Investigation of Workload Fluid Characteristics in Vibratory Finishing

Thomas A. Silman and Joseph P. Domblesky, Dept. of Mechanical Engineering, Marquette University, Milwaukee, WI

While the workload in vibratory finishing is comprised of discrete solid objects, it also has many characteristics of a fluid while the bowl operates. An investigation was conducted to determine if any of the analogous fluid properties had an effect on material removal rate (MRR). For the study, a series of experimental measurement techniques were developed to characterize the workload in terms of fluid properties and to arrive at metrics which described workload density, viscosity, and velocity as a function of bowl acceleration. The study then attempted to determine if any of these quantities showed a significant correlation to material removal in vibratory finishing.

For More Information Contact:
Thomas A. Silman
Marquette University
1515 West Wisconsin Avenue
Milwaukee, WI 53233
Tel - (414) 288-5423
e-mail - Thomas.silman@marquette.edu

Introduction

While a number of surface finishing processes employ a media aggregate composed of solid objects that impart abrasive action to workpiece surfaces, little consideration appears to have been given to the fact that the workload (collectively composed of media and workpieces) takes on many of the characteristics of a fluid while in operation. As various practitioners have reported that different finishing behavior is observed when the nature of the workload motion changes, it is of interest to determine whether the workload can be described in terms of fundamental fluid properties and to establish whether there is a correlation to finishing performance. This will help to further elucidate key process parameters that influence finishing behavior and improve efforts to develop a process model for operations which employ solid media. In the current paper, the results of an investigation conducted at Marquette University to study workload flow behavior is described. Because vibratory bowls are among the most widely used in industrial operations, vibratory finishing (Figure 1) was selected as the candidate process for this investigation. The fluid properties that were of interest in the study were as follows:

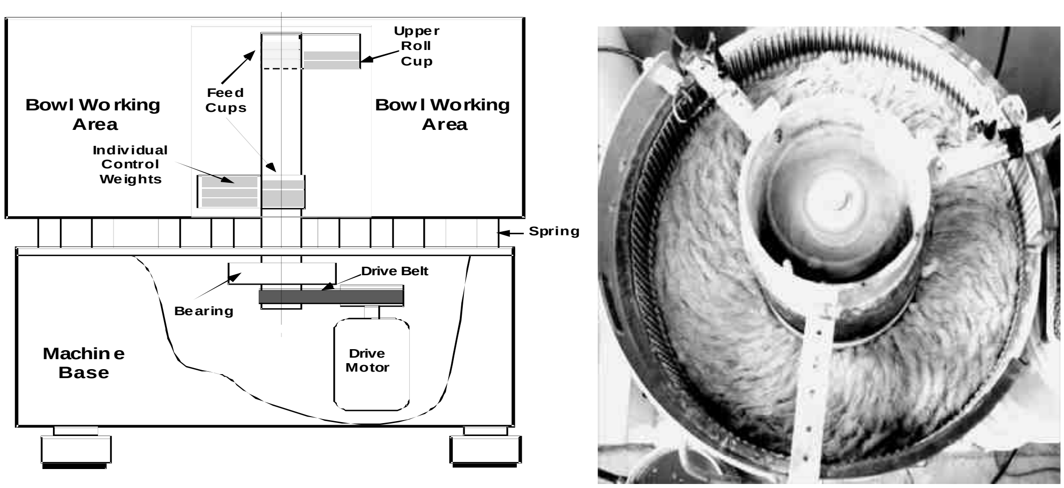

Figure 1. Cross-section of a vibratory finishing machine (left) and a top view during a finishing operation (right).

1) Velocity – It is well known from tribology [1] that the level of abrasive action in wear processes is proportional to the velocity between 2 contacting objects. Based on the results of previous research [2] which predict that differential velocity is proportional to material removal rate (MRR), it was of interest to develop a suitable method to measure object velocity and ultimately allow the differential velocity between the media and workpieces in a mass finishing operation to be calculated.

2) Bulk media density – Previous work by Domblesky and Evans [2] showed that the material removal rate is proportional to bowl acceleration. However, when the effect of acceleration is further considered, two questions arise. The first is that does the media become more dilatated as bowl acceleration increases? The second is to what extent is this influenced by the bowl weight settings that are used?

3) Viscosity - Viscosity is a measure of a fluid's ability to resist shear deformation. While workload viscosity will vary with different vibratory bowl settings (i.e. bowl accelerations based on weight cup settings used) and is likely related to the workload density, it also offers a possible metric to relate workload flow to finishing performance.

