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Mechanism of Surface Evolution in Vibratory Media Finishing

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Abstract

The mechanism of surface evolution in the vibratory media finishing process is investigated through changes in surface profiles with process time. Using the profile of a masked portion of the surface as reference, changes in the surface profile mean line, peaks and valleys with time are examined. Peak heights are seen to reduce while surprisingly valley depths are also seen to diminish indicating evidence of plastic displacement of material from the peaks into the valleys. The surface evolution is thus shown to be a combination of material removal and plastic deformation of the peaks. This also partially explains the surface roughness saturation with time.

Keywords: Vibratory media finishing, surface evolution, surface profile, surface saturation

1 Introduction

Use of abrasive wear mechanism is very common in machining processes such as polishing to improve component surface finish. Abrasion is carried out either in the 2-body mode or 3-body mode. Examples of 2-body abrasive processes are grinding, coated abrasive polishing where the abrasive particle is rigidly held and is interacting on the component surface; 3-body abrasive process examples are loose abrasive wire sawing and lapping where the abrasive is trapped between a pad and the component surface. A particular case of 3-body abrasion involves the third body being very far away and such interactions can be seen in processes such as vibratory media finishing. In this process the component to be polished is placed along with a bed of media particles in a bath and vibrated. The body wall of the bath acts as the far away third body while the media particles interact with the component surface. The media particles are agglomerates of abrasive particles in a binder. The bath

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being vibrated can contain tens of kilograms of such media. The vibratory action often leads to a patterned motion of the media particles and this causes the media to interact with the component surface leading to surface changes. Abrasion by itself may or may not cause material removal to occur. It has been well documented (Peterson & Winer, 1981) that depending on the geometry of the abrasive particle pure ploughing with material being displaced side-ways can happen at certain abrasive geometries (e.g. highly negative rake angle), whereas in others material removal along with some ploughing action can occur. Given that the media used in vibratory media finishing are shaped agglomerates of media particles, their interaction with the component surface can result in ploughing or material removal or both depending on conditions.

The nature of surface changes and how the surface evolves with time in the vibratory media finishing process is not entirely known. The component surface roughness finished by a vibratory media finishing process is known to saturate with time (Hashimoto & Debra, 1996)(Fig. 1). That is, after a certain process time, no further improvement in surface finish is possible. Detecting when this saturation occurs is important to determine process times. The mass change in the component being finished is however subject to some controversy; while some report continuous increase in changes (Hashimoto & Debra, 1996) others report (Baghbanan, et al., 2003) saturation in this parameter also. It is however reported that a rougher surface yields more material removal than a smoother surface. The cause of such saturation and its link to the nature of the media particles and process conditions are yet to be ascertained (Prakasam, 2014).

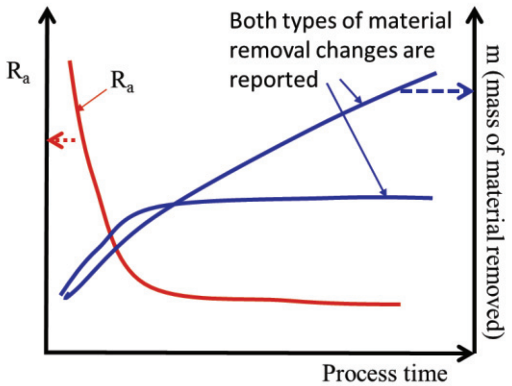


Figure 1. Surface roughness and mass removal changes in vibratory media finishing with process time

The actual nature of interaction of the media particles with the component surface plays an important role in the surface evolution with process time. Wang et al. (Wang, et al., 2000) have performed a Scanning Electron Microscopy analysis for the dry and wet finishing processes and reported their findings. In dry finishing process, the mechanism of material removal seems to be normal impact and in wet finishing, scratching occurs. This is believed to be due to a decrease in friction in wet conditions. Similar observations have been made by Ciampini et al. (Ciampini, et al., 2009) and Yabuki et al. (Yabuki, et al., 2002), who identified an additional mechanism of rolling. The actual movements of the media particles have also been captured using high speed video cameras (Yabuki, et al., 2002), although the actual interaction at the media-surface interface is difficult to capture. However, such investigations, while throwing some light on the surface changes, do not reveal the cause of the surface evolution and how and when saturation occurs.

