Process Modelling and Simulation of Vibratory Finishing of Fixtured Components

Stephen Wan, Weng Seng Fong and Zhan Hui Tay
Singapore Institute of Manufacturing Technology, Singapore
ymwan@SIMTech.a-star.edu.sg

Abstract

The present work was motivated by a need to predict changes in the surface roughness distribution on external three dimensional free form surfaces undergoing vibratory finishing. To this end, we invoked a granular flow dynamics model applicable to dense granular flow in order to describe the flow of the abrasive media over three dimensional free form surfaces. At the same time, based on the assumption of two and three body abrasive wear, we derived a process equation which gives the surface roughness distribution in terms of the granular pressure and velocity. Hence, by solving the granular flow field for the pressure and velocity distribution on a given geometry, we are able to predict changes in surface roughness distribution from the process equation. To the authors' knowledge, this is the first time such an approach has been adopted. In this paper, we also outline the development of a probe for extracting the tribological constants in the process equation as well as the local media flow direction. In this paper, we also outline the development of a probe for determining the local media flow direction and a reference granular pressure. These were input in a computational fluid dynamics (CFD) software package, which was used to solve for the granular flow field and hence predict the surface roughness distribution. We illustrate the application of this method to fixtured cylinders and cuboids (with two rounded ends), and compare predicted results against experimental data.

1 Introduction

Vibratory finishing is a ubiquitous mass finishing technique, in which quantities of work pieces to be processed are immersed in abrasive particles in a bowl. As indicated Figure 1, the bowl is vibrated by rotating a central pair of eccentric fly weights , which in turn causes the abrasive particles to roll and feed round the bowl in a toroidal motion. Details of vibratory finishing systems and processes can be found

in [1]. For high value add parts, such as medical implants, it may be necessary to immobolize such workpieces in order to prevent them from colliding into and hence damaging one another. The present work was motivated by the need to understand the effect of fixturing such workpieces which often have complex free form surfaces. To this end, we first derive a process equation which gives the surface roughness distribution in terms of the granular pressure and velocity. We then input a granular flow dynamics model as well as the workpiece geometry into a CFD software package in order to calculate the pressure and velocity field. Finally, we compared the simulated predictions against experimental measurements of surface roughness.

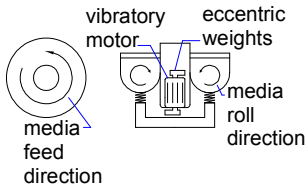

Figure 1. Plan and cross-section views showing media feed and roll directions

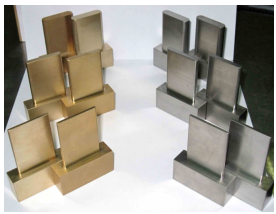

Figure 2. Workpieces used in experimental study

2 Outline of process model derivation

The starting point of the derivation is the analysis of transient wear by Queener et al [2], who assumed that the total wear volume, V consists of a volume wear from a transient mechanism, V_T and a steady-state volume wear, V_S that is:

$$V = V_T + V_S \; ; \quad V_T = V_0\left[1 - \exp\left(K_T L\right)\right] ; \text{ and } V_S = K_S L \qquad (1)$$

where V_0 is the original volume available for removal by the transient mechanism; L = distance slid and K_T, K_S = a constant. Next, by rewriting the well-known law for two and three body wear, $V_S = \left(k_s W L\right)/H$ as $h_S = \left(k_s p_a v t\right)/H$ where k_S is the wear coefficient, W is the normal load, and H is the hardness of the worn surface, h_S is the steady-state wear depth, v is the sliding velociy, $p_a = W/A_a$ is the apparent pressure and $L = vt$; and by comparison with equation (1), we see that $K_S = \left(k_s p_a A_a\right)/H$, which we write more compactly as $K_S = \left(k_S p_a\right)/H$, where $k_S = k_s A_a$. Likewise, we assume that, for the transient component, K_T takes a similar form. Hence we arrive at: $h_T = h_0\{1 - \exp[-\left(k_T p_a v t\right)/H]\}$ where $h_T = V_T / A_a$;

and $h_0 = V_0 / A_a$. To express the above relations explicitly in terms of surface roughnesses, we assume that $(R_i - R_\infty) \cdot A_a \propto V_0$ and $(R_i - R_a) \cdot A_a \propto V_T$;or $h_T = a(R_i - R_a)$ and $h_0 = a(R_i - R_\infty)$ where R_i = initial surface roughness, R_∞ = limiting surface roughness, R_a = current surface roughness and a is some constant. Thus for the total wear depth, $h = h_T + h_S$, we have:

