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ScienceDirect
C. R. Mecanique 336 (2008) 794–799
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MECANIQUE
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Correlation between surface topography and tribological mechanisms of the belt-finishing process using multiscale finishing process signature

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Received 4 February 2008; accepted after revision 30 July 2008

Available online 9 October 2008

Presented by André Zaoui

Abstract

In practice, two surfaces statically equivalent can be issued from two different manufacturing processes (grinding, belt finishing, honing, …) or obtained using different working process variables (abrasives grits size, contact pressure, …). The common tools and different norms used for industrial surface characterization (ISO 4288, ISO 12085, …) have the main limit of discriminating them through their process signatures. This Note introduces a multiscale decomposition method of the surface topography based on continuous wavelets transform. This approach allows the determination of the multi-scale transfer function of the morphological modification on the surface topography after a finishing process. This technique has been successfully applied to discriminate two surfaces obtained by the belt-finishing process. Moreover, it makes it possible to connect the surface topography modification to the physical and tribological mechanisms of the process (ploughing, cutting, …). ***To cite this article: S. Mezghani et al., C. R. Mecanique 336 (2008).***

Résumé

Corrélation entre topographie de surface et mécanismes physiques du procédé de toilage par la signature multiéchelle du procédé. Dans la pratique, deux surfaces statiquement équivalentes peuvent être usinées à partir de deux différents procédés de fabrication (rectification, toilage, rodage, …) ou obtenues à des conditions différentes du procédé (taille de grains abrasifs, la pression de contact, …). Les différents outils communs et les normes utilisées pour la caractérisation de surface industrielle (ISO 4288, ISO 12085, …) présentent la principale limite de les discriminer à travers la signature de leurs procédé. Cet article introduit une méthode de décomposition multiéchelle de la topographie de surface basé sur la transformée en ondelettes continue. Cette approche permet de déterminer une signature multiéchelle de la modification morphologique de la topographie de la surface après un processus de finition. Cette technique a été appliquée avec succès pour la discrimination de deux surfaces obtenues par toilage. Elle permet, en plus, de faire le lien entre la topographie de la surface obtenue aux mécanismes physiques et tribologiques du procédé (labourage, coupe, …). ***Pour citer cet article : S. Mezghani et al., C. R. Mecanique 336 (2008).***

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1631-0721/$ – see front matter
doi:10.1016/j.crme.2008.09.002

Keywords: Material engineering; Multiscale characterization; 2D continuous wavelet transform; Manufacturing signature; Abrasive finishing

Mots-clés : Génie des matériaux ; Caractérisation multiéchelle ; Transformée par ondelettes continues 2D ; Signature du procédé ; Finition par abrasion

1. Introduction

Topographical aspect is a characteristic of a surface that is as important as its chemical composition with regards to its functional properties [1]. The high performance of industrial applications, requires increasingly technical functional surfaces, in particular from the point of view of topography and micro texture. Moreover, development in term of higher demands of product performance and cost efficient production systems, calls for a systematic approach towards detailed knowledge about the connections between product features (tolerance such as waviness, form and roughness) and the manufacturing process working variables. Topography can be mainly described by three kinds of roughness parameters: amplitude, frequency and hybrid parameters [2–4]. These surface characterization parameters are based on a single process surface and not related to the working process parameters variations. In today's industry, functional surfaces are produced by multi-process manufacturing methods. Thus, the generated surface texture is the superposition of the successive manufacturing processes signatures [5]. Some more adapted multiscale surface characterization approaches were developed. X. Liu et al. [5] present hence a multiscale features analysis of 3D surface topography based on mathematical morphology. The surface components are obtained directly in space domain. X. Chen [6] introduced a multiscale approach by using wavelet transform. Wavelets are a kind of mathematical function that cut up data into different frequency components, and then study each surface component with a resolution matched to its scale. They present advantages over traditional methods in analyzing physical situations, especially where the signal contains discontinuities and sharp peaks. The methodology takes into account all the scale of decomposition without any cut-off. Based in this approach, H. Zahouani et al. define a multiscale parameter SMa [7–9] which quantify the arithmetic mean value of the of roughness and waviness amplitude at each scale. It used to express a multiscale transfer function of surface roughness modification as a signature of manufacturing process [10].