Experimental Set-up and Procedures

Capturing and measuring the bulk fluid properties of the workload was complicated by the fact that most existing methods for analyzing fluid flow cannot be applied to vibratory finishing. Traditional fluid investigation methods require that the fluid be transparent or, at the very minimum, sufficiently translucent such that particle movement and direction within a flowing stream can be observed visually. Mass finishing media, by its use and design, is opaque and relatively large. This created a problem in designing effective experimentation and necessitated the development of alternative observation methods to study the workload flow behavior which are discussed in detail below.

Workload Object Velocity

The first property examined was media and workpiece velocity as a function of bowl acceleration. Initially, the bulk workload velocity was captured using a method adapted from nautical navigational – the taffrail log. In this method, a fixed length of line is attached to an object which is dropped into the water and then paid out behind a moving vessel. Distance traveled (given by the line length) over time can then be used to calculate an average velocity as follows:

$$Velocity = \frac{\text{distance}}{\text{time}} \qquad (1)$$

It is known that there is a 5%-15% error contained in the readings produced by a taffrail log and while the velocity obtained is a scalar rather than a vector, this is still a useful technique in that it is inexpensive and can rapidly produce a measure of velocity for individual media and workpieces in a mass finishing process. For the study, a 243.8 cm (96 inches) length of 0.43 mm (0.017 inch) diameter polypropylene line was used. Polypropylene was selected in order to reduce the effects of friction between the line and media. A 243.8 cm line length was selected to ensure that the test object traveled a distance that would minimize the standard deviation from the mean measurement yet also be sufficiently short to prevent fouling or tangling while in the bowl. To determine if velocity was affected by material density, cylindrical test objects consisting of three materials; brass, steel and aluminum were manufactured. Two levels of acceleration at 2.1 and 3.1g were used where g represents the gravitational constant.

In an effort to check the accuracy of the taffrail log measurements, it was decided to develop a non-contact procedure. Due to the opaque nature of the workload, this required that an object be resident on the surface for a sufficient time period and thus limited application to capturing individual media velocity. It also assumes that surface velocity is representative of all points in the bowl. To measure the surface velocity, the travel distance for an individual media piece was captured using an Olympus C-4040 digital camera set to operate in AVI movie mode at 15 frames per second. Since the media is homogenous in its color and texture, tracking of a particular particle was accomplished by using a florescent and highly visible particle with a similar size and mass to the AH-41 media that was used. The distance that the tracer traveled in successive 1/15 second time periods was measured using NIH-Image software (http://rsb.info.nih.gov/nih-image/). The software was calibrated using a 10mm scale, inscribed on clear Polycarbonate plastic and placed above the media flow as shown in Figure 2. An average bulk media velocity was then calculated by the usual means.

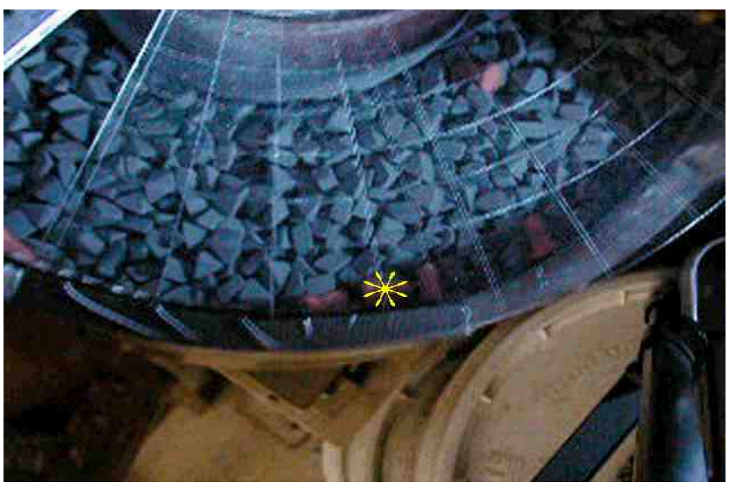

Figure 2. Top view showing noncontact (optical) measurement method used to capture media surface velocity in a vibratory bowl.

Workload Density

The density of the workload can not be treated as a fixed value as it will vary as a function of acceleration while the vibratory bowl is in operation and will also likely vary with the bowl depth. Based on the vibratory bowl's geometry, media movement is constrained on three sides and dilatation can only occur near the top of the bowl which represents an unconstrained boundary. As it was not possible to experimentally determine density as a function of depth, it was necessary to calculate a representative bulk density for the workload. To measure this, the workload volume needs to be known while the machine is in operation. As the top of the workload typically presents a non-uniform surface, the height and profile of the free surface of the workload was measured using a non-contact method which employed laser illumination as seen in Figure 3. The laser used to illuminate the top surface off the workload was a LaserMark Magna Level (Class IIIa) Laser with a beam spreader to generate a plane. The height of the workload was determined along the bowl's radial axis by employing NIH image analysis software to measure the height between the workload surface and a polycarbonate reference template that was mounted near the top of the bowl. A key advantage of this method is that it does not disturb the media flow. An assumption was made that the shape of the vibratory bowl was consistent all around. This of course is a simplification but greatly facilitated the calculation of average bulk density.

