Grinding Wheel Texture and Diamond Roll Plunge Dressing Feed-Rates

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Abstract. Textures were measured with a scanning laser microscope from replicas taken after dressing with different feed-rates. F-tests applied to area-scale analyses show that the lowest feed-rate, 0.5 mm/min is differentiable from the three larger feed-rates 1.5, 4.0 and 8.0 mm/min, over the scale ranges from 1000 to 5000 µm². Regression of volume-filling versus feed-rate indicate strong correlations ($R^2>0.9$) from about 10 000 to 100 000 µm². F-tests applied to volume-filling analyses show differentiability with regard to feed-rate over similar scales. Comparison with the grain area(56 000µm²) suggest more grain fracture at high feed-rates and grain pull-out at lower feed-rates.

1. Introduction

The objective of this work is to determine how and over what scales the texture, i.e., topography, of dressed, grinding wheels vary with the feed-rate used in plunge dressing with a diamond roll. Area-scale (ASME/ANSI B46.1 2002 CH. 10) and scale-based volume-filling analyses are used to characterize the texture over a range of scales.

Diamond roll plunge dressing is used extensively in the manufacture of antifriction bearings. The outer ring of a typical ball bearing has a form on its inner surface consisting of (1) a section for the retainer to ride on, (2) a curved ball track for the balls to run in, (3) another section for a seal, resulting in a complex profile on the inside diameter of the outer ring. In manufacturing the outer ring it is common practice to dress the complex profile into the OD (outside diameter) of a grinding wheel by using a diamond roll having that profile on its OD. Since the production of automobiles is so large, the production of antifriction bearings is a high volume process.

The efficiency of the internal grinding process is directly related to the "sharpness" or lack thereof, of the dressed grinding wheel. Depending on the dressed surface texture, the grinding wheel may act "sharp" or may act "dull". It is therefore important to discover conditions that produce "sharp" wheels. In production grinding a number of parts may be ground before it is necessary to restore the precision complex profile and "sharpness", by executing a diamond roll plunge dressing operation. If the feed-rate and its influence on the texture of the grinding wheel were known, and if the influence of the texture on the grinding operation were also known, then the dressing process could be optimized.

In most industrial applications the real feed-rate in dressing is unknown. Pre-specified compensation distances and feed-rates are used to engage the diamond dressing roll in the grinding wheel during each dressing cycle. The compensation distance is based on an estimated amount of wheel wear during the previous grind cycle. The actual feed-rate in dressing will depend on the specified feed-rate and on the elasticity of the system and the actual amount of wear the wheel has suffered during grinding.

If the resulting textures of grinding wheels are strongly influenced by the feed-rate during dressing, then the problem of determining the actual texture characteristics at certain feed-rates is exacerbated by what happens to the texture during the retraction of the diamond roll at the end of dressing cycle. In plunge dressing the spinning wheel and roll can move through several rotations with progressively lower feed-rates during the retraction. This has the possibility of masking the wheel the texture of the set feed-rate with texture characteristic of lower feed-rates.

Current practice requires machine tool builders to mount diamond rolls on a rotating spindle. Those rolls often run out 2 to 3 µm producing some error in the wheel's surface. The machine tool builder usually makes grinding tests on a batch of the bearing manufacturer’s raw parts to "qualify" the machine and process to meet the precision specifications. Often that is not easy to do and requires some time and expense. Diamond rolls may have to be altered. Some rolls "cut" better than others. Some rolls produce "dull" wheels. Some rolls, especially wide ones, require a large force to overcome threshold forces. The amount fed into the wheel, the feed-rate, and the dwell affect the cutting characteristics of the wheel.

Lindsay and Hahn (1971) found that low dress leads and dressing ratios produce low surface finishes, and that force was the most important factor influencing surface finish. Marinescu et al. (2004 ch 10) review the current state of grinding wheel measurement, replication, and subsequent analyses. The cutting edges on the grinding wheel, have been analyzed (König and Lortz (1975) and Shaw and Komanduri (1977), and parameters that can be used for characterizing the cutting edges statically and dynamically have been proposed (Verkerk et al. 1977) Modeling of surface generation based on peak spacing and chip formation has been done by Badger and Torrance (2000).