Examining changes in the surface profile itself with process time is another way to study how the peaks and valleys of the surface evolve with time and lead to the observed saturation. This is the method adopted in this paper. We use measured changes in the peaks and valleys to detect if and how much material removal occurs and if and how much indentation type of material displacement happens. Detecting changes in peaks/valleys requires comparison of surface profiles at various time intervals is a non-trivial issue since accurate datum are not available during surface profile measurements.

The idea of using surface profile changes to explain whether material removal or indentation type ploughing is occurring can be explained as follows. Consider that we have a structure surface profile with well discernable peaks and valleys to start with as shown in Fig. 2a. The mean line is measured and can be used as datum. The peak height and the valley depth from this reference mean line can be recorded. Under pure material removal conditions only the peaks will get eroded and resulting profile will be as in Fig. 2b. The new mean line will shift downwards but the height of the peaks and depth of valley from the original mean line (not the new mean line) can indicate if pure material removal occurs – peak height will change, but not the valley depth form the original mean line. If the valley depth also changes as shown in Fig. 3b, then some amount of indentation type ploughing and plastic displacement has occurred; in this case the cause of peak height changes can be because of material removal or plastic indentation.

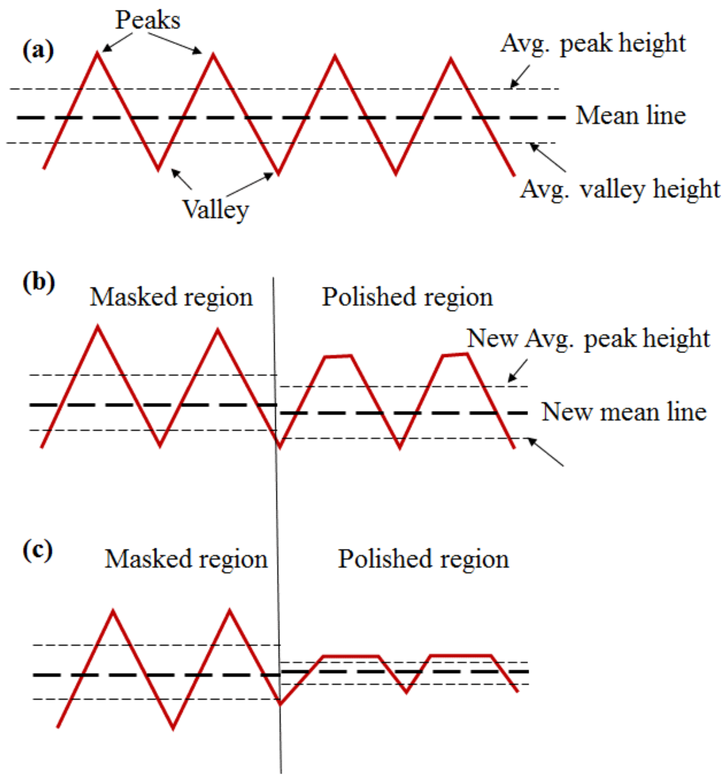


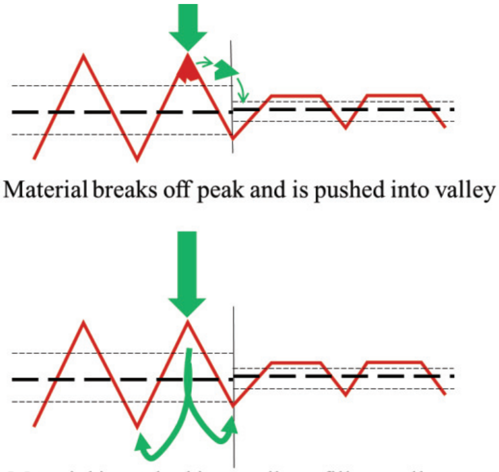
Figure 2. (a) Initial starting surface profile (b) Surface profile if pure material removal is occurring (c) Surface profile if some material removal and ploughing is occurring

The observations of peak height and valley depth changes and their interpretations can be summarized as in Table 1.