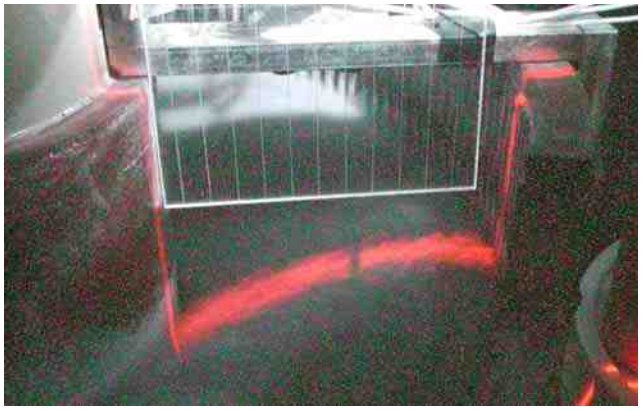

Figure 3. A representative surface profile of the workload during vibratory bowl operation. The surface was obtained using laser illumination and a 4044 bowl setting.

The average media density was calculated by using the cross sectional area captured by the laser illumination. This was initially done manually using points taken from a photograph but was later determined that using NIH-Image was more suitable for making such measurements. As the media mass remains constant, the media volume was calculated by using the measured surface profile and integrating about the axis of the bowl. The average bulk density was obtained by dividing the workload mass by the calculated toroidal volume.

Media Pseudo-Viscosity

Viscosity is a measure of the resistance of a fluid to deformation under shear stress and, while media in its unexcited state acts as a monolithic solid, as vibratory energy is put into a granular system the media begins to “flow”. This behavior corresponds to that typically displayed by a Bingham plastic fluids and a coefficient of pseudo-viscosity can be defined using equation (2).

(2) $$\mu = \left(\frac{ShearingStress}{VelocityGradient}\right) = \frac{\left(\frac{ShearForce}{SurfaceArea}\right)}{(acceleration)\left(\frac{\Delta \mathrm{time}}{\Delta \mathrm{distance}}\right)}$$

Acceleration was obtained from accelerometers mounted on the bowl and fluid velocity, $\frac{1}{\left(\frac{\Delta \text{time}}{\Delta \text{distance}}\right)}$, experimentally obtained using the taffrail log procedure. The velocity gradient was assumed to be linear with the boundary layer at the outer wall set equal to zero which is consistent with a Newtonian fluid. The surface area exposed to the shearing fluid can be calculated from the dimensions of the test object used. The shear force was gathered by measuring the pull exerted on a test object placed in the flowing stream of media and is based on the assumption that most of the useful force acting on the work piece is due to fluid shear rather than impact. For the force measurement, a 25.4 mm diameter (1 inch) drilled steel rod was tethered to a 6-axis 50 Newton force sensor and an average force calculated as the media stream flowed past the object. Force sensor data was collected for approximately 30 seconds during each run.

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. Details regarding the vibratory bowl and set-up has been described elsewhere in the literature [2, 3] and will not be repeated here. A "smooth" cut (Fortune AX-44) and an "aggressive" cut media (Fortune AH-41) were selected based on their wide use in industry and availability for the study. The preferred workpiece shape was a sphere as this would eliminate edges which represent a preferential location for material removal during vibratory finishing. However, spherical metal balls are difficult to obtain and prohibitively expensive. Consequently, cylinders which have minimal edges, were thought to be a reasonable compromise and were selected for their simplicity of manufacture and their availability. All workpiece objects were machined from 25.4 mm (1 inch) round stock with all dimension being held to ± 0.076 mm (0.003 inches). All surfaces were finished for 8 hours in the vibratory bowl using the smooth cut media to ensure consistent surface conditions on all of the workpiece objects used in the study.

