2005

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Recommended Citation

Carrano, Andres, "Geometric Modeling of Engineered Abrasive Processes*" (2005). *Journal of Manufacturing Processes* , vol. 7 (1), pp. 17-27. Accessed from
http://scholarworks.rit.edu/article/303

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Abstract

One of the common issues that arises in abrasive machining is the inconsistency of the surface roughness within the same batch and under identical machining conditions. Recent advances in engineered abrasives have allowed replacement of the random arrangement of minerals on conventional belts with precisely shaped structures uniformly cast directly onto a backing material. This allows for abrasive belts that are more deterministic in shape, size, distribution, orientation, and composition. A computer model based on known tooling geometry was developed to approximate the asymptotic surface profile that was achievable under specific loading conditions. Outputs included the theoretical surface parameters, R^sub q^, R^sub a^, R^sub v^, R^sub p^, R^sub t^, and R^sub sk^. Experimental validation was performed with a custom-made abrader apparatus and using engineered abrasives on highly polished aluminum samples. Interferometric microscopy was used in assessing the surface roughness. Results include the individual effects of pyramid base width, pyramid height, attack angle, and indentation depth on the surface descriptors.

Introduction

Some abrasives occur in nature (flint, garnet, etc.), and some are man-made (aluminum oxide, silicon carbide, zirconia, CBN, and so on). Until now, most coated abrasive tools have consisted of single or multiple layers of oriented grits of approximately the same size that are attached to a substrate. The size of the particles used on coated abrasives is established by sifting the crushed grits through screens of standard mesh (NBS), by sedimentation, or by air flotation. The application of the abrasive grits to the belt backing is either achieved through gravity or electrode-induced polarization. This traditional manufacturing practice, however, yields an abrasive belt that presents variations in grit size, shape, distribution, and orientation. Moreover, the geometry of the cutting grits changes from particle to particle, making it impossible to know, for instance, the rake or attack angle for any given grit or cut.

The task of modeling the interaction of the grit and the surface of the part in an abrasive machining process has been attempted in several ways by previous researchers (Torrance 1987; Bahin 1987; Lin et al. 1996a, 1996b; Li and Liao 1997; Abede and Appl 1988; Dornfeld 1981; Buttery and Hamed 1977, 1978). The random size, shape, and relative placement of abrasive particles on the sandpaper has always presented a difficult problem to attack from a process modeling standpoint. Using statistical distributions of particle size and making assumptions about particle shape and relative placement on the substrate have allowed some researchers to estimate overall process results based on process parameters (Torrance 1987; Li and Liao 1997). This method, which is probabilistic in nature rather than deterministic, has typically served as a basis for a correlation of predicted and actual results. Another common approach to abrasive process modeling has been the single-grit approach (Abede and Appl 1988; Dornfeld 1981; Buttery and Hamed 1977; Lin et al. 1996b). This method seeks to deterministically model the interaction of a single abrasive grit and the surface of the part. Major contributions to the literature have been made via this modeling method especially with regard to the ploughing phenomenon and elastic/plastic effects (Abede and Appl 1988; Dornfeld 1981; Lin et al. 1996b; Buttery and Hamed 1978). The major shortcoming of this method is the lack of interaction of the multiple abrasive grits on the surface of the part. The actual abrasive process is the sum total of many single abrasive grits of different sizes and shapes and their effect on the surface.

Recent advances in manufacturing processes have allowed replacement of the random arrangement of minerals on conventional belts by a patented technology called microreplication. The technology is a spin-off of work that was originally used in the manufacturing of reflectors. Since the original development by 3M, other companies have also produced their own engineered abrasives in similar manners (Mason 1999; Norton 2000). To date, engineered abrasives have been targeted at the much larger metals market, but interest has been shown from the wood and composites markets. As defined by 3 M (1997), microreplication is the science of creating small, precisely shaped, three-dimensional structures and reproducing them on a variety of surfaces. The belt's surface, in this case, consists of pyramidal structures containing micron-graded minerals that are uniformly applied to a backing material (see Figure 1).

This development has been around for several years, but it was not until recently that commercial fabrication of belts became feasible. This new genre of abrasive tools is usually referred to as engineered or structured abrasives. They consist of abrasive belts that are more deterministic than the traditional counterpart: the shape, size, distribution, and orientation of the cutting grits are known and controlled. This provides a very even distribution of mineral and yields a more consistent rate of cut and surface finish. The motivation for pursuing such abrasives lies in the idea that, by removing variation in the grit geometry, it is possible to remove variation in the finish quality. However, a better understanding of the impact of the individual geometric features of the abrasive on the surface roughness is required as a basis for proposing an optimized geometry and for assessing the degree of performance improvement. It is believed that the future of abrasive-based machining is in microengineered belt patterns and that further job-based customization of these patterns will be a future step. Optimization of the resultant workpiece surface and machining parameters will also be possible.

The main objective of this research was to develop and validate a 3-D computer-based model that would help in understanding the impact of the individual geometric features of the grit on the surface roughness of the workpiece. To date, most geometric models of abrasive processes have been developed based on a single-grit tooling supposition (Abede and Appl 1988; Dornfeld 1981; Buttery and Hamed 1977; Lin et al. 1996b; Oxley 1997), thus neglecting interactions between grits (multiple-pass effect), or consisted of theoretical approximations due to unknown geometry (Torrance 1987; Li and Liao 1997, Mulhearn and Samuels 1962). These are assumptions that simplify the models but also make them somewhat unrealistic and provide no basis for optimization. The model developed here was based on a pyramid-shaped abrasive grit, incorporated the effect of multiple passes, and was validated on commercially available products. Other literature relevant to abrasive process modeling is included for reference (Gahlin and Jacobson 1999; Komanduri 1971; Larsen-Badse 1968; Sin, Sada, and Suh 1979).