Table 1. Surface profile change interpretations

Observation	Interpretation
Peak height increase	Not possible
Peak height decrease	Pure material removal if valley depth does not change; plastic deformation can cause this

	unless valley depth changes.
Valley depth increase	Could be due to ploughing (if accompanied by peak height increase) or material removal
Valley depth decrease	Plastic deformation from the peaks filling the valleys



(a) Material breaks off peak and is pushed into valley

(b) Material is pushed internally to fill up valley

Figure 3. Two ways in which valley height can decrease (a) debris from removed material gets pushed into the valley (b) plastic deformation of the peak gets pushed internally to rise the valleys

In this paper we combine such a surface analysis with electron microscopic examination of the surface to determine how the peaks and valleys evolve with time, the peaks being either abraded away or pushed into the valley.

2 Experimental Method of Detecting Surface Profile Changes

Two necessary conditions for the surface profile changes to be detected are:

1. The profile peaks and valleys are uniform throughout the surface: Since the surface modification mechanism depends on the shape and size of the surface peaks and valleys, if the peaks and valleys are not uniform throughout the surface, different mechanisms can be obtained at different points of the surface.
2. The mean line of the original profile is retained. In order to measure the change in peak and valley height, the original mean line must be retained. Without this, the change in peaks and valleys cannot be measured.

To achieve the first condition, the surfaces of the component were machined using a single-fly cutter in a CNC milling machine to generate uniform structured surfaces of about 10μm height and 150μm spacing. The fly-cutter used was a standard carbide cutting tool with ground edges. Hence the tool edge radius is expected to be around 7-15 micrometers. The material selected for analysis a titanium alloy. To attain the second condition one region of the component surface is masked as shown in Fig 4.

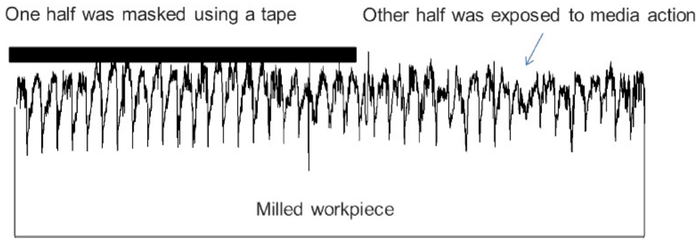


Figure 4. Masking one region of the surface being finished to retain the original mean line datum. Surface profile trace measurement is taken together in the masked (after removing the tape) and unmasked finished region together in one setup.

The entire component surface together with the masked and unmasker regions are subjected to vibratory media finishing. At certain process time intervals, the component surface is measured by taking a surface profile trace measurement in the masked (after removing the tape) and unmasked finished region together in one setup. This way the original mean line datum is retained for comparison. The steps involved are thus as follows.

- Step-1: Calculate mean of first half of profile (masked in the experiments) which will act as height of masked reference line
- Step-2: Calculate the mean of second half of profile which will act as height of analysis reference line
- Step-3: Store values above analysis reference line as peaks
- Step-4: Store values below analysis reference line as valleys
- Step-5: Calculate the difference between masked reference line and peaks and store as peak height; calculate the average peak height
- Step-6: Calculate the difference between the masked reference line and valleys and store as valley depth; calculate the average valley depth