Roll and feed are industry terms that are commonly used for qualitatively describing the workload flow. The toroidal motion of the media is characterized by two descriptors where “Roll” refers to the rotation of the media in the bowl about the x-z plane and “Feed” is the flow of the media in the y-z plane. Changing the weight cup loadings produces changes in the roll and feed of the media though it must be noted that this does not guarantee that a unique value of bowl acceleration will be obtained. For simplicity, the descriptors utilize a clock position with 6:30 representing the cup that drives the “roll”, and 9:00 representing the cup that primarily drives “feed” according to unverified industry sources. Utilizing this convention, the upper cup’s weights are summed first and then the lower ones are summed. For example, a weigh cup setting of 2420 means that the 6:30 top weight cup contains 2 weights. The 9:00 top cup contains 4 weights. The 6:30 bottom weight cup contains 2 weights and the 9:00 bottom cup contains no weights.

Results and Discussion

Media Velocity

It is well known from tribology that more material is abraded when the relative velocity between sliding objects is increased [1] and this effect is also predicted to occur in vibratory finishing [2]. However, as little data and information is available on object velocity, it was of interest to further explore this effect in vibratory finishing and the first experiment focused on measuring and establishing whether media velocity changed with different bowl weight cup settings (i.e. as a function of acceleration). The experimental results for object velocity for various workpiece materials and AH-41 media are shown in Figure 4 where it can be seen that the media velocity increases with the acceleration input from 2.1 to 3.1g though the effect is somewhat modified by the weight combination used at each level of acceleration. What is interesting to note is that workpiece velocity for each material is approximately consistent at each level.

The differences in velocity at each acceleration level are attributed to be the result of the different roll and feed settings (bucket weights) used as previously discussed. While different roll and feed settings were used, the settings were chosen, based on results from previous experimentation, to ensure that a constant magnitude of acceleration was achieved. The results highlight the fact that different bowl weights result in variation in process conditions and also demonstrates that further work is needed to understand how they influence process behavior. Based on Figure 3, materials and density do not appear to play a significant role and it appears that object size is more important factor with respect to velocity than material density and object weight.

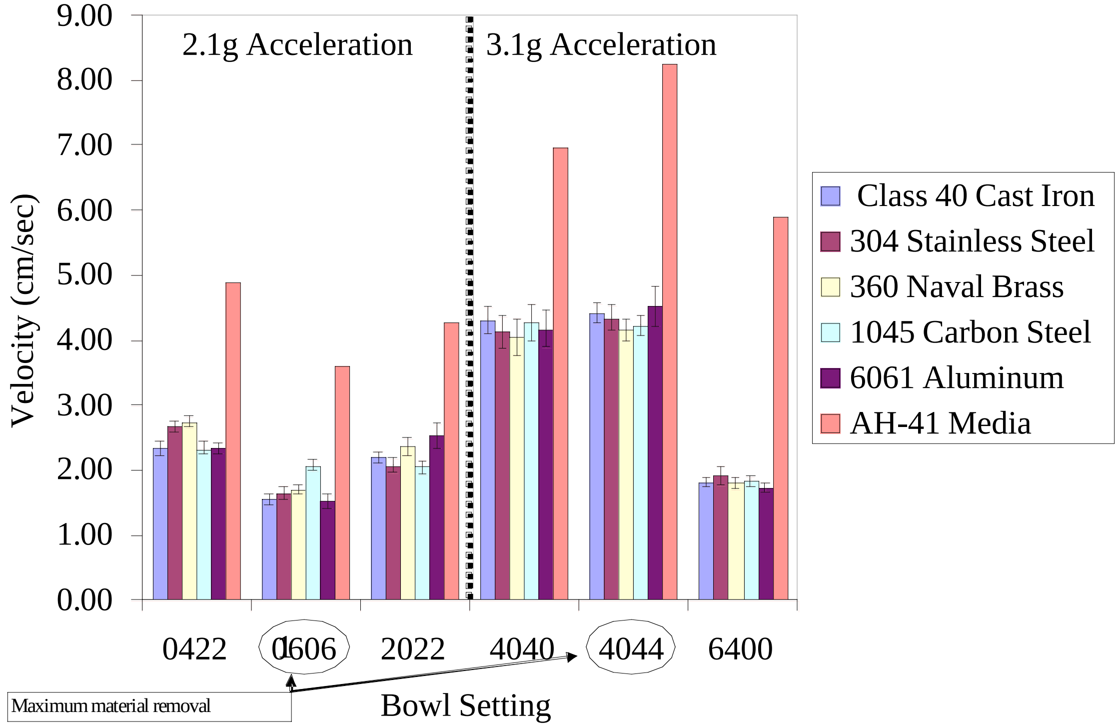

Figure 4. Effect of acceleration on the velocity of different object materials and a rough cut media.

