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Novel Approaches to Determine Element Trajectory in the Centrifugal Disk Finishing Process

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Abstract

Mass Finishing (MF) is a mechanical process frequently used for finishing large quantities of small parts or small batches of parts possessing a complex geometry. MF technology is witnessing wider adoption as it used to satisfy the greater demands on surface finish and quality and the introduction of new part production methods, for example: metal additive manufacturing (AM). However, it remains challenging to understand the effects of the large number of process variables on the outcomes. The investigation of the flow phenomenon of media is important as suggested in previous studies, particularly for abrasive modelling, understanding of surface evolution and for the development of simulation tools that will aid process optimisation and efficiency. Thus, in this work, various novel approaches to the determination of media element and workpiece trajectories within a centrifuge disc machine were investigated.

Keywords: mass finishing, media, flow pattern, particle trajectory

1. Introduction

Mass finishing (MF), also called loose abrasive finishing, is a mechanical process for burnishing, deburring, clearing, polishing or other surface finishing engineering components in quantities ranging from a few pieces to thousands [1]. The mechanisms of MF are mainly mechanical: sliding and scratching. In past decades, interest in this technology has been accelerating rapidly across a range of sectors including aerospace, automotive, auto-sports, biomedical and space industries, with the demand for cost effective, consistent quality and precision finishing being the main driver. Meanwhile, mass finishing has evolved from hand to machine, from a simple deburring method to modern high – technical methods by optimizing various finishing components involved in the process, including: machine type, media, liquid compound and workpieces. The most widely used MF processes includes barrel finishing, vibratory finishing, centrifugal disk/barrel finishing and other types of finishing. All of those process methods are mechanical systems that use media in a fluidized bed. Media is one of the key elements in the process which is grouped into 5 principal classes based on material: ceramic based media, plastic based media, steel media, organic media and other media. Liquid compounds generally serve as a coolant and lubricant for the process. The mechanical properties of workpieces and the load ratio (workpiece : media) are the most important parameters of mass finishing. Other elements of the process cannot be chosen without that information [1, 2].

Centrifugal disk finishing is a high energy process which offers an efficient alternative to traditional vibratory type processing. The mechanism of this machine type is that workpieces are immersed in abrasive particles in a bowl. The bottom disk within the bowl rotates to create a rolling motion to workpieces and media that force them to flow in a helical path around the bowl. An intensive grinding is generated in the operation due to a high pressure and relative movement between workpieces and media, thus this technique is suitable for strong deburring, degreasing and radiusing. Media used in this process are typically made from materials such as plastic, glass, steel and other organic compounds such as walnut shell. The size of the media is relative small compared to other systems, and can be changed depending on the desired finish. Due to the small media size, a much finer finish can

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be obtained, as it penetrates hard to reach places, such as regions about complex geometries and interior features of the component [1, 2].

2. Literature Review

Mass finishing processes are controlled by a large number of variables and a better understanding of those parameters is therefore needed. There are a small number of experimental and theoretical studies that have been reported on mass removal and deburring effects [3-7] and the contact forces caused by the media [8-10]. However, it remains difficult to predict the outcome of a finishing cycle on the quality of a surface without extensive pre-production testing.

In previous studies, Wang et al. [8] used a small colour video camera mounted in an aluminum workpiece to measure the normal contact force in bowl-type vibratory finisher and correlated them with the changes in material surfaces roughness and hardness. They observed that the average relative speed between the workpiece and the 9 mm media was found to be 11cm/s, 7cm/s and 4cm/s under dry, water-wet and detergent-wet conditions, respectively. They also found that as the amount of lubrication increased, both the absolute workpiece speed and the speed of media relative to the workpiece decreased. Yabuki et al. [9] used a similar videotaped method in their research work where three types of impact between the media and workpiece were identified: normal impact, sliding impact and relative impact. It was found that the sliding type of media contact on the workpiece did not occur in the dry condition. Ciampini et al. [10] proposed a new method to study the surface-normal impact velocity distribution, impact frequencies and impact power per unit area. A piezoelectric force senor was used to measure normal forces. The results indicated that those parameters are closely related to the degree, rate and character of plastic deformation and erosion of workpiece surface in vibratory trough finishing.