Like any other measurement technique, this measurement technique is also prone to errors. By analyzing the errors and taking them into account during the interpretation of the results, we can ensure that no data is lost or misinterpreted. As explained in the previous section, by performing precision milling of the surface, uniformly sized peaks and valleys can be fabricated. But there is a tolerance limitation for any type of machining process. Hence our results will be subject to the tolerance which can be achieved by the machining process. By using the masked reference method, this problem is eliminated, since each time the masked reference line is measured, the change in dimensions due to tolerance error will be taken into account. Hence the change in dimension of the surface due to waviness, tolerance error will be eliminated by using masked reference method. As the peaks and valleys are calculated based on the new mean line which varies with respect to time, there is a possibility of some points being misinterpreted. For example, when both the peak and valley positions move together towards the original mean line, the new mean line will go down, but the new valley position might not change. This means that there is a plastic deformation happening, but not reflected in the calculation. But this does not happen in large deformations. Hence a small change or no change in valley position calculated using this method cannot be treated as a sign of change in surface modification mechanism. Hence the results should be interpreted considering the change in peak and valley position in a general trend and the small changes (<10% change) should not be considered.

The surface profile was measured at 5 different points of the surface and the change in peak height and valley height was calculated for every 20 minutes of vibratory finishing. Finishing was carried out in an industrial scale vibratory machine using standard off the shelf media and process conditions were fixed at one frequency and amplitude value. A Taylor Hobson Formtracer was used to measure the surface profiles. The workpiece was taken out every 20 minutes for measurement of surface profile and scanning electron microscope (SEM) analysis.

3 Results and Discussion

The evolution of surface as quantified using the surface roughness parameter Ra is shown in Fig. 5. Typical saturation of the surface roughness is seen. Changes in Ra at the process intervals indicate a monotonic decrease in the change with time. More interesting trends are seen in the peak height changes and valley depth change with process time as shown in Fig 6. Peak heights are seen to reduce monotonically and saturate while valley depths are seen to decrease and also reach saturation. Peak height saturation, valley depth saturation and surface roughness parameter Ra saturation all occur at a time close 100 minutes. It is clear from Fig. 6 that the process is not just one abrasion of peaks, since this is accompanied by valley depth decrease. Valley depth decrease could occur by debris pile-up but no evidence of this seen in the microscopy pictures to be discussed later. This means some of the peaks are getting pushed by plastic deformation into the valleys. If the percentage change in valley depth can be considered as an indication of plastic deformation, then one can plot the change as shown in Fig 7. Evidence of plastic deformation can also be observed by examining microscopy pictures of the surface. This is presented next.

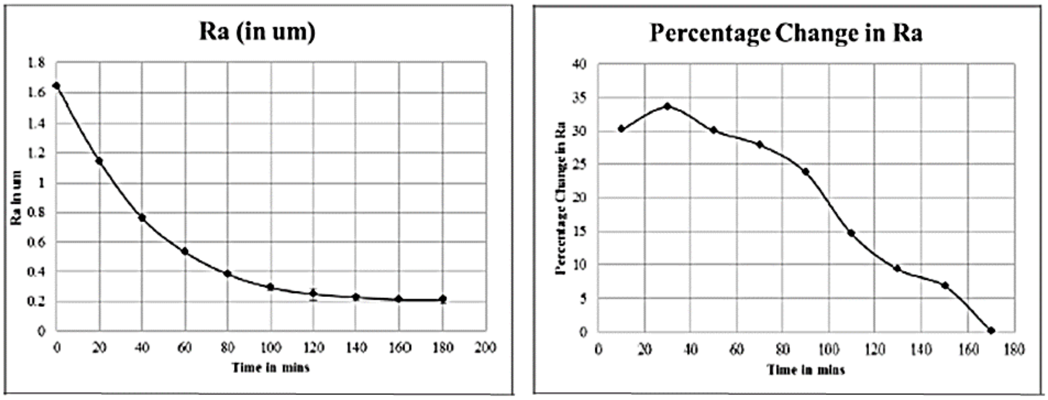


Figure 5. (a) Surface roughness parameter Ra evolution with process time (b) Percentage changes in Ra

