A Process Model for Surface Material Removal in Vibratory Bowls and Finishing Processes

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In recent years, increased attention has been given to mechanical surface finishing processes as manufacturers and finishing companies seek to improve process efficiency while meeting increasingly stringent product specifications and environmental regulations. Although vibratory finishing is a widely used mechanical finishing process, relatively little scientific information is available on the process and this lack of understanding has not only restricted development of optimum finishing processes but has also tended to users' abilities to exploit the advantages that mechanical-based preparation offers. This paper summarizes the results of a research study that was conducted to investigate material removal in vibratory finishing and to develop a model of mass removal rate. Experimental validation confirmed the model's predictions and results indicate that bowl acceleration and workpiece mass/velocity are important process variables in controlling material removal.

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Introduction

While surface preparation usually encompasses cleaning, it can also include structural modifications such as abrading a surface to remove blemishes and generate a non-directional finish to improve paint adhesion or reducing surface roughness to promote highly reflective plated surfaces. Within recent years there has been greater interest in mechanical-based preparation processes as they represent a viable alternative to solvent-based cleaning and preparation operations for a variety of components. A key reason for this is that mechanical-based processes in general tend to be more environmentally friendly with minimal air emissions and problems related to the handling/disposal of VOC's and solvents.

However, when comparing different processes, electro-chemical methods are often viewed as being superior to equivalent mechanical processes for use in surface preparation. Mechanical-based processes such as vibratory finishing are often viewed as being empirical, artisan operations which lack a firm technological foundation and tend to be uncontrollable, and hence unpredictable [1]. This perception is in large part due to the lack of understanding that currently exists as recent work has established that mechanical-based processes are not only consistent, but also controllable.

In an effort to generate a better understanding of vibratory bowl finishing, research has been undertaken at Marquette University to analyze and study surface modification. The investigation focused on characterization of vibratory machine behavior, experimental protocols, and development of a process model that could link key process parameters and finishing behavior. This paper summarizes results obtained to date regarding the material removal investigation and model development.

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Overview of Vibratory Bowl Finishing

The first vibratory finishing machines were developed in the 1950's when it was realized that small vibratory shakers and jewelry polishers could be scaled up to more efficiently handle larger workpieces [2]. The process gained widespread usage during the 1960's in the metalworking sector as manufacturers recognized that vibratory machines required less floor space and facilitated process monitoring in comparison to tumbling. However, while a significant amount of experience has been compiled, the level of understanding regarding the process has lagged with the result most vibratory operations continue to be developed using a combination of empiricism and trial/error. This has not only restricted development of optimum finishing operations but has also tended to limit significant advances in media design and process equipment.

During vibratory bowl finishing, surface modification on workpieces is achieved via abrasive action between the media and workpieces in a re-circulating flow of aggregate material. While some operations are performed dry, most vibratory finishing is done wet using a flow-through system that continuously flushes the bowl with a water-based solution to evacuate particulates, inhibit part corrosion, provide lubrication, and reduce heat build-up in the workload. The type of media used is dictated by whether the objective is to accomplish metal removal or impart a smooth, lustrous finish.

Most vibratory bowls are based on a vibrating spring-mass system where finishing action is governed by two opposing sets of eccentric weights mounted on opposite ends of a belt-driven shaft (Figure 1). One set of weights controls circumferential motion around the bowl (feed motion) while the other controls the rate of radial tumbling (roll motion) with the resulting motion being a toroidal helix (Figure 2). The weights also control the acceleration imposed on the workload which also has a significant effect on the finishing action. Depending on

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the drive RPM that is used, the bowl oscillates at a frequency that is normally ranges between 20-40 Hz [3].

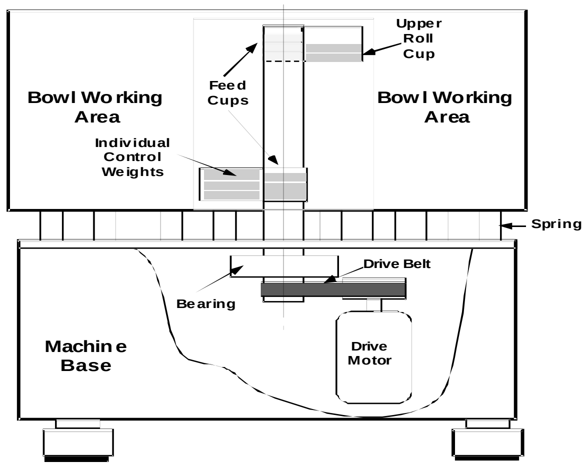

Figure 1.Schematic of a typical vibratory bowl machine.