In this Note, the above technique was applied to the belt finishing process. This abrasive process consists in applying a belt on the rotating work piece with a defined pressure and axial oscillation. During the abrasive tape motion, the abrasive grains undergo an oscillation of a specific frequency in the direction perpendicular with that of the abrasive tape motion. The results highlight the power of this manufacturing process signature to establish a link between topographic properties of the surface and the physical and tribological mechanisms of the process (ploughing, cutting, ...).

2. Experimental procedure

The super-finishing process considered in this study is the belt finishing. Finishing tests have been realized on wet conditions varying the size of Al_2O_3 abrasive grains (d) (cf. Table 1).

A contact pressure of 0.8 MPa and six abrasive belts of different grains size (9, 15, 30, 40, 60, 80 μm) have been considered, while the other working variables kept constant (see Table 2). For each contact pressure/grains size combination, tests have been repeated five times and the reported results are validated by a statistical analysis (Shapiro–Wilk and Aspin–Welch tests). The composition and properties of the steel cylindrical samples are shown in Table 3.

Table 1
Properties of the abrasive belt used

Studied	Abrasive belts	Physico-mechanical properties[a]	
Type	Microfinishing 372	Kind of abrasive	Al_2O_3
		Type of base	Polyester
Supplier	3M	Band width (mm)	19.84
		Average grits size (μm)	9, 15, 30, 40, 80

[a] As specified by 3M.

Table 2
Working conditions

Workpiece rotation speed	100 rpm
Oscillation frequency of shoes	2.5 Hz
Oscillation amplitude of shoes	1 mm
Cycle time	12 s
Inserts hardness	95 shores
Lubrication fluid	Strict oil
Abrasive belt feed	None

Table 3
Workpiece characteristics before belt finishing

Workpiece material	D38MSV5S steel (%C 0.35/0.40)
Diameter	54.8 ±0.005 mm
Axial width	30 mm
Fabrication steps	Turning, Induction hardening, Grinding
Superficial hardness	≈55 HRC
Initial roughness	$2 < R < 4$ μm

The steps involved in their fabrication before belt finishing are: turning, induction hardening (until a surface hardness higher than 50 HRC) and wheel grinding with a roughness parameter Ra of 0.9 μm. Surface topography parameters, before and after the test, were measured by a three dimensional white light interferometer (WYKO NT 3300). The surface was sampled in 640 × 480 points with a 1.94 μm step scale in the x-direction and y-direction.

3. Multiscale surface analysis using 2D continuous wavelet transform

The study of the signature of finishing process in a wide range of topographical scales was investigated before and after finishing by the 2D continuous wavelet transform.

The surface topography components pass through a filter bank which is a set of contracting wavelets obtained from a single wavelet or mother wavelet $\psi(t)$ by dilation (or compression).

One defines the 2D wavelet transform of a 2D surface topography $f(x, y)$ by:

$$W_{b,a}(x, y) = \frac{1}{\sqrt{a_x a_y}} \int_{-\infty}^{+\infty} f(x, y)\psi\left(\frac{x - b_x}{a_x}, \frac{y - b_y}{a_y}\right) \mathrm{d}x\,\mathrm{d}y \tag{1}$$

where a_x, a_y are respectively the contraction coefficients according to the x and y directions, b_x and b_y the translation coefficients according to the x and y directions.

The "Mexican-hat-2D" wavelet given by the following expression is used [8,9]:

$$\psi(x, y) = (2 - r)\exp(-r/2), \quad \text{with } r = x^2 + y^2 \tag{2}$$

Various working process variables have an impact on the roughness of the obtained surfaces: nature of the abrasive, abrasive size, support of the abrasive load (paper, fabric, felt, etc.), and pressure applied to the sample.... For that, we need the use of a quantitative measurement technique sensitive to all these variables. The methodology consists on the extraction of each scale by inverse wavelet transform, and hence on the quantification of their arithmetic means value for each scale. In fact, the idea is to determine the spectrum of arithmetic mean value from the scales of waviness to roughness SMa [8–10]:

$$SMa(a) = \sum_{x=1}^{M} \sum_{y=1}^{N} \frac{|W_a^{*f}(x, y)|}{MN} \tag{3}$$

where $W_a^{*f}(x, y)$ is the component altitude of the surface "f" at scale "a" in the point coordinate (x, y). This component is obtained by a 2D wavelets transform. N and M represent the size of the surface in the x- and y-direction.