A review of the literature for granular flow of particulates also provided a model that appears to be applicable to vibratory finishing. A non-linear function proposed by Grochowski et al. [4] was found to correlate to the experimental velocity data. The so-called "tau function" was developed for use in modeling granular powders on vibrating conveyors though the analysis and assumptions used showed a high degree of commonality with conditions that exist in vibratory finishing. The tau function can be given as:

(3)
$$\Gamma = \frac{A_z \cdot \sin\left(\frac{a_Z}{a_Y}\right) \cdot (2 \cdot \pi \cdot f)^2}{g}$$

Where Γ is a dimensionless function and A_z is the amplitude of the vibratory bowl's motion in the Z (vertical) axis. Acceleration in the z and y axes are denoted by a_z and a_y respectively. The frequency, denoted by f, was determined for the Rotofinish bowl using a Strobotac Electronic Stroboscope and found to be 24.3 Hz. The z-axis amplitude of the bowl motion was measured using a graphical method (Figure 5). A gamma value greater than one implies that enough surface motion exists to cause an object placed on the surface to lose contact with the surface in the course of the sinusoidal vibration. A plot of this relation along with experimentally obtained bowl parameters and velocity values are shown in Figure 6 for AH-41 media and shows reasonable agreement between the velocities captured by the taffrail log and optical method and that they mirror the trend predicted by the Tau function. This suggests that velocity in vibratory finishing should be predictable and that a possible means for doing so could be pursued using a suitable modification and adaptation to Grochowski's model.

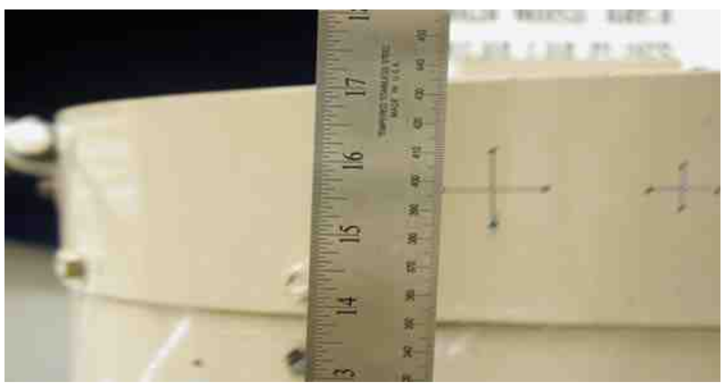

Figure 5. Measurement of vertical amplitude (z-direction) forhe Rotofinish vibratory bowl.

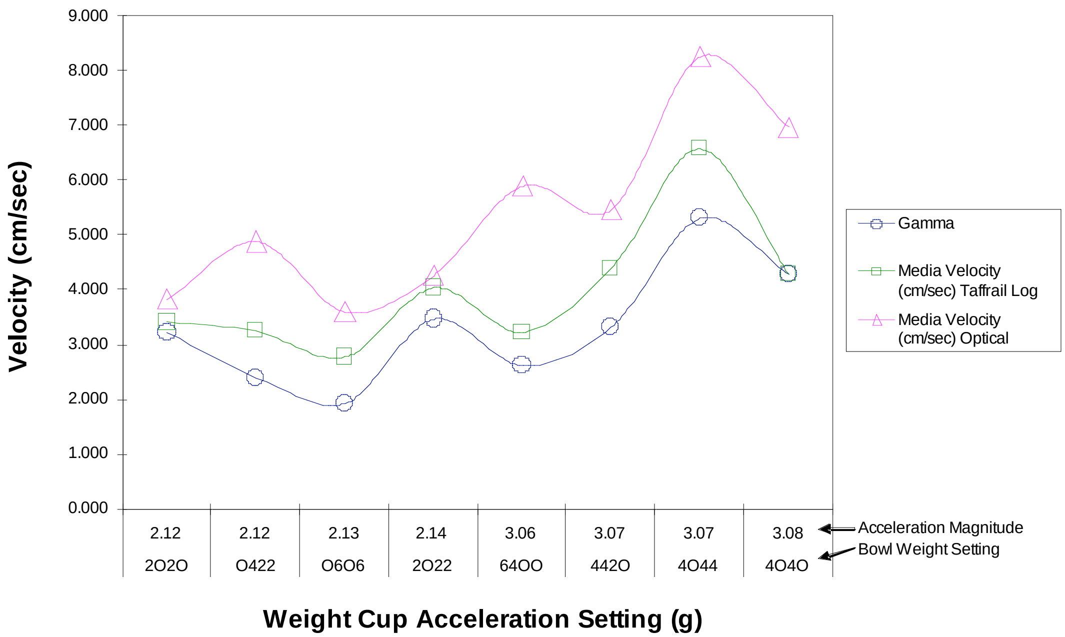

Figure 6. A comparison of media velocity as a function of acceleration and bowl settings in a vibratory bowl.