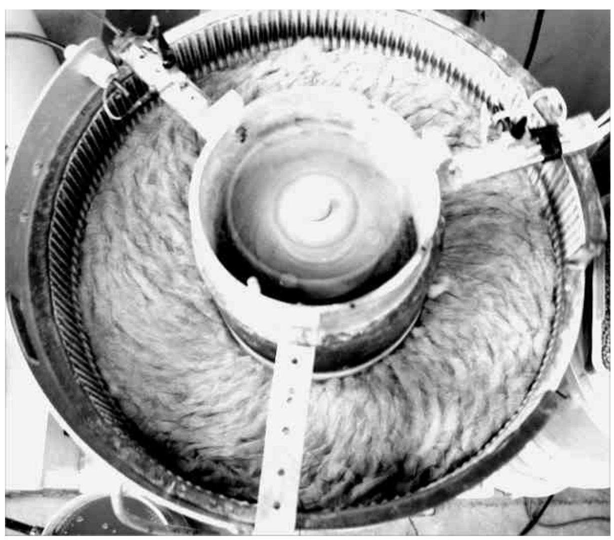

Figure 2. Representative flow pattern of the workload in a vibratory bowl.

A key difficulty in process optimization [1] and experimentation is that a relatively large number of process variables need to be controlled. Key process variables include: media (shape, grit material, and size), compound solution (flow

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rate and composition), workpiece material (hardness and composition), and bowl characteristics (capacity, shape, acceleration, and frequency). While some of these variables are fixed in a given process, an important task of the initial research centered on studying and identifying those factors that could vary during an operation and developing suitable experimental protocols to ensure consistent and repeatable results. This has been covered in detail in a previous paper [4] and will only be summarized here.

Previous Research

A review of the literature shows that, until recently, that very little scientific research has been performed on the topic of mechanical preparation and finishing. Although numerous trade articles and empirical studies have been published that attempt to describe how surface finish and material removal are affected by different process parameters in mechanical finishing processes, this information has limited usefulness in that it is based largely on observations drawn from individual operations rather than rigorous scientific experimentation. As such, the articles provide limited physical insight and are not always applicable under general finishing conditions.

One of the first vibratory finishing studies to appear in the literature was presented by Hashimoto [5]. Hashimoto experimentally determined that surface roughness dropped rapidly at the beginning of the finishing cycle after which a steady-state value appeared to be achieved. Hashimoto also found that material removal rate was essentially constant over time. While models were developed to describe this behavior, their usefulness is limited by the fact that only time and initial surface roughness are included. A later study by Wang et al. [6] has considered the effect of wet and dry media on surface finish and resulting hardness in 6061 aluminum workpieces. Using a force transducer and a miniature video camera mounted inside of a cylindrical workpiece, they also were able to measure average normal load and contact duration between the workpiece and surrounding media. Although the force data was limited to the normal direction and did not distinguish between individual media effects, it does provide some insight into force magnitude and contact conditions existing at the workpiece.

Experimental Setup

For the experimentation, a Roto-Finish ST-1 vibratory machine from Roto-Finish Corp. (Kalamazoo, MI USA) was used. The ST-1 has a urethane-lined bowl with a one cubic foot capacity and operates at a fixed frequency of 24.3 Hz. As the bowl was not equipped for measuring acceleration, it was instrumented for the study using three Kistler 8002K accelerometers mounted mid-radius at the top of the bowl. The accelerometers were connected to a data acquisition board and personal computer which enabled acceleration to be collected at 10 Hz over ten-minute intervals. Bowl acceleration was controlled by adding and removing 52 g steel plates in the top cups (Figure 3) while the bottom weights were fixed at five roll and four feed weights.

Figure 3. Top weight cups used to control acceleration in the Rotofinish vibratory bowl.

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For the study, finishing time, bowl acceleration, media, and workpiece material were selected as the independent variables. The media used was an offset triangular prism geometry that was supplied by Abrasive Finishing Inc. (Chelsea, MI USA). Three different media types (Figure 4) having different roughness characteristics designated as smooth, medium and rough were selected. The rough media is termed a “fast cut” media designed for high removal rates whereas the smooth media is primarily non-abrasive and intended for minimal cutting action.

