pp.61–78.

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