Finally, using Eq. (3) we can rewrite this equation in terms of a weight function to compute the change of the finished surface $F(x, y)$ and its initial topography $I(x, y)$ at each wavelet scale "a". Hence, using this representation, the multiscale transfer function of the machining process $T_\psi(a)$ associated with a wavelet of given scale "a" is defined as the ratio of $SMa(a)$ spectrum and given by:

$$T_\psi(a) = \frac{SMa^F(a) - SMa^I(a)}{SMa^I(a)} \cdot 100 \tag{4}$$

This multiscale transfer function can be compared directly with the multi-scale modifications of the surface topography, which depicts the signatures of the machining process in terms of essential changes of the surface state produced on the original surface.

4. Results and discussion

Fig. 1 shows the surface topography of the original steel workpiece surface and the one obtained by belt finishing with two different abrasive grits size (9 µm and 80 µm).

Even if these two surfaces are obtained by two types of finishing operations (fine and rough belt finishing), they are, practically, similar in their statistical normalized parameters (ISO 25178). Hence, these global parameters of surface topography cannot discriminate the two finished surfaces (Table 4).

Multiscale roughness spectrums of these surfaces provide for identification of their corresponding transfer functions over a range of wavelengths up to 400 µm. This range of wavelengths group micro and macro roughness scales.

Fig. 2 explains that the surface carried out with fine grits is generated by an auto-similar process at the whole analyzed scales. Actually, the roughness attenuation is constant for all scales. The attenuation obtained by belt finishing with big grit sizes has almost the same mean attenuation rate (equal to 58%). However, this attenuation is widely depending on the roughness scale. The micro-roughness scales are more affected by the process than the macro-roughness scales. This variation of the evolution of the process signature expresses a change in the activated abrasive mechanisms related to the belt finishing type (fine or rough).

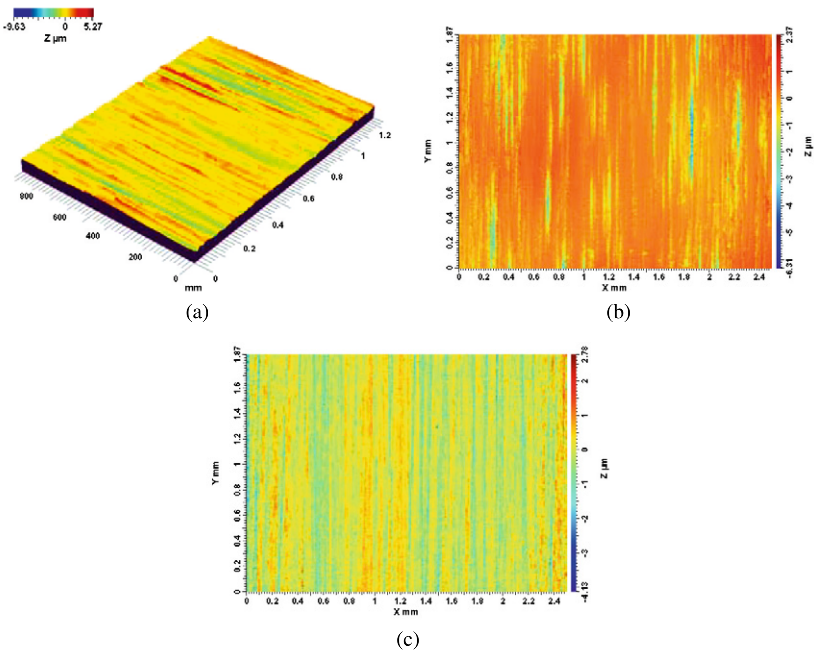


Fig. 1. (a) Original steel workpiece, surface topography obtained by belt finishing, (b) with 9 µm abrasive grits size, (c) with 80 µm abrasive grits size.