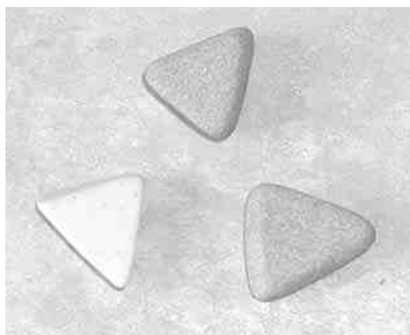

Figure 4.Triangular ceramic media used in the investigation.

The majority of media that is used in vibratory finishing is a resin or ceramic bonded abrasive that wears with usage. For most bonded media, rapid volumetric loss occurs initially, after which a steady-state condition is achieved following several hours of use. As media loss will cause the work load mass to change, potentially affecting process behavior, it has been suggested that it should be treated as a process variable [7]. Prior to performing the experimental runs, the effect of media loss on bowl acceleration was assessed by recording acceleration for dry media masses ranging from 0 Kg to 23 Kg in increments of 4.5Kg. Results showed that while the workload mass has a linear effect on acceleration, the change in acceleration was less than 5% for up to 10 Kg difference in bowl mass which indicates that media loss could be neglected during each run.

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For each experimental run, 21.6 Kg of wet media was used as this is considered to be the optimum loading for the bowl capacity used [8]. Water mixed with a one percent solution of XL-528, a general purpose alkaline based liquid compound from Roto-Finish Corp., was pumped into the bowl at a constant flow rate of 5.7 liters per hour. Bowl loading was limited to 15 parts to achieve a volumetric ratio of 90:1 to minimize part-to-part contact and potential surface damage. All media was “broken in” for 25 hours in the vibratory bowl prior to usage to prevent media roughness from significantly changing during the experimentation. Results published by Wang [6] show that media roughness can affect finished workpiece surface conditions and that media roughness tends to level off after twenty hours of use. Thus media which has been broken-in will provide consistent finishing performance. Furthermore, based on previous studies, where material removal rates were found to be constant over time when broken-in media is used, it can be assumed that the media is self-sharpening [9] and that cutting action will not change significantly over time.

Workpiece materials consisted of UNS C36000 Brass, AISI 1018 steel, and AA-6061 aluminum rods which had Brinell hardness of 105, 181, and 111 Bhn respectively. Individual specimens were machined into cylinders 25.4 mm in diameter and 25.4 mm in height with all edges being radiused to 2 mm. Specimens were also pre-finished using a polymer-bonded media to ensure consistent surface conditions. Material removal on each of the specimens was recorded at one-hour intervals for a total of eight hours using a Mettler-Toledo AB204-S electronic balance that was accurate to within 0.0001 g.

Analysis and Model Development

During vibratory finishing, workpiece surfaces are modified by a combination of peening, micro-cutting, and burnishing [10]. While peening and burnishing will influence surface finish, as they do not influence the rate of material removal,

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they were neglected in the study. To facilitate the analysis, it was considered that material removal results from the cumulative action of a large number of grits simultaneously shearing material over time. As a workpiece is essentially enveloped by the media during finishing, it should be possible to treat material removal as being a continuous process. While media action is not locally continuous on a surface, effects will be aggregated over the entire workpiece during a finishing cycle and it is reasonable to consider the bulk or effective rate of material removal.

Neglecting effects from adjacent media, the forces acting on an individual piece of media on a surface during material removal will consist of cutting and thrust forces at the tip. Due to the differences that exist between the media and workpiece, a relative velocity, $v_{w/m}$, will be created between the workpiece and media [2]. The power consumed during material removal can thus be considered to be the product of the cutting force, F_c, and $v_{w/m}$ and can be defined as:

(1) $$P = F_c \cdot v_{w/m} \quad \text{(N-mm/s)}$$

where: F_c is the cutting force and $v_{w/m}$ is the relative velocity between the workpiece and a surrounding piece of media. As the mass of an individual workpiece tends to be greater than that of individual pieces of media by a factor of 3 or more and as it is necessary to introduce the bowl acceleration, power can be rewritten as follows:

(2) $$P = m_w \cdot a \cdot v_{w/m}$$

where: m_w is the workpiece mass and a is the acceleration magnitude. While testing has shown that different weight settings provide similar magnitudes, results indicate that, in general, that magnitude is more important that acceleration components in governing material removal. Although acceleration will vary with bowl radius, the average workpiece location will fall at mid-radius of the bowl. Thus, it can be assumed that this location will be representative of the acceleration acting on an individual workpiece during a finishing cycle and was used in the analysis.