Differential Velocity

While it is of interest to measure object velocity, relative velocity will be more important in terms of influencing the effective surface finishing action. If two objects are traveling at the same speed in the workload stream, there will be little opportunity for the media to abrade the workpiece surfaces. Determination of the differential velocity between the workpiece objects and the media was only possible using data from the taffrail log since the optical capture method is only useful for capturing the surface velocity of the bulk media stream. The differential velocity for selected workpiece materials and AH-41 media is shown in Figure 7 at 2.1 and 3.1g accelerations. Figure 7 shows the calculated differential velocity which suggests that as the difference in velocity is essentially constant for different workpiece materials of similar size.

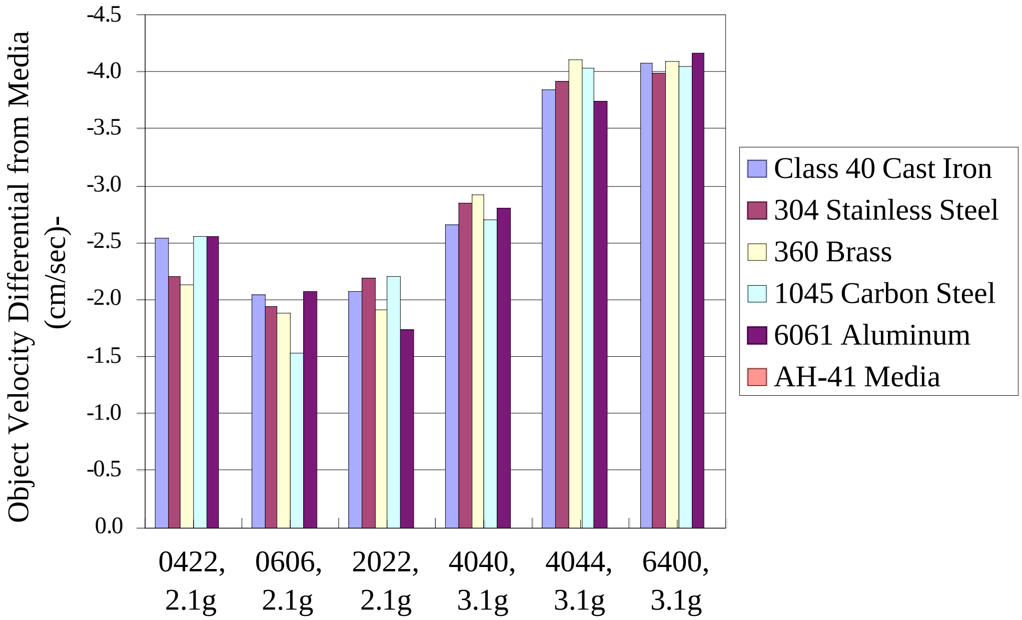

Figure 7. Comparison of object-media velocity differential in a vibratory bowl for two levels of acceleration.

However, the effect of differential velocity on material removal is not as clear-cut. In Figure 8, the material removal rate for aluminum using AH-41 media is plotted as a function of differential velocity and it can be seen that the maximum differential velocity does not necessarily correlate to the peak material removal rate when the 0422 (2.1g) and 4044, 6400 settings (3.1g) are examined.

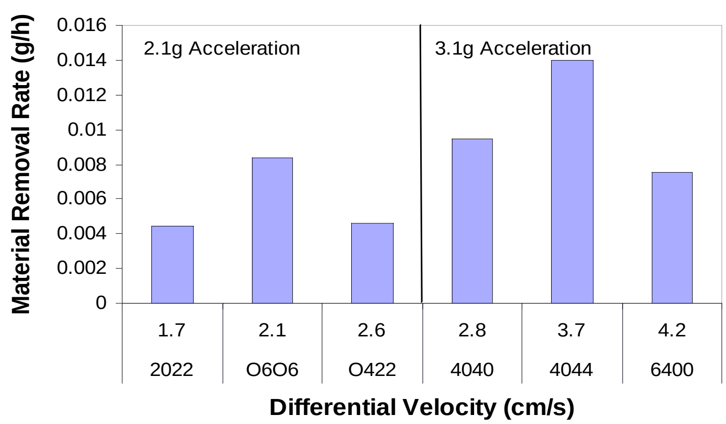

Figure 8. Comparison of material removal rate for 6061-T6 aluminum workpieces as a function of differential velocity at 2.1 and 3.1g acceleration.