$$h = a\{R_i - R_\infty\}\{1 - \exp[-(k_T p_a vt)/H]\} + (k_S p_a vt)/H \quad (2)$$

and for the surface roughness:

$$R_a = [R_i - R_\infty] \cdot \exp[-(k_T p_a vt)/H] + R_\infty \quad (3)$$

3 Experimetal setup

Walther Trowal vibratory bowl model CMM-305S and Walther Trowal PI 4 X 10 A/C TRI ceramic media were used in the experimental studies. Workpieces made of brass and stainless steel such as those shown in Figure 2 were fixtured at 45 degrees in the centre of bowl annulus. Vibratory speed and feed direction were varied to obtain the validation data.

4 Process simulation setup

We have chosen the continuum based granular flow dynamics model of Jop et al [3], because of its simplicity and elegance. Briefly, the model takes the form of a non-Newtonian viscoplastic viscosity, η given by: $\eta = \mu(I)P/|\gamma|$, where P is the isotropic pressure, and $|\gamma|$ is the second invariant of the shear-rate tensor. μ is some function of the inertia number, $I = |\gamma| d / \sqrt{P/\rho}$ where d and ρ are respectively the diameter and density of the media grains. The model and workpiece geometry were input in ANSYS CFX v. 12, a CFD package; and the pressure and velocity field calculated accordingly. A proof-of-concept tribometer, in the shape of a cube, with built in force sensors, was used to determine media flow direction and to extract process model constants for input into the CFD package.

5 Comparison of experimental and simulated results

For ease of comparison, the various regions of the cross-section of the workpieces are designated as indicated in Figure 3. Then the normalised drop in surface

roughness, $\left[1-\left(R_a-R_\infty\right)/\left(R_i-R_\infty\right)\right]$ is plotted against the arc length (normalised against the perimeter) of the cross-section. These experimental plots were then compared against the predicted normalised polishing strength, $\varsigma/\varsigma_{\max}$ (where $\varsigma=\partial/\partial t\left[\ln\left(R_a-R_\infty\right)/\left(R_i-R_\infty\right)\right]=-\left(k_T\,p_a\,v\right)/H$) distribution over the whole workpiece. Of all the validation cases, the most critical case is perhaps the comparison between predicted and experimental results obtained for media feed in the reverse and forward directions. As can be indicated by the experimental plots in Figure 4, there is a sharp difference in the surface drops in the downward pointing end of the workpiece when subjected to opposite media directions. This difference was clearly reproduced by the simulated results (Figure 5).

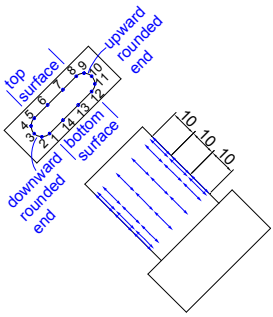

Figure 3. Designation of cross-section regions

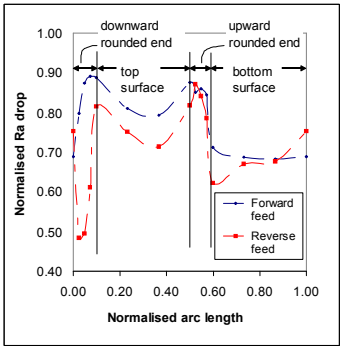

Figure 4. Plot of normalised Ra drop versus normalised arc distance

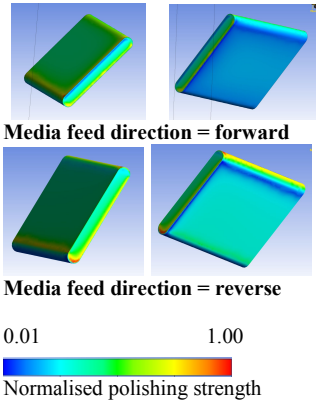

Figure 5. Predicted polishing strength

Conclusions

There appears to be reasonable semi-quantitative and semi-qualitative agreement between experimental and predicted results. Work is ongoing to improve the design of the tribometer.

References:

[1] La Roux Gillespie. Mass Finishing Handbook. Industrial Press Inc, New York, 2006

[2] C A Queener, T C Smith and W I Mitchell. Transient wear of machine parts. Wear, 8 (1965) 391-400.

[3] Jop P, Forterre Y, Pouliquen O. A constitutive law for dense granular flow. Nature 441:727-30, 2006.