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Small-wavelength form error compensation during hydrodynamic polishing

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ABSTRACT

This paper proposes a process control strategy for removing small-wavelength form error during hydrodynamic polishing, that is, by planning a tool dwelling time appropriate to accurately remove the form error. Volume removal analysis suggests that removal of an arbitrary error profile requires the tool to dwell at a given position for a period that is a linear function of the error profile. The dwelling-time distribution of the tool is solved by the non-negative least squares method. The residual error between the actual and desired profile is induced by this strategy. Residual error occurs mainly at the peaks and valleys of the profile, in addition to the boundaries of the machining area. Results indicate that the dominant factors in deciding residual error are the size of the machining zone, tool step, and wavelength and amplitude of the error profile. It is shown that *larger residual error occurs in bands with wavelengths smaller than the machining zone, and vice versa. If the wavelength is sufficiently large, a small tool step effectively reduces the residual error. Furthermore, large variations in the amplitude of the error profile can be effectively reduced when the wavelength is large.* Experimental results confirm that the proposed polishing strategy can remove an arbitrary profile and automatically reduce the small-wavelength errors. However, it is not *effective when the wavelength of the error profile is near the size of the machining zone.*

1. Introduction

This paper proposes a process control strategy to remove a symmetric error profile on a work surface during hydrodynamic polishing (HDP). In particular, the effects of the wavelength of the original error profile on the final form precision after HDP are examined. The proposed strategy seeks to design a dwelling-time distribution for the tool that allows accurate removal of the symmetric error profile. HDP is a floating process that makes use of the hydrodynamic effect to float the tool above the work surface during polishing. Fig. 1 shows a schematic diagram of the machining system. It is known that the machining behaviour of the process will remain consistent if the machining parameters are properly controlled [1]. This deterministic tendency makes HDP suitable for form error compensation [2].

The process of accurately removing an arbitrary form error from a work surface is defined as form error compensation. Consider a work surface with a specific form error profile (as shown in Fig. 2) left by the previous machining process. If a polishing process has the capability to remove an arbitrary profile, it can be applied to the shaded part of the error profile so that the form precision can be improved. The key to implementing the compensation strategy is to give the polishing process the ability to remove an arbitrary profile. This can be realized by properly controlling the dwelling-time distribution for tool motion around the domain area of the error profile. Su et al. [2,3] suggested that the tool dwelling time is a linear function of the depth function. They also proposed a process compensation strategy for applying HDP to an arbitrary profile. Their results showed that the work precision can be improved from 2 to 0.15 μm by a polishing machine with a positioning precision of 10 μm.

A drawback of this strategy may be the reduction in form precision when the wavelength of the error profile is less than the size of an instantaneous machining zone. A basic principle for this machining strategy is that the machining zone (minimum machining size) must be much smaller than the wavelength of the error profile. In contrast to theory, however, the instantaneous machining zone is not a mathematical point but instead covers a finite area in practise. If the wavelength of the error profile is much larger than the machining zone, the tool dwelling time at one position is not influenced by adjacent peaks or valleys in the error profile to be removed. Thus, the necessary tool dwelling time at that point can be evaluated accurately. However, if the wavelength of the error profile is smaller than the machining zone, it is difficult to accurately plan the dwelling time because the wide instantaneous machining zone will span the tops of

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Nomenclature

A	infinitesimal region (mm^2)
a_1	a constant (μm)
a_2	a constant (μm)
c	a constant (mm)
$D(r)$	depth function of error profile (μm)
$[D_i]_n$	depth function matrix (μm)
E_R	residual error percentage (%)
L	range of tool dwells (mm)
m_o	a constant
m'	machining rate distribution (μm/s)
Mj (r)	machining rate occurring at radius r as the tool dwells at the j-th location
M_{ij}	machining rate at i-th point on work surface as tool dwells at j-th location
$[M_{ij}]_{nxn}$	machining rate matrix (μm/s)
r	location of an infinitesimal machining zone (mm)
r'	location of an infinitesimal machining zone (mm)
r_i	i-th radius of the work surface(mm)
$t(\rho)$	tool dwelling-time distribution (s)
$T(\rho_j)$	tool dwelling time at the j-th tool location (s)
$[T_j]_n$	tool dwelling time matrix (s)
$V(r)$	actual machining volume of the work surface at radius r ($mm^3\,s^{-1}$)

Greek

$\theta_{1,2}$	angular corresponding to the machining zone area A
λ_1	wavelength of sinusoidal profile (mm)
λ_2	size of the machining zone (mm)
ρ	tool location (mm)
ρ_j	j-th tool dwelling location (mm)
η_r	roughness removal efficiency
$\delta Vp(r)$	volume machining rate (μm/s)
Δ	tool step size (μm)
δ_t	a small positive value

several adjacent peaks and valleys simultaneously. This implies that the wavelength of the error profile is a significant factor in the planning of tool dwelling time. Hence, for high fabrication precision, the proposed strategy considers the impact of the wavelength on form precision.