In the studies of Naeini and Spelt [11], they applied a discrete element method to study the model of bulk flow of spherical media in a two-dimensional vibrational fluidized system, and then compared it with the experimental measurements of media bulk flow velocity and the local and global bed expansion under two conditions. Cariapa and Park et al. [7] investigated both the flow behaviour and material removal mechanism. They successfully modelled the motion of a spherical ceramic media and metal workpieces in a centrifugal disk finishing machine based on fluid dynamics theory. Similar studies have also been carried out by Tian and Zhong et al. [12], in a vibratory finishing machine. A corresponding motion simulation was developed and verified by a digital high speed camera. The results showed that the media movement was a circular-feeding helical motion. In a recent study of Mullany and Shainian et al. [13], a similar optical imaging system was designed and introduced to assess the media flow under vibration excitation by recording the flow motion of media. The system consisted of a CCD video camera and a halogen light. The recorded video was converted into a series of frames for analysis. Those frame were then transferred to Particle Image Velocimetry (PIV) software for the investigation of vertical and horizontal components of velocity.

In previous work, it was observed that complex flow patterns, such as recirculation and rolling could affect the performance about the component and thus the uniformity of surface finish [11-13]. In this study, various appropriate experimental methodologies were designed to investigate the media particle trajectories and velocities in a centrifugal disk machine, including (i) a high speed video camera system coupled with a particle image velocity method was used and (ii) a micro-wireless sensor and purpose designed housing was introduced into the flow for the first time in this field of mass finishing.

3. Theory of Centrifugal Disk Finishing

In the studies of Cariapa and Park et al. [7], the moving workload in a centrifugal disk machine was treated as a homogenous pseudo-fluid which accords with the observation of its flow pattern following a helical path, hence fluid-dynamic theories were employed to model the motion of workload in a centrifuge disk. For this model, the fluid was considered as a non-compressible and steady-state flow, that is, the flow properties are constant throughout the field with respect to time at a fixed speed. A cylindrical coordinate system (*r*, *Θ*, *z)* was also used to describe the position of any point in the space of stationary tub.

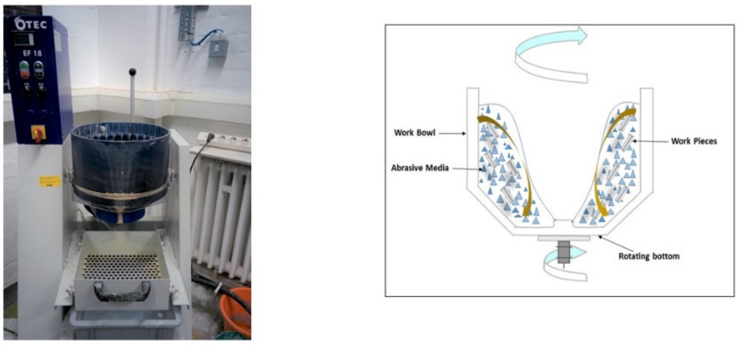

Figure 1. Diagrams of a centrifugal disk finishing machine

The corresponding continuity equation for the conservation of mass are expressed as follows:

$$\frac{\partial v_r}{\partial r}+\frac{v_r}{r}+\frac{1}{r}\frac{\partial v_\theta}{\partial \theta}+\frac{\partial v_z}{\partial z}=0 \qquad [1]$$

where v_r, v_θ and v_z are the local velocity of the moving workload in the coordinates of r, θ, and z respectively, r is the radius of the rotating disk.

The expressions of the conservation of momentum in the r, θ, and z directions are shown by:

$$v_r\frac{\partial v_r}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_r}{\partial \theta}+\frac{\partial v_z}{\partial z}-\frac{v_\theta^2}{r}=-\frac{1}{\rho}\frac{\partial p}{\partial r}-\frac{\mu}{\rho}\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial (rv_r)}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 v_r}{\partial \theta^2}+\frac{\partial^2 v_r}{\partial z^2}-\frac{2}{r^2}\frac{\partial v_\theta}{\partial \theta}\right] \qquad [2]$$

$$v_r\frac{\partial v_\theta}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_\theta}{\partial \theta}+\frac{\partial v_\theta}{\partial z}-\frac{v_r v_\theta}{r}=-\frac{1}{\rho r}\frac{\partial p}{\partial \theta}-\frac{\mu}{\rho}\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial (rv_\theta)}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 v_\theta}{\partial \theta^2}+\frac{\partial^2 v_\theta}{\partial z^2}+\frac{2}{r^2}\frac{\partial v_r}{\partial \theta}\right] \qquad [3]$$

$$v_r\frac{\partial v_z}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_z}{\partial \theta}+v_z\frac{\partial v_z}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}-\frac{\mu}{\rho}\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial (v_z)}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 v_z}{\partial \theta^2}+\frac{\partial^2 v_z}{\partial z^2}\right] \qquad [4]$$

where p is pressure, ρ is mass density of the workload in media and μ is absolute viscosity. The boundary conditions used in this model are: 1) the local velocities (v_r and v_z) of the moving workload in the r and z directions were assumed zero at the bottom face of the rotating disk, 2) the velocity in *z* direction and pressure on the top surface of the workload were considered as constant, 3) the velocity in *r* direction and pressure at the inner surface of the workload were assumed as constant and 4) the velocities in all three directions (v_r, v_θ and v_z) at the outer surface of the workload were assumed as zero.