Since specific energy, *U,* is considered to be a fundamental measure of cutting resistance in metals, this quantity can be used to relate material removal to cutting power. For a material removal process, *U* is the ratio of power consumed during cutting and the resulting volumetric rate of material removal, *VRR*.

(3) $$U = \frac{P}{VRR} \quad \left(\frac{\mathrm{N \cdot m}}{\mathrm{mm^3}}\right)$$

Though normal convention is to use volumetric material removal rate in metal cutting analyses, in vibratory finishing it is more convenient to represent material removal on a mass basis as dimensional changes are small and typically on the order of 10^{-6} mm. As cycle times are relatively long and only small amounts of material are removed, mass removal rate, *MRR*, and *VRR* can be placed on a hourly basis and are related by workpiece density as shown in equation (4).

(4) $$MRR = \rho \cdot VRR \quad \left(\frac{\mathrm{g}}{\mathrm{hr}}\right)$$

From equations (2) and (3), *MRR* can be represented as:

(5) $$MRR = \frac{\rho \cdot m_w \cdot a \cdot v_{w/m}}{U} \quad \left(\frac{\mathrm{g}}{\mathrm{hr}}\right)$$

As workpiece density is a material constant, mass removal rate can be seen to be a function of bowl acceleration, workpiece mass, velocity, and specific energy. Equation (5) also suggests that the mass removal rate is independent of cycle time and this is consistent with data obtained by Hashimoto [5] and Evans [11]. As material removal will also be affected by the media used and a correction is needed in the specific energy term to account for size effects, these effects can be incorporated using a dimensionless cutting factor, *K*, in equation (6). As the cutting factor and velocity are difficult to determine analytically, these must be determined from experimental data though work is currently underway to experimentally obtain media and workpieces velocities.

(6) $$MRR = \frac{K \cdot \rho \cdot m_w \cdot a \cdot v_{w/m}}{U} \quad \left(\frac{\mathrm{g}}{\mathrm{hr}}\right)$$

Results and Discussion

Material removal rate for each material was considered first and the experimental results that were obtained are shown in Figure 5. As similar results were obtained for all media, only those for rough media are shown. It can be seen that material removal rate is essentially constant over time at each level of acceleration and confirms the use of averaging assumption used in the model and the time independence predicted by the model. The constant rate of material removal also indicates that while media loss will occur during vibratory finishing, small losses do not have an adverse impact on the finishing performance of the media.

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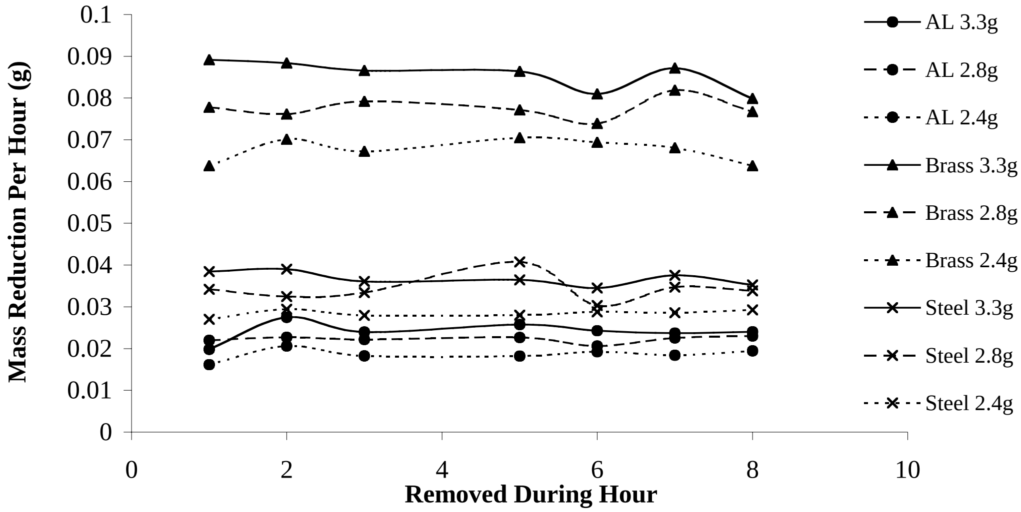

Figure 5. Material removal rates at various bowl accelerations over an 8 hour period for the fast cut media.