Cutting edges have been measured on grinding wheels after dressing using stylus scanning directly on the wheel with 6 and 10 µm sampling intervals by Blunt and Ebdon (1996), although correlations between wheel roughness and stock removal appeared inconclusive (Butler et al. 2002). Inasaki (1996) measured 3D scanning with dynamic focus sensor and developed an algorithm for finding cutting edges with a simulation based on complete removal by each peak. In process measurements were made on grinding wheels using a triangulation sensor and bearing area parameters by Brinksmeier and Werner (1992) and acoustic emissions by Olivera, Dornfeld, and Winter (1994).

Malkin (1989 sec 7.5) reviewed work on ground surface roughness and dressing, and noted the absence of grit size influence on ground surface roughness due to grain fracture and multiple cutting edges on each grain.

In the current work, after dressing at different feed-rates, the textures are measured with a scanning laser microscope from replicas taken after dressing with different feed-rates. The measured textures are characterized using primarily, area-scale analysis and scale-based volume-filling algorithms, as the more common conventional parameters do not have the capacity to identify the specific scales over which correlation or differentiation exist. F-tests and linear regression analyses are used on the results of the area-scale (ASME/ANSI B46.1 2002 ch. 10) and on the results of volume-filling analyses to determine the level of certainty of differentiation and correlation coefficients as a function of scale. The scales of differentiation and correlation are compared with the abrasive grain size to better understand the material removal mechanisms active in dressing at different feed-rates.

2. Methods

2.1 Diamond Roll Plunge Dressing

A Hahn Force Adaptive Grinder (Model 1, Serial Number 0001) with grinding wheel mounted on a shaft driven by a 5 horsepower, 3600 rpm motor (Pope, Haverhill, MA) and a dressing roll mounted on a shaft moved by a permanent magnet DC servomotor (Powertron, Charlotte, NC).

The plunge dressing tests were run on a grinding wheel (3SG80-MVS, 7x1/2x1-1/4, Saint-Gobain, Worcester, MA) rated at 3600 rpm. The wheel was 177.8 mm in diameter, 12.7 mm in width and had an inner hole with a diameter of 31.75 mm for mounting on the shaft. The grain number of 80 indicates that the average grain diameter is 267µm and the average grain area is about 56 000µm².

A 20mm wide, reverse plated diamond roll dresser was used with dressing feed-rates of 0.5, 1.5, 4.0 and 8.0 mm/min. The wheel speed was approximately 3600 rpm producing about 33.53 m/s (6600 sfpm) surface speed on the 177.8mm (7 in.) diameter wheel. The diamond roll speed was 600 rpm producing about 3.2m/s (628 sfpm) on the 101.6mm (4 in.) diameter roll and was operated in the "climb" mode where the relative rubbing speed is about 30.3 m/s (99.4 sfpm).

During the dwell and retraction of the diamond roll from the grinding wheel the actual roll penetration rate is different from the slide feed-rate. As the slide, which controls the feed-rate initially, comes to rest the elastic forces unload and continue to remove material from the grinding wheel at progressively lower rates (spark-out). A linear encoder was used to record the slide motion. A dwell of 0.6 sec. is recorded allowing for 36 rotations of the grinding wheel and 6 of the dressing roll before retraction began.

2.2 Surface Measurement and Analysis

Eight replicas were made forty-five degrees apart from the grinding wheel after dressing with each of the four feed-rates. A polyvinylsiloxane dental ISO 4823 type 1, high consistency replica material was used. Six measurements were made on each replica using a scanning laser profiler (UBM-Microfocus, Solarius Development) with a Keyance model LC-2210 triangulation sensor. The measurements were made over a 5x5mm region with a 10µm sampling interval.

Arithmetic average (Sa) and root mean square roughness (RMS or Sq) values were calculated using Solar Map Universal (Digital Surf). Area-scale analysis (ASME/ANSI B46.1 2002 ch. 10) was used to calculate relative areas at scales over a range from 50µm² to 12.5mm². The relative area is the calculated (apparent) area divided nominal (projected) area at a particular scale. The calculated area is determined by virtual tiling over the surface using triangles whose area represents the scale of calculation, or observation. The relative areas are generally displayed on log-log plot versus scale. The volume-filling algorithm uses rectangular prisms and calculates a fraction filled at scales over a range from 10µm² to 25mm². The fraction filled is the volume filled between the surface and a reference plane, which is parallel to the nominal plane of the surface at the height of the highest point on the surface, divided by the total volume between the reference plane and a plane parallel to it including the lowest point on the surface. The areas of the bases of the rectangular prisms are used to indicate the scale of filling. The fractions filled versus scale can be displayed on a log-log plot (Brown et al. 1996).