Table 4
Roughness parameters for two surfaces obtained by belt finishing with two different abrasive grits size

	Grits size (9 μm)	Grits size (80 μm)
Ra (nm)	331.44	377.97
Rq (nm)	501.06	482.75
Rz (μm)	4.96	4.57
Rt (μm)	5.51	4.95

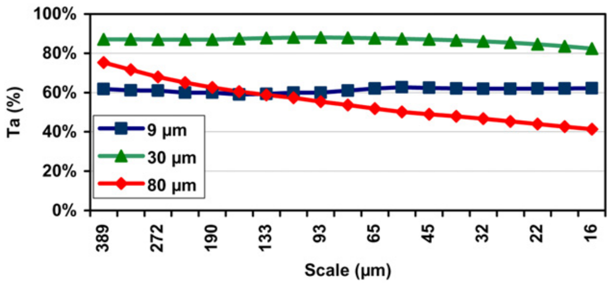
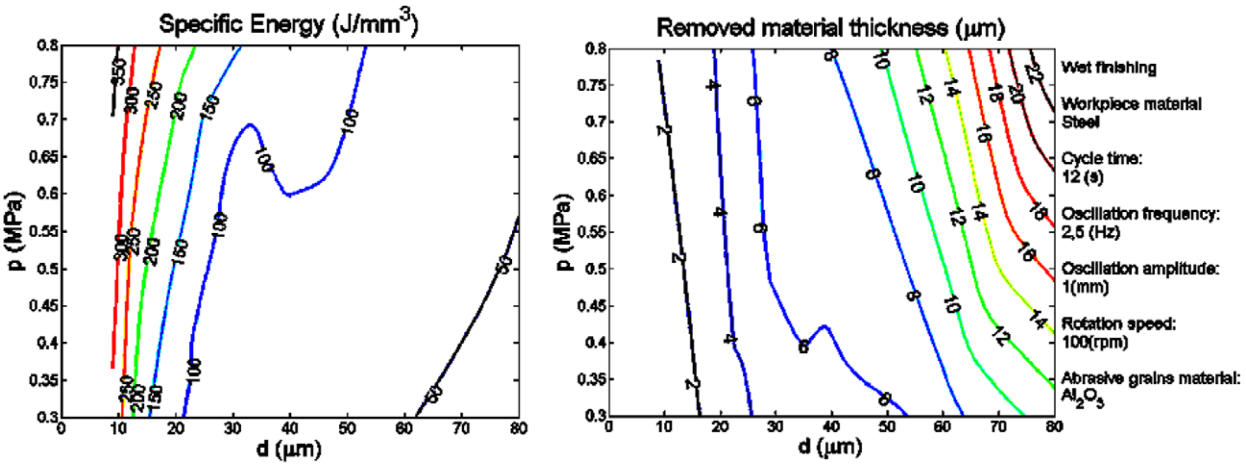


Fig. 2. Multiscale transfer function of belt finishing process for three different abrasive grits size (9, 30, 80 μm).



(a) (b)

Fig. 3. Energetic analysis of the effect of contact pressure "p" and abrasives grits size "d" in belt finishing process. (a) Specific energy, (b) Removed material thickness.

In order to better understand the influence of abrasive grains size on the activation of the fundamental abrasion mechanisms (cutting, ploughing, and sliding, ...), the specific energy parameter (E_s) has been introduced [11–13]. The analysis of its evolution with the two investigated working variables is based on the following assumptions:

- cutting, ploughing and sliding can be taken into account simultaneously by the specific energy according to the equation: $E_s = E_{cutting} + E_{plowing} + E_{sliding}$ [12,13];
- The specific energy component due to cutting, $E_{cutting}$, depends entirely on the working material [14] and it almost equal to the specific energy at the material melting point (for steel: $12 < E_{melting} < 30\ \mathrm{J/mm^3}$) [13].

