Identification of the multiscale diamond turning signature of optical lens surfaces

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Abstract. Functional surfaces of optical lens are commonly achieved by a multi-stage diamond turning. This high precision process acts in a wide range of wavelength and allows producing 3-dimensional free form optical surfaces with excellent surface finish that meets application requirements. However, the relationships between process variables and surface characteristics are not yet predictable. In this paper, the concept of the multiscale process signature (MPS) is applied to track the effect of diamond turning process variables (cutting velocity, feed rate, cutting depth, tool roughness, ...) on the surface topography from micro-roughness to waviness.

The MPS is developed based on continuous wavelet transform and it depicts the essential changes of the surface state produced on the original surface after diamond turning. Using this concept, the effects of different working variables are isolated and theirs active wavelength bands were identified.

1. Introduction

The functional ‘Mirror’ surface of ophthalmic plastics lenses is actually produced by multi-processes, turning and polishing [1]. The turning stage plays an important role in the production process and it has two main functions [2]. First, it allows achieving the expected optical surface in terms of geometry to obtain the right light rays deviation for medical eyesight correction; Secondly, it has the important task to make the surface compatible with the post-polishing scale to remove tool marks and to get the desired level of transparency. Hence, the monitoring of the turning process is essential because this process is influenced by lot of working variables such as tool wear, feed rate, and depth of cut [3, 4]. An imprint of all the static as well as dynamic forces, stresses and strains during the cutting process resulting from the operating conditions are left in the generated surface profile in wide range of wavelength. Then, an accurate analysis of the surface features dynamic is necessary to extract the process signature [5].

In this work, the concept of multiscale process signature (MPS) [6, 7] is applied as a new experimental investigative approach for monitoring the dynamics of surface generation during single-point diamond turning of ophthalmic optical lens. As we will see in subsequent sections, the multiscale approach acts as a powerful indicator to extract the turning process signature. It also helps monitoring of the diamond tool wear and the scale of turning process impact in relation to the process working variables.
In particular, the effect of the cutting tool acuity is demonstrated in enhanced finishing of optical surface that will conditioning the generation of ‘Mirror’ surface after polishing.

2. Experimental procedure

In this work, single-point diamond turning experiments were carried out on industrial machine (Satisloh VFT-compact) (figure 1). Table 1 show machining conditions used in production line of ophthalmic lenses. In this process configuration, surface of ductile cutting is generated.

![Figure 1. Photograph of the single-point diamond turning machine](image)

| Turning stage          | Rough | Finish |
|------------------------|-------|--------|
| Lens workpiece material| Polycarbonate |       |
| Rake angle of the tool  | 0°    | 0°     |
| Tool nose radius $r_e$ (mm) | 1.7   | 2.2    |
| Spindle speed $V_s$ (rpm) | 5000  | 2000   |
| Feed amount $f$ (µm)   | 52    | 66     |
| Depth of cut $a$ (mm)   | 2     | 0.2    |

The workpiece consists of aspherical polycarbonate lenses with diameter equal to 75mm. The turning process is started by the movement of the cutting tool along the z-direction by the z-carriage of the diamond turning machine until a defined depth of cut ($a$) of the lens array. During the process, the spindle is moved along the x-direction by ($f$) feed step (Figure 1). Each turning test was repeated five times. Three topographic profiles were automatically recorded with a mechanical stylus on a SURFASCAN (Hommel-Somicronic) profilometer at different location on the lens sample diameter, before and after each turning stage.

3. Concept of the multiscale process signature (MPS)

To derive the quantitative expression for each stage of turning process, a multiscale analysis of the surface texture is considered which involves the decomposition of its topographic profiles into wide range scales. This decomposition uses continuous wavelet transform which can be considered as a mathematical microscope, where the resolutions are the basic functions obtained from a single wavelet or mother wavelet $\psi(x)$ by dilation (or compression) and translation [6, 7]. The "Morlet 1D" wavelet given by the following expression is used:
\[ \psi(x) = \pi^{-1/4} e^{\omega_0^2 x^2 - x^2/2} \]  

(1)