Scale-based differentiation and correlation are performed by F-tests and linear regressions at each scale (Brown and Seigmann 2001). The relative areas and fractions filled are used at each scale as texture characterization parameters. The linear regression coefficients (R^2) and the mean square ratios (MSR) from the F-test are plotted versus scale in order to detect the scale ranges where correlations and differentiation exist.

3. Results

Typical textures measured from replicas taken from the grinding wheel surface resulting from the two extreme dressing feed-rates are shown in Figure 1. The textures are shown with heights indicated by gray level with some shading.

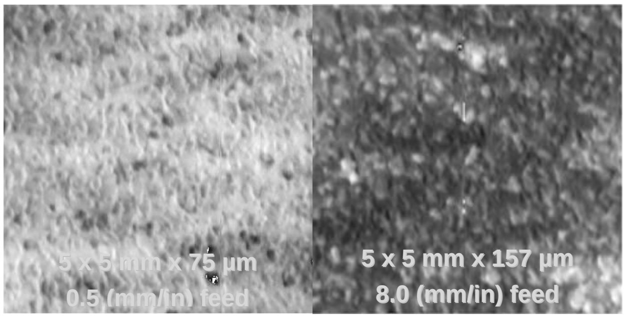

Fig. 1. Height maps of two surfaces measured from replicas from grinding wheels after dressing

The RMS values (Sq) are shown in Table 1. The F-tests showed that the only the 0.5mm/min feed-rate can be consistently differentiated from the all the others with confidence levels above 97% by both Sa and Sq. There were no correlations with regard to the feed-rates with R^2 values greater than 0.37.

Table 1. Root mean square roughness, Sq.

Feed-rate	**0.5 mm/min**	**1.5**	**4.0**	**8.0**
Mean	26.9 µm	30.1	29.8	29.0
Std dev	3.6 µm	3.2	3.8	2.2

The means of the relative areas at each scale for the four different feed-rates are shown in Fig. 2. The regression analysis applied to the results of the area-scale analyses showed that there were no correlations between mean relative areas and feed-rates with R^2 values above 0.1.

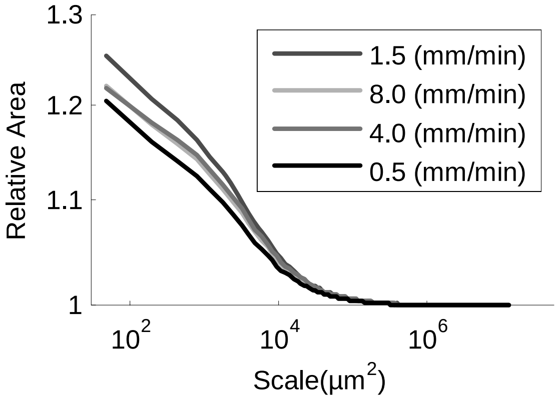

Fig. 2. Mean relative areas for the different feed-rates versus scale.

The F-tests applied to the relative areas at each scale show that the texture of the wheel dressed at 0.5mm/min is differentiable from all the other feed-rates with at least 97.5% confidence at scales between 1000 and 50 000 µm². Of the textures from the higher feed-rates however only the 1.5 and 8 mm/min. are differentiable from each other at scales between about 100 and 5000 µm² with confidence levels of 90%. Fig. 3 shows the mean square ratios as a function of scale for differentiating the textures generated at feed-rates at 0.5 and 8 mm/min using the relative areas at each scale.

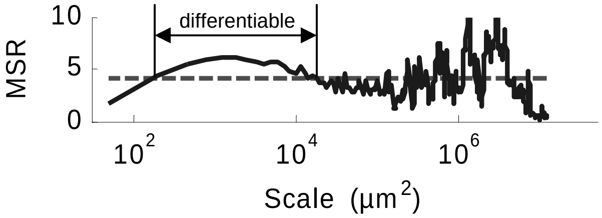

Fig. 3. Mean square ratio versus scale calculated from the F-test, showing 95% confidence level for differentiating 0.5mm/min feed-rate from 8.0 mm/min using the relative area at each scale.