Density

As expected the bulk media density was somewhat influenced by the level of bowl acceleration with higher values of acceleration at 3.1g in general tending to yield lower densities than that obtained at 2.1g (Figure 9). This is consistent with more dilatation as increased energy is imparted to the workload and would cause a larger volume for a fixed workload mass. What is interesting to note is the larger spread in density obtained at 3.1g using different weight settings and that the overall trend appears to be that is that MRR is inversely related to density at this level of acceleration. While more investigation is needed, it appears that there may be conditions where a denser media packing may result in an effective abrasive action if the appropriate bowl settings are used as evidenced at the 0606 setting (2.1g).

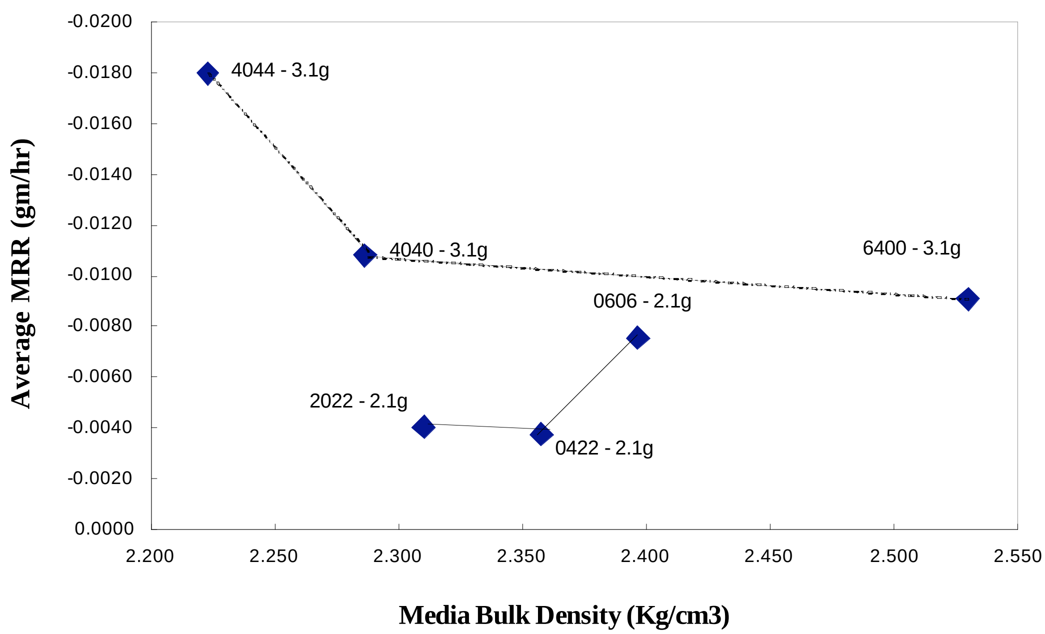

Figure 9. Comparison of material removal rate as a function of differential velocity at two levels of acceleration.

Viscosity

The results for calculated workload viscosity are plotted as function of velocity in Figure 10 along with corresponding material removal rates for aluminum. Figure 10 shows that a relation may exist at higher viscosity values and material removal rates though this needs to be considered further. While the average bulk density calculations in the preceding section assume that density is constant in the bowl, viscosity measurements taken near the top and bottom of the bowl (referred to as shallow and deep in Figure 11) indicate that the viscosity changes with the bowl setting and depth. When comparing viscosity differences in Figure 11 to the material removal results in Figure 9, an interesting possibility arises in that minimum/maximum viscosity differences to the workload correlate to maximum/minimum material removal rates for the aluminum workpieces at both 2.1 (0606/0422 settings) and 3.1g (4044/6400 settings) accelerations. This follows intuitively when it is considered that minimum difference in viscosity will result in work is being done more consistently on the workpiece throughout the operation whereas a maximum difference in viscosity will result in differing work on the surface over time and finishing action will be dependent on the amount of time spent at a given depth in the bowl.