Although it has long been known that bowl acceleration and material properties are important process variables, their effect on mass removal has not been quantified up to this point. Equation (6) predicts that material removal is proportional to acceleration and inversely proportional to specific energy. The effect of acceleration is shown in Figure 6 where it can be seen that, while there is some deviation at the highest acceleration setting used, MRR is essentially linear over the range of bowl acceleration considered. Overall the results confirm the model which predicts that *MRR* is proportional to acceleration and indicates that more aggressive cutting action is obtained at higher levels of acceleration. A further implication is that higher accelerations should reduce cycle times in applications such as edge radiusing where rapid material removal is desired.

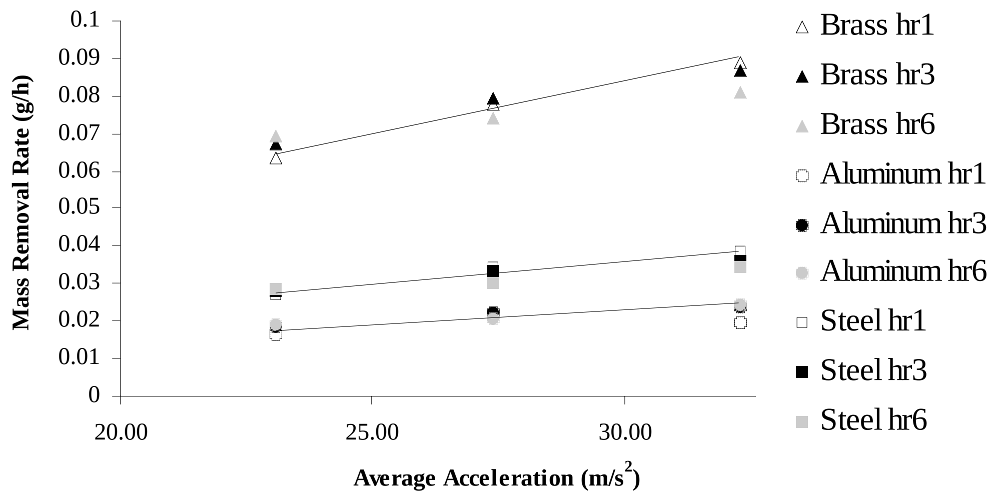

Figure 6. Material removal rates as a function of accelerations for brass, steel, and aluminum workpieces used in the study. Acceleration is expressed as multiples of the gravitational constant.

To assess the effect of workpiece specific energy, material removal rates were compared for each material at each level of acceleration. The specific energy values for the material hardnesses used were found to be 0.7, 1.6, and 2.2 N-m/mm^3 for aluminum, brass, and steel respectively [12]. In most metal cutting operations, the effect of increasing specific energy would result in a lower mass removal rate and, based on the values of specific energy, aluminum was expected to have the highest *MRR*. However, this was not the case as evidenced in Figure 6 where it can be seen that aluminum demonstrated the lowest material removal rate and brass the highest at each level of acceleration. A possible explanation for this can be obtained by analyzing the effects of density, mass, velocity, and specific energy in equation (6). As material removal is influenced by mass as well as strength, it is useful to consider mass effects with respect to material properties. Such a comparison can be made by considering the ratio of material density to specific energy for each workpiece material (Table 1). From Table 1 the density/specific energy ratio is similar for all three materials indicating that material properties alone would not account for the differences in mass removal rate that were observed. In comparison to other metal cutting processes where cutting force is independent of the workpiece mass, the cutting force in vibratory finishing will be a function of the workpiece mass with heavier workpieces experiencing greater material removal at a given acceleration. Furthermore, the combined effect of increased mass and velocity should have a linear effect on material removal rate as predicted by equation (6). This is in fact supported by Figure 7 which shows a linear relationship between mass*velocity and material removal rate and confirms the significantly higher material removal rate observed for brass and a slightly higher removal rate for steel over that of aluminum.

Table 1. Values of density/specific energy ratios for the materials used in the study.