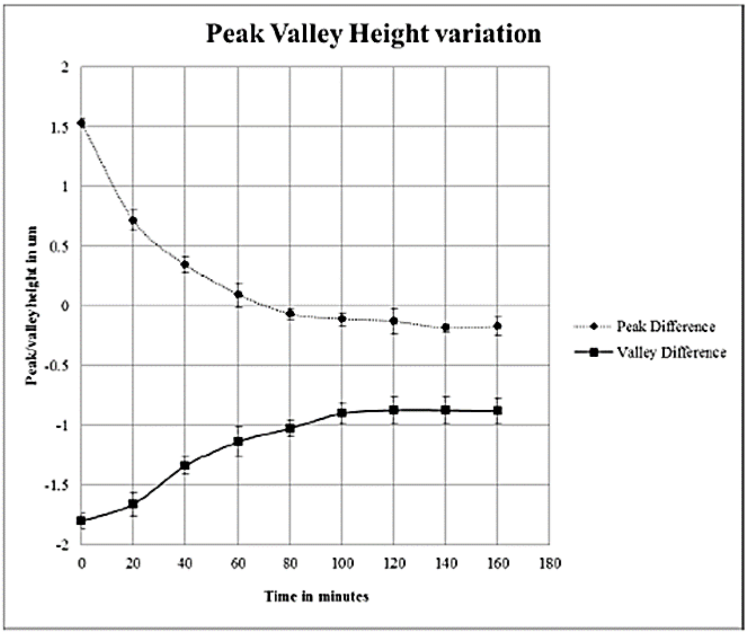


Figure 6. Peak height and valley depth changes with process time

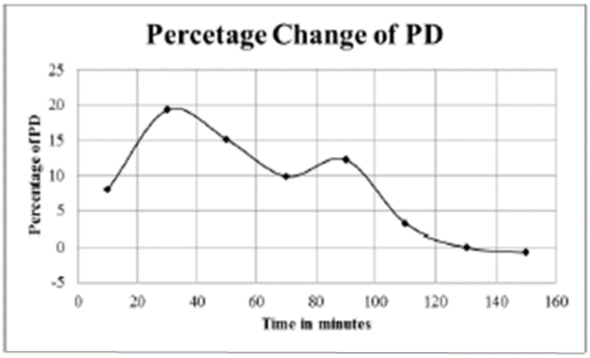
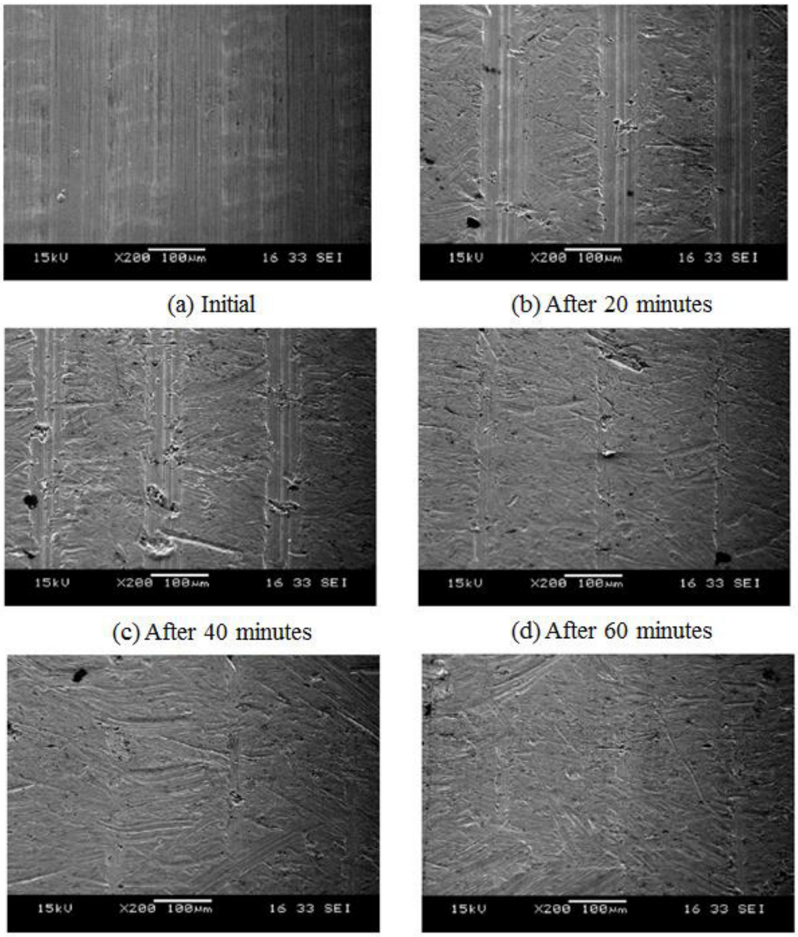