4. Experimental Details

In this study, a centrifuge disk finishing machine (OTEC – CF18 element series) was used. It consists mainly of an open-top bowl (Ø 330mm), a control unit and a manual separating unit. This machine provides a high energy finishing process for small and medium size workpieces with a speed up to 310 rpm. Recycled glass media (conical shape with a dimension of 12 mm) were employed. 18 litres of media were used to fill the bowl during test. To investigate the trajectory of workpieces a plastic conical shaped disk with an embedded wireless sensor was introduced into the media flow during experiments.

4.1 High-speed high resolution CCD camera/Particle Image Velocimetry

The digital image system is set up as shown in Figure 2 and is composed of a CCD camera (JAI GO-5000M-PML), a tripod where the camera is attached and a computer. The CCD camera was set to face down to the bowl to record the motion of media and workpieces. For trajectory acquision, the frame speed was set at 105 frames/second with resolution of 1000 *1000 pixels. All videos obtianed from the camera were then processed by Image J and PIV software in Matlab to determine the trajectories of media and workpiece during the process.

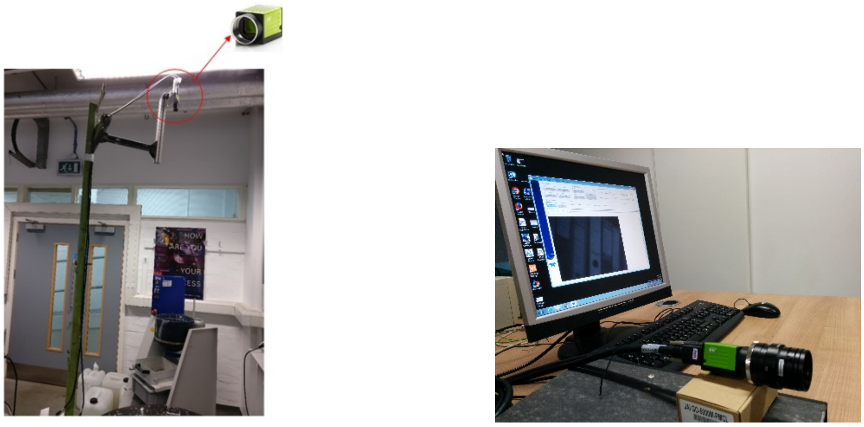

Figure 2. The experimental setup of a digital imaging system

4. 2 Micro-wireless sensor

A wireless inertial motion tracking system (MetaWear C 6 Axis) was used to measure three orientations of media and work-piece in motion, is shown in Figure 3. This sensor consists of an accelerometer and a gyroscope that allows the user to track rotational and translational motion. The gyroscope is used for measurement of angular velocity and can be integrated over time to obtain the orientation, subject to the initial conditions being known. The accelerometer is used to measure changes in gravitational acceleration. Due to the fact that both signals are very sensitive to noise and may cause a corruption in the direction of gravity, an orientation filter was employed. In this work, an orientation estimation algorithm developed by Madgwick, et al. [14] was used.

Figure 3. A typical micro – wireless inertial motion tracking system

As shown in Figure 3, the sensor was embedded within a plastic cylindrical shaped disk which enabled it to flow freely within the media without damage to the bowl. Additionally, this device also facilitated bluetooth communication that allowed continuous data transfer from the measuring kit to a data receiver (e.g. mobile phone or computer) through a wireless medium. The frequency rates used for both accelerometer and gyroscope were 100 Hz.

5. Results and Discussion

5.1 High-speed high resolution CCD camera/Particle Image Velocimetry

Figure 4 shows a series of 2D images of a moving workpiece (marked by red circle) captured by video using a high-speed high resolution CCD camera. Those images show workpiece position from the static to dynamic period over equal time intervals. In the top view of the bowl, it can be seen that the workpiece gradually moves from the centre of the bowl toward to the side wall. According to the studies of Gillespie [1] and Cariapa et al [7], media and workpiece were found to follow a helical motion, which could be attributed to the mechanism of the machine. As the bottom disk rotates, the media/workpieces within the bowl start to move outward with constant acceleration. The inner wall of the bowl is made of a high resistance polyurethane material which acts as a brake to mass flow and results in a decrease in speed when mass moves along the wall. With decreasing acceleration and increasing gravity, the media/work-pieces are observed to follow a continuous helical motion. This view is also supported by Figure 5, showing average media velocity vectors that were derived from the media flow. It was observed that the velocity vectors move outward from the centre of the bowl in one direction from the static to dynamic case.