Material	**ρ/U (g/N-m)**
aluminum	3857.14
steel	4875.00
brass	4045.45

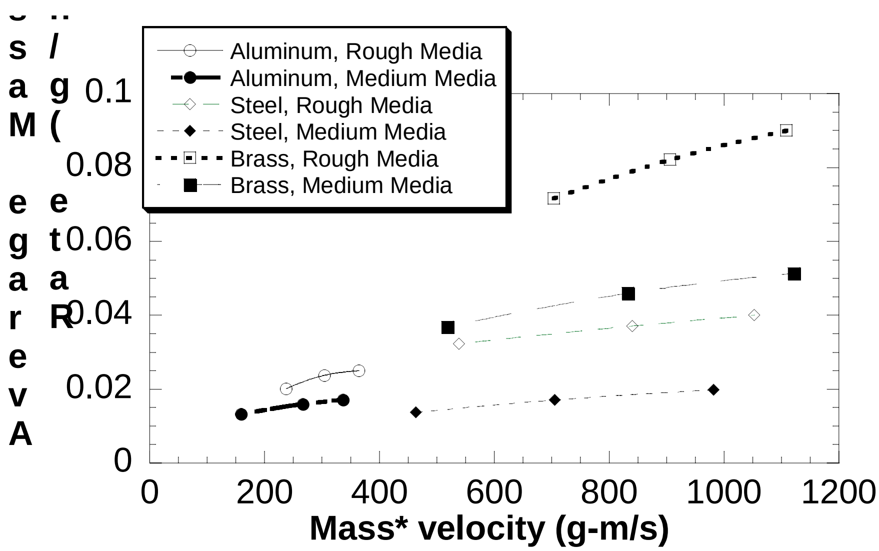

Figure 7. Comparison of mass-velocity on material removal rate.

Abrasive Wear Factor, K

While it is necessary to generate empirical values for the abrasive wear factor *K*, it is of interest to compare values of *K* in vibratory finishing to those obtained in

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other abrasive processes such as component wear and abrasive paper. As *K* is expected to vary with the severity of the abrasive action, this also provides a potential means for classifying different finishing actions and media effectiveness.

For most abrasive paper and wear processes with "broken-in" abrasive surfaces, tabulated values of *K* are between 10^{-3} and 10^{-5} [13] with higher values corresponding to coarse grit papers and lower values for polishing. Based on vibratory finishing data obtained for brass, steel, and aluminum workpieces at constant levels of acceleration and using different media, *K* (Table 2) was determined to be between 10^{-3} (rough media) – 10^{-6} (smooth media) which is in general agreement with published values from other processes and for each material reflects the action of the media used (i.e. cutting or polishing) for a given bowl acceleration.

Table 2. Calculated values of the abrasive wear factor, K, for vibratory finishing.

	Acceleration 3.3g		
Material	rough	medium	smooth
aluminum	$1.0x10^{-3}$	$7.2x10^{-4}$	$1.8x10^{-4}$
brass	$8.6x10^{-4}$	$4.9x10^{-4}$	$2.9x10^{-5}$
steel	$7.0x10^{-5}$	$3.6x10^{-5}$	$2.5x10^{-6}$
	Acceleration 2.8g		
	rough	medium	smooth
aluminum	$1.4x10^{-3}$	$7.9\ x10^{-4}$	$2.2x10^{-4}$
brass	$1.1x10^{-3}$	$5.2x10^{-4}$	$2.6x10^{-5}$
steel	$9.1x10^{-5}$	$3.7x10^{-5}$	$3.0x10^{-6}$
	Acceleration 2.4g		
	rough	medium	smooth
aluminum	$1.7x10^{-3}$	$7.6x10^{-4}$	$4.1x10^{-4}$
brass	$1.5x10^{-3}$	$4.9x10^{-4}$	$4.2x10^{-5}$
steel	$1.4x10^{-4}$	$3.4x10^{-5}$	$4.1x10^{-6}$

An additional observation that can be made from Table 2 is that the calculated values indicate that for all three materials that *K* is inversely proportional to the

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level of the bowl acceleration used though intuitively it is expected that *K* should increase at higher accelerations, reflecting the more aggressive cutting and higher mass removal rates observed. Although a possible explanation for this is increased workload dilatation, this behavior will be considered in detail in a future investigation.

Summary and Conclusions

In the present investigation, a model has been developed for material removal in vibratory finishing. The model predicts that material removal rate is a function of acceleration, object mass, velocity, and workpiece specific energy. An experimental study was performed to validate the model and confirm assumptions made with respect to media performance. Additional research is being conducted into the effect of media roughness and shape on mass removal rate and also to elucidate the mechanics of material removal in greater detail. For the range of conditions considered, the model has good correlation to the experimental data and the following can be concluded:

1. A linear relationship between bowl acceleration and the material removal rate exists in vibratory finishing. Furthermore, bowl acceleration is not significantly affected by small changes in total bowl mass.
2. Brass demonstrated the highest mass removal rate while aluminum had the lowest. Steel was found to have an intermediate material removal rate.
3. For the materials and geometry considered, the ratio of density/specific energy was similar and workpiece mass/velocity may be more influential in controlling material removal rates than specific energy.
4. The model has good correlation with the experimental data and correctly demonstrates the trends predicted.

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