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Modeling of material removal mechanism in vibratory finishing process

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ABSTRACT

In industry today, the use of vibratory finishing processes as a final manufacturing step is increasing rapidly. Through the ability of these processes to achieve stable material removal rates, very consistent results in the control of surface texture are achieved. Even though the importance of these processes to manufacturing industry is increasing, the fundamentals of the material removal mechanism have not yet been established, and the associated lack of scientific understanding is an obstacle for process optimization. This paper proposes a mathematical model of the material removal mechanism based on abrasive finishing theory. The proposed model is used to identify key parameters and analyze their effect on the material removal mechanism. Experimental tests were conducted to validate the proposed model and provide correlation with the results obtained from the theoretical analysis. For the first time, fundamental abrasive machining process parameters such as the equivalent chip thickness and specific cutting energy realized through vibratory finishing are revealed.

1. Introduction

There are five kinds of mass finishing processes in use. These are vibratory finishing, barrel tumbling, centrifugal barrel finishing, centrifugal disk finishing and spindle drag finishing. Among them, the vibratory finishing process, especially bowl type vibratory finishing, is the most widely used, due to its productivity, process controllability and cost competitiveness. Its application as a final finishing process in component manufacturing has been increasing in industry, because of its ability to improve surface texture without negatively affecting the underlying component geometrical accuracy. Vibratory finishing creates a unique surface integrity on functional components which improves performance attributes such as fatigue life, torque and heat generation [1,2], and provides very consistent control in surface roughness and material removal rate [3]. In spite of growing application and a general trend toward tighter tolerance requirements, fundamental knowledge on the finishing mechanism is not readily available, and as a manufacturing technology, the vibratory finishing process is still treated as an art, rather than a science. The lack of scientific knowledge on the material removal mechanism in vibratory finishing is a serious obstacle to obtaining optimum processing conditions without resorting to empirical procedures.

Very little scientific research with respect to vibratory finishing technology has been published and few mathematical models relating to the material removal mechanism have been proposed. Hashimoto [3] presented a model of the material removal processes consisting of a transient process inducing a change to the incoming surface topography and a steady-state process having a constant removal rate over time. Wang et al. [4] measured contact forces between media and aluminum workpieces during vibratory finishing, and presented that the contact forces changed significantly with the excitation frequency of the machine. Yabuki et al. [5] took video of media motion and concluded that the media contact-patterns on work surfaces were classified by three modes described as; free impact, rolling over and stationary press. Normal and tangential forces were measured, and the force ratios were presented. Also, very small sliding motion of media on workpieces was indicated. Domblesky et al. [6,7] investigated bowl type vibratory finishing processes and proposed a model to describe material removal rate. The model indicated that the rate remained constant over time and was governed by bowl acceleration, workpiece mass and velocity. Song et al. [8] discussed the role of chemical solutions on the material removal process. The above researchers provide very important knowledge about the influence of process parameters on the finishing process. However, the systematic analysis of the material removal mechanism in vibratory finishing process has not been presented and a mathematical model to determine key process parameters in the material removal mechanism has not yet been established.

The present paper proposes a mathematical model of the material removal mechanism based on abrasive finishing theory. It discusses the effect of key parameters identified by the proposed model on the removal mechanism. Experimental tests were conducted to qualitatively clarify key parameters, such as the properties of the processing media as well as the workpieces being processed including their shape, vibration system, contact forces, impact velocities, etc. The experimental results are discussed in terms of validating the proposed model, and the results obtained from the theoretical analysis are also reviewed. For the first time, fundamental parameters, such as the equivalent chip thickness and specific cutting energy realized through vibratory finishing are revealed.

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2. Modeling of material removal mechanism

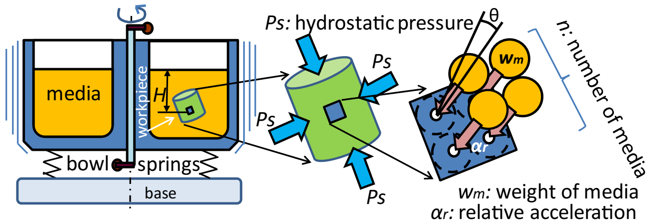
In vibratory finishing, a bowl or tub supported on multiple springs is charged with abrasive media and workpieces, and shaken with forced vibrations induced by a rotating spindle with eccentric masses [9]. A workpiece located at a depth H from the top surface of the media receives two normal force components. These are induced by hydrostatic pressure due to media weight as well as forces generated by media impacts, as illustrated in Fig. 1. The normal force F_n acting on a unit area of the workpiece surface can be expressed:

$$F_n = P_s + n\frac{w_m}{g}\alpha_r \cos\theta \tag{1}$$

where P_s is the hydrostatic pressure on the workpiece surface, n is the number of contact points of media with the workpiece surface per unit area, w_m is the weight of a single piece of media, α_r is the relative acceleration between the media and the workpiece, θ is the impact angle from normal to the workpiece surface. The hydrostatic pressure P_s is represented as follows:

$$P_s = [\{\eta_m w'_m(1-R_v)\} + \{\eta_w w'_w R_v\}]H \tag{2}$$

where w'_m and w'_w are the specific weights of media and workpieces, respectively. R_v is the volume ratio of workpieces to media in the bowl. η_m and η_w are the occupancy ratios of media and workpieces in a unit volume. The value of the occupancy ratio is determined only by the geometrical shape of the body (media or workpiece). For instance, in the case of ball media, the theoretical maximum occupancy-ratio η_{max} of the total volume of media to a unit volume is $\sqrt{3}\pi/9$. It means that the maximum volume percentage of balls occupied in a unit volume is 60.4%, which is independent of the ball size.