The effects of grains size on the specific energy agree with those described in previous studies [14,15]. In fact, a transition of the specific energy and the removed material thickness evolution is observed at grain size ∼35 μm. It was noted that, in finishing by coarse grains size, the cutting mechanism prevails largely on ploughing and sliding ones ($E_s \to E_{cutting}$). This leads to elevated material removal with low specific energy. Whereas, the workpiece/abrasive belt contact is governed essentially by ploughing and sliding ($E \to E_{max}$) when finishing by fine grains size. This due to the low cutting ability of the abrasives grains so that not even the superficial irregularities can be removed. This energetic analysis does not let one specify the working conditions allowing the minimization of the surface roughness. However, it confirms that the roughness attenuation has been obtained by different abrasion mechanisms according to the belt grain size. The multiscale transfer function is scale dependent when cutting is the dominant wear mechanism. However, it is not dependent on scale when the ploughing and sliding are the predominant mechanisms. It approves then the correlation between the multiscale transfer function and the activated abrasion mechanisms.

5. Conclusion

The analysis and computation of the 3D surface topography show that multiscale analysis based on 2D continuous wavelets transform is an effective method to track the manufacturing process signature. It draws attention on the modification of the band of wavelengths during abrasive process. This multiscale signature has been successfully applied to discriminate two surfaces obtained by belt-finishing process with different process working variables. Moreover, it makes it possible to connect the surface topography modification to the physical and tribological mechanisms of the process (ploughing, cutting, ...).

References

[1] S. Giljean, D. Najjar, M. Bigerelle, A. Iost, Multiscale analysis of abrasion damage, Mecanique et Industries 7 (1) (2006) 13–20.
[2] T. Thomas, Trends is surface roughness, International Journal of Machine Tools and Manufacture 38 (5–6) (1998) 405–411.
[3] W.P. Dong, P.J. Sullivan, K.J. Stout, Comprehensive study of parameters for characterizing three-dimensional surface topography: Parameters for characterizing amplitude and some functional properties, Wear 178 (1) (1994) 29–44.
[4] W.P. Dong, P.J. Sullivan, K.J. Stout, Comprehensive study of parameters for characterizing three-dimensional surface topography: Parameters for characterizing spatial and hybrid properties, Wear 178 (1) (1994) 45–60.
[5] X. Liu, Y. Huang, K. Liu, C. Gui, Multiscale features analysis of 3D surface topography based on mathematical morphology, in: Sixth Intl. Symp. on Instrumentation and Control Technology, Proc. SPIE 6357 (2006) 63572.
[6] X. Chen, J. Raja, S. Simanapalli, Multiscale analysis of engineering surfaces, International Journal of Machine Tools and Manufacture 35 (2) (1995) 231–238.
[7] S.H. Lee, H. Zahouani, R. Caterini, T.G. Mathia, Morphological characterization of engineered surfaces by wavelet transform, International Journal of Machine Tools and Manufacture 38 (5–6) (1998) 581–589.
[8] H. Zahouani, S.H. Lee, R. Vargiolu, J. Rousseau, Characterization of surface topography by continuous wavelet transform, Acta Physica Superficierum IV (2001) 1–23.
[9] S. Mezghani, E. Sura, M. El Mansori, The effect of belt finishing process variables on the topography of finished surfaces, Tribology Transactions 51 (2008) 413–421.
[10] H. Zahouani, S. Mezghani, R. Vargiolu, M. Dursapt, Identification of Manufacturing Signature by 2D Wavelet Decomposition, Wear 264 (5–6) (2008) 480–485.
[11] S.W. Date, S. Malkin:, Effects of grit size on abrasion with coated abrasives, Wear 40 (1976) 223–235.
[12] I.D. Marinescu, W.B. Rowe, B. Dimitrov, I. Inasaki, Tribology of Abrasive Machining Processes, William Andrew Publishing, 2004.
[13] M.C. Shaw:, Principles of Abrasive Processing, Oxford Science Publications, Clarendon Press, Oxford, 1996.
[14] T.K. Puthanangady, S. Malkin, Experimental investigation of the superfinishing process, Wear 185 (1995) 173–182.
[15] A.P. Mercer, I.M. Hutching, The deterioration of bonded abrasive papers during the wear of metals, Wear 132 (1989) 77–97.