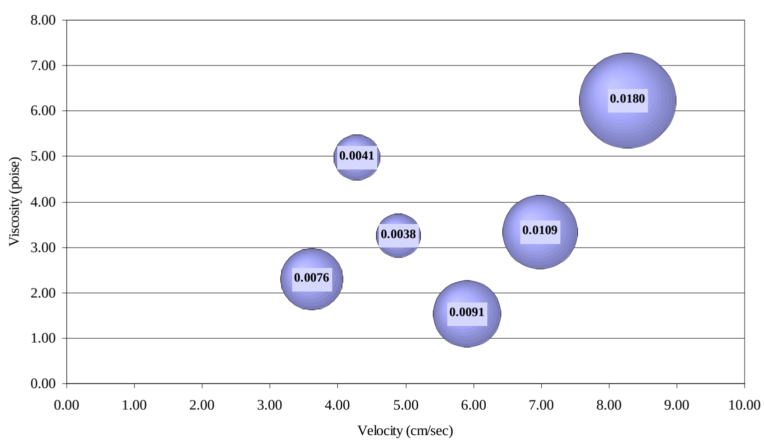

Figure 10. Experimentally obtained viscosity as a function of velocity. Material Removal Rates at each data point are indicated inside each circle.

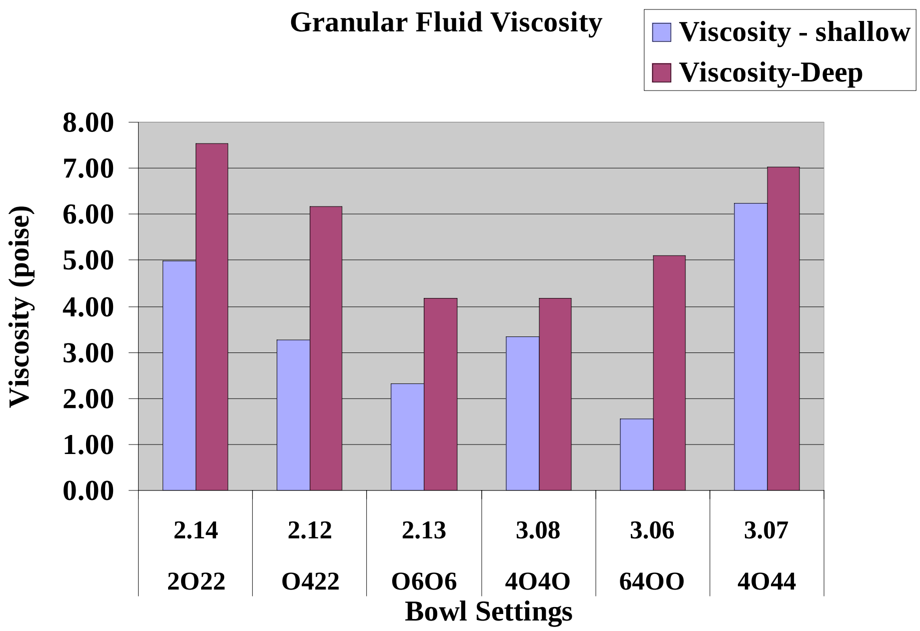

Figure 11. Media Viscosity at two different bowl depths in the Rotofinish vibratory bowl.

Conclusions

In the present study, the fluid behavior of the workload in the vibratory finishing process was considered and several flow characteristics were considered. Due to the opaque nature of the workload, alternative methods for capturing velocity, density, and viscosity were developed for use in the study. Based on the results obtained, the flow characteristics of the workload can be studied in a systematic way and the following may be concluded:

1. Object velocity in the workload can be measured using the taffrail log technique. Using this simple technique, the experimental data indicate that density does not significantly affect the object velocity based on tests conducted with various engineering materials. Size however appears to be more important in that smaller pieces of media tend to have a consistently higher velocity at both levels of acceleration that were considered.

2. Differential object velocity was measured. However, maximum material removal rate does not necessarily correlate to the largest measured velocity differential in the data.
3. Workload density can be determined and appears to vary with bowl acceleration. While density does vary with the bowl setting (roll and feed weights), in general it appears that material removal is inversely related to workload density.
4. Viscosity in the workload can also be characterized and suggests that it varies depending on the depth of the bowl. Initial results suggest that material removal effectiveness may be related to differences in viscosity in the bowl and that this is affected by the weight settings of the bowl.

References

1. Rabinowicz, E., *Friction and wear of materials*, John Wiley & Sons, New York, 1995.
2. Domblesky, J., Evans, R., and Cariapa, V., "Material removal model for vibratory finishing", *International Journal of Production Research*, Vol. 42, No. 5, 2004, pp. 1029-1041.
3. Domblesky, J. Cariapa, V. Evans, R. "Investigation of vibratory bowl finishing", *International Journal of Production Research*, Vol. 41, No. 16, 2003, pp. 3943-3953.
4. Grochowski, R., Walzel, P., Rouijaa, M., Kruelle, C. A., and Rehberg, I., "Reversing granular flow on a vibratory conveyor," *Applied Physics Letters*, vol. 84, 2004, pp. 1019-1021.