The results of the volume-filling v scale analyses are shown in Fig 4, with the mean fraction filled for each feed-rate plotted versus scale. It can be seen that there is a scale above which no volume elements fit in the surface, about 300 000 µm², and that the fraction filled increases with decreasing scale. It is also apparent that there are scale ranges where the ranking of the surfaces by mean volume filled is regular and stable. These are the regions of high correlation coefficients shown in Fig. 5 and 6.

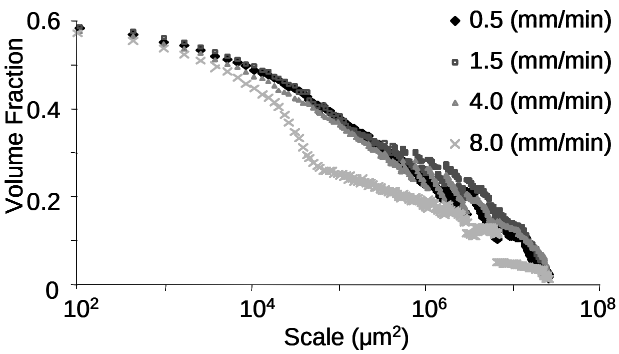

Fig. 4. Mean fraction filled versus scale for all feeds

Sample linear regressions of the volume fraction filled as a function of scale are shown in Fig. 5 with the scales and correlation coefficients. It can be seen that the volume fraction filled decreases with increasing feed-rate. The scales of the sample regressions are indicated in Fig. 6, which shows all the calculated regression coefficients versus scale.

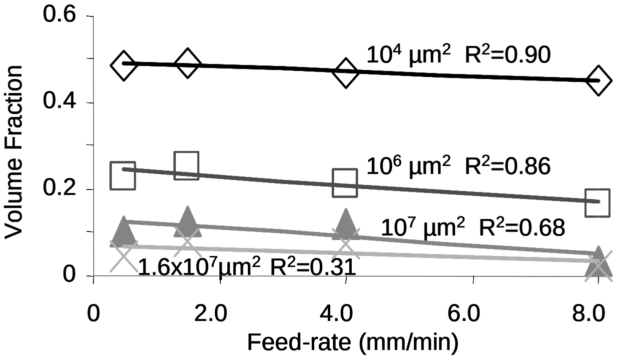

Fig 5 Sample regression analyses for the mean volume fraction filled versus feed at several scales with corresponding scales and R^2 values.

In Fig. 6. It can be seen that the regression coefficients increase twice with decreasing scale with a third increase starting at about 1mm² where the R^2 values exceed 0.9. The remarkably high R^2 values continue to scales of about 10 000 μm², then decrease to the lowest scale, 100μm².

F-tests on the volume filling results show that there is differentiability with 90% confidence or better in four out of the six feed-rate comparisons, and three with 99% confidence or better (Fig. 7). The scales of the high confidence levels correspond well with the scales of high correlation coefficients.

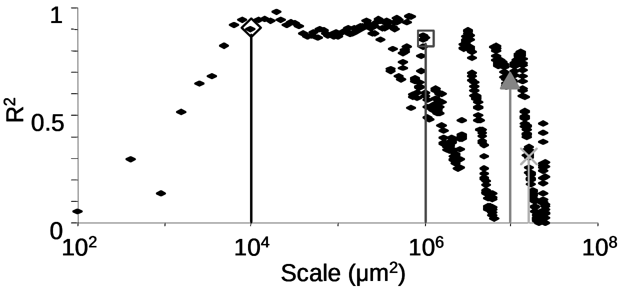

Fig 6. R^2 for fraction filled v. feed, plotted versus scale. The four scales shown in Fig. 5 are indicated here with vertical lines

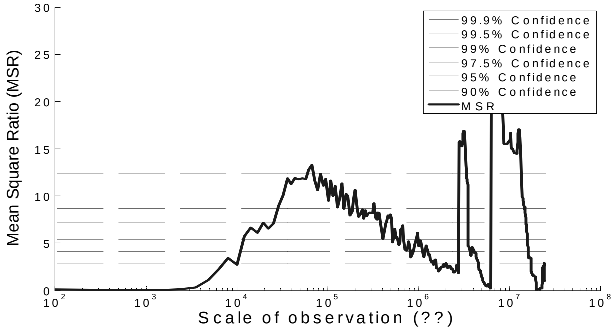

Fig. 7. Mean square ratio versus scale calculated from F-tests, showing 90% and 95% confidence levels for differentiating all the feed-rate pairs using the fraction filled at each scale.