Figure 7. Interpretation of change in valley-depth as plastic deformation



(a) Initial (b) After 20 minutes

(c) After 40 minutes (d) After 60 minutes

(e) After 80 minutes (f) After 100 minutes

Figure 8. Scanning electron microscope examination of surface at various process time intervals

Scanning electron microscope images of the surface condition at different time intervals are shown in Fig 8. Fig. 8a shows the morphology of the initial surface before finishing and Fig. 8b after 20 minutes of finishing. It can be noted that the patches of surfaces have been modified by the finishing process, leaving behind traces of unchanged surfaces. These patches indicate the peak region of the structured surface. The peaks are modified initially, leaving the valley unaltered. This is also reflected in the peak and valley height change as shown in Fig. 8b at the 20 minutes time interval. Figure 8c shows the SEM pictures of surfaces formed after 40 minutes and Fig. 8d after 60 minutes. It can be noted that after 40 minutes, the valleys start getting affected by the media action. There are also presence of scratch marks on the surface, indicating the scratching behavior which causes more material removal than plastic deformation. This is also reflected in Fig. 8c, where the amount of plastic deformation is very less compared to material removal in the initial stages. After 60 minutes, it can be noted that the width of the valleys slowly reduces. If this change in surface morphology is due to material removal, the depth of the valleys will increase. But measurement of surface profile shows that the valley depth decreases, indicating that the peaks are being plastically deformed and pushed into the valleys. There are also no presence of wear debris particles present as seen in the SEM pictures. After 80 minutes (Fig. 8e), it can be noted that the valleys are almost deformed, and after 100 minutes (Fig. 8f) there is no clear separation between peaks and valleys. Also there are more number of plastically deformed edges indicating an increase in plastic deformation. We note here that the trends seen here are a strong function of material behavior (ductile vs brittle). A more brittle material such as hardened steel would perhaps show more peak erosion and less of plastic deformation. The material chosen here is an industrially used aerospace alloy and hence has practical relevance.

4 Conclusions

The surface evolution in vibratory media finishing was studied by comparing surface profile traces at various time intervals. Datum for the comparison of surface profiles was used by masking a portion of the finished surface and measuring the surface profile trace together with the masked and unmasked regions.

- As reported in the literature, surface roughness parameter Ra is seen to saturate with process time
- Peak heights were seen to decrease monotonically with process time indicating either material removal or pushing of the peaks down.
- Valley depths were also seen to decrease monotonically with process time indicating that plastic deformation is causing the valleys to fill up; no evidence of debris pile up was seen in microscopy images suggesting other reasons for valley depth decrease
- Peak heights and valley depths were seen to saturate at the same time as saturation of surface roughness parameter
- Considering valley depth changes as a sign of plastic deformation, this was seen to monotonically decease with process time leading to saturation.
- Saturation can be regarded as the time that the media cannot push or abrade the peaks anymore to cause valley fill-up.

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