(a) Cut section of vibratory finishing machine (b) Workpiece immersed in media at depth of H (c) Number of media acting on unit area of workpiece surface

Fig. 1. Forces acting on surface of workpiece immersed in media.

Fig. 2 illustrates the relative motion of media to workpiece before and after collision and the resulting impact forces acting on the workpiece surface. The relative velocity v_r of media to the workpiece surface and the average velocity v_τ are:

$$v_r = A_r\Omega\cos(\Omega t + \varphi), \quad v_\tau = (\sqrt{2}/2)A_r\Omega \tag{3}$$

where A_r is the relative amplitude of media to the workpiece, Ω is the angular velocity of the forced vibration which is given by the spindle speed of the vibratory finishing machine, φ is the phase angle [9]. Although the average velocities of the tangential components $v_{\tau t}, v'_{\tau t}$ are constant before and after collision, the average velocities of the normal components $v_{\tau n}, v'_{\tau n}$ change in both magnitude and direction.

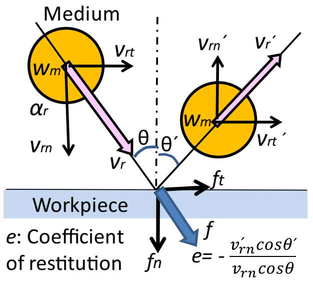


Fig. 2. Relative motion of media to work surface and impact forces.

$$v_{\tau t} = v'_{\tau t} = (\sqrt{2}/2)A_r\Omega\sin\theta, \tag{4}$$

$$v_{\tau n} = (\sqrt{2}/2)A_r\Omega\ \cos\theta, \quad v'_{\tau n} = -(\sqrt{2}/2)A_r\Omega\cos\theta\cdot e \tag{5}$$

where e is the coefficient of restitution between a medium and workpiece surface as defined in Fig. 2. As the number of media n contacts a unit area on the workpiece surface, the resultant force $F_\cdot$ and the tangential force F_t can be expressed as follows:

$$F_\cdot = \frac{nf_n}{\cos\theta} = \frac{p_s}{\cos\theta} + n\frac{w_m}{g}A_r\Omega^2 \tag{6}$$

$$F_t = F_\cdot\sin\theta = \mu F_n, \quad \mu = F_t/F_n = \tan\theta \tag{7}$$

where μ is the force ratio of tangential force to normal force. f, f_n and f_t are the resultant, normal and tangential forces given by a medium, respectively. The relative average cutting speed v_s of media to the workpiece can be written as:

$$v_s = v_{\tau t} + v_{sl} \tag{8}$$

where v_{sl} is the relative average sliding velocity between the media and workpiece surface while both circulate in the bowl of the vibratory finishing machine.

The relative average velocity v'_τ of media to workpiece after collision can be expressed by:

$$v'_\tau = (\sqrt{2}/2)A_r\Omega\cos\theta\sqrt{e^2 + \mu^2} \tag{9}$$

Therefore, the average energy loss ΔE per unit area on the workpiece surface at each collision can be expressed by the following equation:

$$\Delta E = \frac{n}{4}\frac{w_m}{g}(A_r\Omega)^2[1-(e^2+\mu^2)\cos^2\theta] \tag{10}$$

In vibratory finishing, the amount of material removal with respect to time $S_r(t)$ can be expressed [3]:

$$S_r(t) = mt + 4(I_r - D_r)(1 - e^{t/T}) \tag{11}$$

where m is the surface penetration speed of media into the workpiece surface. I_r and D_r are initial and final roughnesses in R_a, respectively. T is the time constant of the finishing system. The first term represents the material removal rate m [mm/s] during the steady-state process. The second term is for the transient removal process due to the changing surface topography. Therefore, the material removal rate per unit area Q_w [mm^3/(mm^2 s)] in the steady state process can be represented by multiplying m and a unit area.

The equivalent chip thickness h_{eq} represents the thickness of a ribbon shaped cuboid whose volume is the total material volume removed per unit of time. Its length is proportional to v_s and it has unit width. The parameter h_{eq} governs fundamental process output parameters such as roughness, force, residual stress, etc. The h_{eq} is defined as Q'_w/v_s, where the Q'_w [mm^3/(mm s)] is the specific material removal rate. As $Q'_w = (Q_w a)$ where a is the depth of cut, the equivalent chip thickness in vibratory finishing is represented by:

$$h_{eq} = \frac{Q_w a}{v_s} = \frac{ma}{(v_{\tau t} + v_{sl})} \tag{12}$$

The specific energy u is the energy consumption required for removing a unit volume of material. The energy represents the machinability of materials under given finishing conditions, such as cutting force, cutting speed and stock removal rate. The following equation allows the calculation of the specific cutting energy in vibratory finishing.

$$u = \frac{F_t v_s}{Q_w} = \frac{\mu F_n(v_{\tau t} + v_{sl})}{m} \tag{13}$$

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