4. Discussion

The results of the regression and F-test analyses on average and root mean square roughness, and the area-scale and volume-filling calculations suggest that the grinding wheel texture is influenced by the feed-rate in diamond roll dressing. The measurement and calculating methods used here are sufficient to capture and detect differences in the grinding wheel texture due to dressing feed-rate. From these results it appears that the volume fraction filled is a better indicator of the feed-rate than the relative area or conventional parameters.

Average and root mean square roughness have been previously shown to be highly correlated in grinding (Terry and Brown 1997), as they appear to be here. The area-scale and volume filling analyses appear to be independent in this study.

The area-scale and volume-filling analyses can have clear physical interpretations with regard to the topography and its function. Relative areas are related to the inclinations on the surface as shown in equation 1, where the summation is over the individual tiles and θ_i is the inclination of the normal of ith tile with respect to the normal to the nominal surface, p_i is the area of the ith tile projected onto the nominal surface plane and A is the total nominal area evaluated.

$$\mathrm{RelA}=\Sigma(1/\cos\theta_i)(p_i/A) \qquad (1)$$

It could be supposed that a better performing wheel would have higher inclinations on the surface acting as more efficient rake angles. A better performing wheel also might have higher volume fractions filled, thereby indication that there is more room in the grinding wheel texture for coolant and chips.

Optimization of the dressed surface of the grinding wheel in plunge diamond roll dressing would appear to be a coupled problem if controlled by just the feed-rate. These tests indicate that wheels with higher inclinations of the facets, as indicated by the relative areas, also have less volume in the wheel texture available for filling.

The scales of high R^2 values in the correlation tests and MSR values in the F-tests are indicative of scales of features on the surface that are responsible for the correlations and differentiation.

The differentiability of the feed-rates by the F-test applied to the relative areas is over scale ranges, 100µm² to 5000µm², which are significantly smaller than the grain area, 56 000µm². The scales of high regression and differentiability by volume-filling coincide well and include the grain area. There appears to be an important change in the confidence of differentiation just below the scale of the grain area. These results indicate that the feed-rates may influence the material removal mechanisms. The higher feed-rates appear to cause more complex fractures and higher facet angles on the grinding wheel. The lower feed-rates appear to leave more volume in the surface texture acting on scales of the grain, possibly indicating grain pullout, or total grain disintegration during dressing. The larger scales where there is good differentiation and correlation do not appear on first analysis to be correlated with the grain size.

In plunge roll dressing the differences in grinding wheel texture due to different feed-rates may be partly obscured by modifications during the spark-out. Spark-out occurs during the dwell and retraction of the diamond roll from the grinding wheel as the slide comes to rest and the elastic forces continue to remove material from the grinding wheel. The actual feed-rate becomes progressively lower, possibly modifying the grind wheel texture so that all final surface textures could resemble the textures created at lower feed-rates, or have characteristics of heavy feed-rates followed by light feed-rates. Since the higher feed- rates correspond to higher dressing loads, the wheel will be subject to more penetration by the roll during spark-out at the higher feed-rates. The higher complexities found by the area-scale analysis in the textures created at highest feed-rates could be due to fracturing of prominent asperities during spark-out. This asperity fracturing during spark-out mechanism also would be consistent with lower volume fractions calculated at the higher feed-rates by the volume-filling algorithm.

5. Conclusions

1. Conventional texture analysis parameters Sa and Sq provide limited differentiation of the textures and no indication of the scale at which differentiation is possible.

2. Volume-filling analyses show that there are larger volumes in the texture of the grinding wheel dressed at the lower feed-rates at scales similar to and larger than the grains.

3. Area-scale and volume-filling analyses provide a basis for advancing the understanding of material removal mechanisms during dressing.

6. Acknowledgments

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