The result of the decomposition makes it possible to identify the various scales of the topographic signal after a 1D inverse wavelet transformation [6]. The methodology consists of the quantification of the arithmetic mean value for each scale. The objective is to determine a quantitative expression of the spectrum of arithmetic mean value from the scales of waviness to roughness, Ma [6, 7]:

\[ Ma(a) = \frac{1}{N} \sum_{x=1}^{N} |W_n^a(x)| \]  

(2)

A transfer function of the process that characterizes the roughness attenuation at each scale is introduced. It’s obtained by determining the ratio of SMa(a) spectrum between the surface irregularities before and after finishing (Equation 3).

\[ MPS(a) = \frac{Ma_f(a) - Ma_i(a)}{Ma_i(a)} \times 100 \]  

(3)

With \( Ma_i(a) \) and are \( Ma_f(a) \) respectively the roughness spectrum of the surface before and after the considered turning stage.

This computed transfer function constitutes the multiscale process signature. It identifies the effect of machining at any scale, and permits quantification of the quality of the surface finishing at defined wavelength band [6, 7].

4. Identification of the multiscale single-point diamond turning process signature

Figure 2 shows the MPS spectrums of the rough and finish turning stage respectively. It show very clearly the occurrence of a maximum (minimum of surface irregularities attenuation) located at wavelength value equal to the feed amount (f) (figure 3).

**Figure 2.** MPS of the single-point diamond turning process: (a) rough turning and (b) finish turning
This maximum of the MPS represents the turning straight pattern and separate the wavelength range into two domains:

1) for $scale \geq f$, MPS spectrums of rough and finish turning stage present respectively different attenuation rate of surface irregularities. This attenuation rate reaches the 95% at the first turning stage for all scale greater than 200µm. This suggests that the cutting action in rough turning stage occurs in a wide scale range due to a greater contact between the tool and the machined surface. The cutting conditions for each turning stages calculated by using the model developed by Dong et al. in [8] (see Table 2) confirm that the cutting section area $Ac$ in the rough turning step is almost eight times higher than in the finishing stage.

2) for $scale \leq f$, as we can see from the MPS spectrum (figure 2), the finish turning stage leads to a higher reduction of surface micro-irregularities. The MPS in this scale domain seems to be independent from cutting variables as in metallic turning. In fact, in this scale domain, if we consider as an example, the MPS of the rough turning stage shows a maximum located at almost 18 µm. This implies the presence of elementary patterns with 18 µm of size on the lens surface. The topography of cutting tool edge shows an autocorrelation length of 17.5µm (figure 4-b). Hence, the micro-feature on the topography of the rough turning tool and on the generated surface has almost the same size. Then, it represents a fingerprint of the turning tool roughness.

**Table 2.** Cutting conditions computed by the model described in [8]

| Turning stage | Rough | Finish |
|---------------|-------|--------|
| Cutting section area ($Ac$) (mm²) | 0.1040 | 0.0132 |
| Cutting width ($aw$) (mm) | 3.6736 | 0.9695 |
| Cutting thickness ($ac$) (mm) | 0.0283 | 0.0136 |

Hence, the functional impact of the turning process can be entirely described by four parameters that can be used as inputs for the optimization of the post-polishing stage. These parameters are:
- The maximum amplitude of the MPS spectrum;
- The scale of the maximum amplitude of the MPS spectrum ($f$); it define the scale of the turning marks to be removed by polishing;
- MPS rate average for $scale \leq f$;
- MPS rate average for $scale \geq f$;
5. Conclusion

A new investigative approach to monitor the dynamic of surface generation can be used to increase the level of mastery of the single-point diamond turning process. It is capable of throwing light on both macroscopic and microscopic performances of each turning stage.

The conclusions reached from the analysis of the machined surfaces within the industrial operating conditions were as follow:

- Small wavelength components of the roughness, with wavelength less than the feed working variable are independent from cutting parameters. It depends only on the micro-geometry of the tool and hence the mean average of the MPS spectrum in this scale domain can be used as a parameter to monitor the tool life.

- The reduction of surface irregularities of large wavelength components greater than the feed working variable is considerably dependent on the ratio between the depth of cut and tool nose radius \((a/r_n)\).

Overall, this approach can help in the production of high effective cutting tool. This approach is also necessary for the identification of the optimal MPS of turning which can improve the efficiency of the post-polishing stage in relation to the working process variables.

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