Little work has been devoted to the above issue, considerable experimental data is available on one method of precision fabrication, namely, computer controlled optical surfacing (CCOS) [4–17]. CCOS is an iterative process in which the measured surface error is corrected through controlled abrasion. Jones [4–10] and Jones and Geril [11] proposed the use of CCOS in the fabrication of aspherical optical surfaces. Li et al. [12] found that surface correction can be realized by controlling the tool dwell time and also proposed an algorithm for controlling the tool dwell time in CCOS. Yi et al. [13] developed a process using a pin polisher with different grades of diamond paste that can produce an optical surface (R_a~4 nm) on stainless steel meld pins. Cheng et al. [14] designed a six-axis machining system based on CCOS and applied it in fabricating large off-axis aspherical mirrors with subaperture lapping techniques. They reported a reduction in form error from an initial 17.65 μm rms to a final 0.728 μm rms after grinding an aspherical mirror for 200 h. Furthermore, Schinhaerl el al. [15] developed a new method to minimise the effects of measurement error on the influence function using CCOS. They observed improvements of 14%, on average, in the peak-to-valley (PV) value of surfaces polished with the symmetrical rendered influence function rather than the unmodified function. Schinhaerl et al. [16] introduced a new approach considering time-variant influence functions for computer controlled polishing. Their results pointed out that time-variant influence functions may further decrease the process time and they, in fact, realized an approximately 35% reduction in process time using a combination of the dwell time method with time-variant influence functions. For magnetorheological finishing (MRF), Schinhaerl et al. [17] calculated the polishing tool characteristics and verified their results experimentally, which showed that their model afforded enhanced finish quality for aspherical or free-form work geometries. In addition, Su et al. [18] proposed a process planning method for removing an arbitrary and symmetric error profile by the cylindrical polishing process. These and other related studies examined surface precision, but no further studies have been conducted specifically on the effect of the wavelength of the initial error profile of the work surface itself on the final form precision of the work.

In the present study, a modified version of the process control strategy suggested in Ref. [2] was adopted for arbitrary and axially symmetric profiles. The relationship between residual error and the wavelength of the error profile was then analysed. Three experiments were conducted to examine the validity of the modified strategy and the effect of the wavelength of the error profile on the form precision. Finally, the analytical predictions and experimental results were compared and the results are discussed herein.

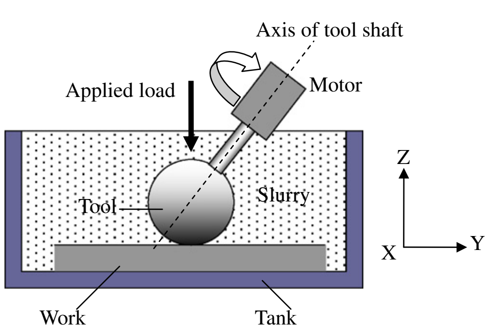

Fig. 1. Schematic diagram of the machining system for HDP.

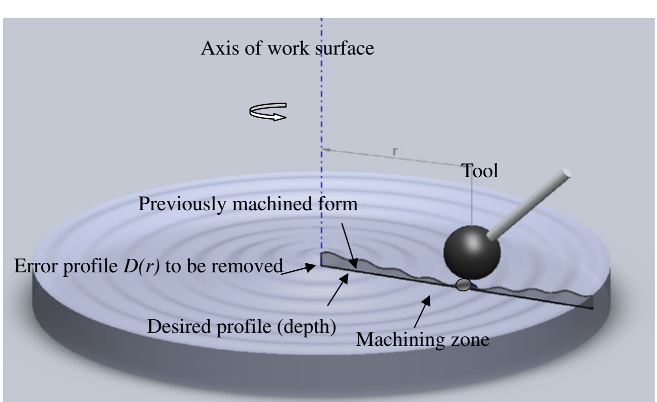

Fig. 2. Schematic diagram of the form error compensation strategy.