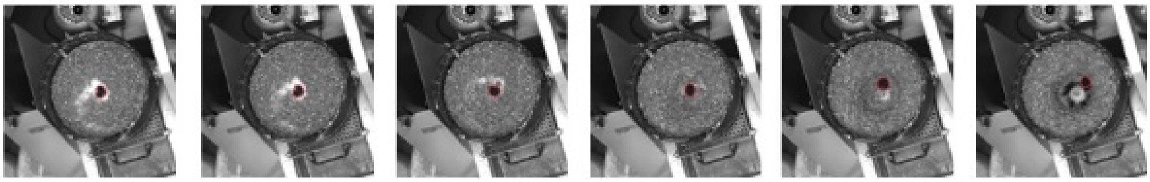

Figure 4. Recorded motion of a wireless sensor in a centrifugal disk machine at different time.

The average velocity of bulk flow was also found to vary with position, as illustrated in Figure 5. The centre of the bowl shows fewer velocity vectors due to the media being accelerated outward to the side wall. The velocity vector obtained approximately 5 cm away from the centre shows a dramatic change. The corresponding velocity was approximate 2.7 m/s. For the region adjacent to the side wall, the velocity was found to decrease to around 1.2 m/s. The velocity measured from the middle region of the flow was 1.9 m/s. In the studies of Cariapa et al. [7], they found the planar velocity of a spherical ceramic media was 0.59 m/s on the top surface of a centrifugal disk machine. This difference might be attributed to different type of media used.

Figure 5. Velocity vectors field generated by PIV from (a) static sate to (b) dynamic state

5.2 *Micro wireless sensor*

The trajectory and average velocity of a single workpiece was measured by an inertial motion tracking system (WIMTS). This approach allowed the sensor to move freely within the media during machine operation and to generate a real 3D workpiece flow. Figure 6 shows typical examples of workpiece trajectory for different angles: (a) in X-Y plane and (b) in X-Z plane. It can be observed that a circular motion was found in the X-Y plane which matches well to that shown in in Figures 4 and 5, in which the path-line starts from the centre of the circle and then moves outward. The corresponding velocity obtained in this plane was about 1.4 m/s when the workpiece was in a steady motion. The motion in the X-Z plane shows a helical movement, in which the workpiece was found to move from upward to downward with various velocities in different positions. These findings suggest that the WIMTS is an effective method for trajectory measurement in centrifugal disk machine providing data of high accuracy.

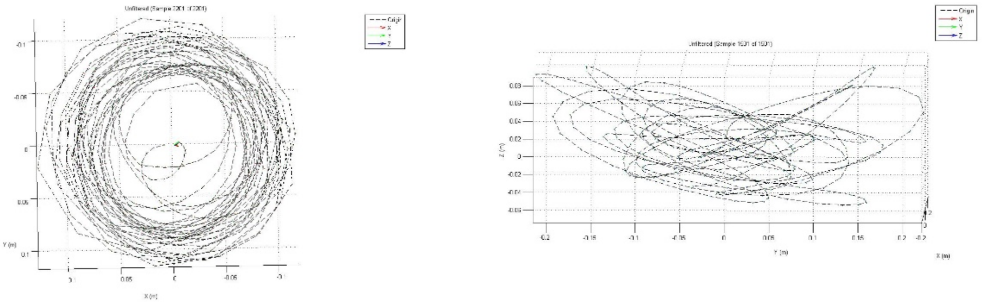

Figure 6. Three dimensional trajectory of media/work-piece obtained from WIMTS: (a) top view in X-Y plane and (b) side view in X-Z plane

6. Conclusions

In this study, the trajectories of media and workpieces in a centrifugal disk machine were investigated using different methods. The results demonstrated that the optical camera system was a reliable method to verify the media flow velocities and workpiece velocity respectively. However, this technology is limited to a two dimensional image, which does not reveal fully the details of trajectories, therefore an advanced technology for understanding and insight of three dimensional flow is required. A new approach employing a wireless inertial motion tracking system (WIMTS) was investigated. The three dimensional trajectory obtained from the WIMTS system combined with velocity distribution data provides key information for further simulation and analysis. In addition, to providing insight on the details of particle position, WIMTS also demonstrated a potential for application in many other applications.

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