Once the model was developed and validated, a second objective was to search for a better understanding of the individual geometric features and their impact on the final quality. Three main parameters were investigated: the attack angle of the belt, the pyramid width, and the pyramid height. These are the features that could potentially be changed during the manufacture of this abrasive. The other inputs to the model were: the amount of indentation (a function of the load applied), the sampling resolution (a function of the instrumentation), the number of grits/row, and the number of rows. Notice that some of these are artificial variables that arise because of the finite nature of the model (such as the number of grits and number of rows in the abrasive matrix) or variables that are not under control by the abrasive manufacturer (amount of grit indentation).

Methodology

The basic idea is to develop a geometric computer model that would parametrically represent the tooling and workpiece, as well as to calculate the surface descriptors that result from the interaction between these. A matrix with several grits per row and several rows, one after the other, was generated in a computer program. Because this abrasive tooling allows for perfectly known geometry, it is then possible to define the geometry as a function of base width and height of the pyramid. Rake and attack angle can be calculated from the design geometry but are also a function of the width and height. By knowing the pyramid orientation with respect to the feed direction, the offset between rows and columns of pyramids, and the depth of indentation into the workpiece (as a function of the applied pressure), it was possible to approximate the resultant 2-D surface profile after n rows of grits have performed a cut. The model assumed that the entire volume of material displaced in the workpiece by the tool was effectively the volume removed. This equates to 100 percent efficiency in the removal of material (Samuels 1978). Proportionality between the amount of indentation of the grits into the workpiece and the pressure applied was assumed.

Geometric Computer Modeling

The computer model was developed to be a fully parametric tool that allows for changes in the following features: height and base width of pyramid, number of grits per row, total number of rows, and depth of grit indentation into the workpiece. The outputs obtained from this include the arithmetic average roughness (R^sub a^), rms roughness (R^sub q^), maximum profile valley depth (R^sub v^), maximum profile peak height (R^sub p^), maximum peak-to valley (R^sub t^), and skewness (R^sub st^) coefficients. A program was developed and written in MatlabÂ® to perform the aforementioned calculations as well as to graphically represent these conditions. Figure 2 represents the abrasive grits as a two-dimensional matrix of pyramidal elements.

It is also necessary to state the angles that these grits would have with respect to the feed direction (which was constrained along the Y axis). These are Î± and Î² in Figure 2. Because they are complementary angles, the program only considered Î± (designated as attack angle), which can be thought of as the take-off angle from the edge of the abrasive belt. The matrix of pyramids was then rotated about Z by means of homogeneous transformation matrices. At this point, it is possible to obtain a 3-D graphical representation of the grits, as shown in Figure 3. In this example, the configuration is four grits per row, four rows, and a 35Â° attack angle.

From Figure 3, it can be noted that projections of the grit matrix onto planes XY and XZ were calculated and plotted. The projection onto plane XY was developed for visualization purposes, while the projection onto plane XZ was the foundation for obtaining the cumulative 2-D tooling profile, the resultant 2-D surface profile, and subsequent descriptor estimation.

There was an important circumstance that, if neglected, could make the model unrealistic: because the abrasive matrix has a finite size, then the entire projection length is never swept by all rows of grits (unless the attack angle is 0Â°). Consequently, it is not possible to use the total projection length as the evaluation length for descriptor calculation. Figure 4 depicts this situation. An algorithm was developed that, for any geometric configuration, would calculate the left-most vertices (or closest to the Y axis) from the first grit on the last row [this is grit (M, 1)] and the right-most vertices (or farthest from Y axis) from the last grit in the first row [or grit (1, N]. These vertices determined the actual length that is swept by all rows present in the configuration and was the length used for the descriptor estimation.

Once the projection onto the XZ plane was obtained, it could be represented in a two-dimensional plot. This profile was the overlapping of all possible rows of grits when moving along the 7-axis and provided for the multiple-pass effect. Figure 5 renders this view for the example previously shown in Figure 3 (four grits/row, four rows, 35Â°). The workpiece is also represented and the interaction between the grits and the workpiece is also shown for a given indentation (pressure).

The interaction between the workpiece and the grits was given by the amount of indentation. This was a function of the load applied to the abrasive and was obtained empirically by performing controlled Vickers tests on the material of interest. Up to now, all the calculations and plots dealt mostly with the abrasive. However, the transition to the surface, through the toolworkpiece interaction, was needed. In this respect, it was first necessary to obtain the equation representing the work surface and those line equations from the abrasive tooling profile that were relevant. These consisted of the line equations for the edges of each grit that were boundaries in the projection. Once this was done, then the limits for the evaluation length were calculated and plotted. Figure 6 presents an example from a configuration with four grits/row, two rows, 35Â° attack angle, and 0.3 units of indentation from the workpiece surface.

Representation of Surface Work and Abrasive Profile (distance units)

An important part of the surface definition algorithm involved calculating the intersection points between the projections as they traverse along the feed direction. These intersection points defined the highest points of the abrasive profile and, in some cases, the highest points in the surface profile. In Figure 6, these intersection points are shown. It can be noticed that some of these intersection points fell outside the evaluation length, in which case they were ignored; some fell inside the evaluation length but above the surface level; and finally the rest fell inside the evaluation length and below the surface level. In the case of those points inside the evaluation length and below the surface level, the intersection points were kept, as they defined peaks or valleys in the new surface. However, in the case of those points inside the evaluation length but above the surface datum, two new points were calculated by intersecting the workpiece surface line with the two lines making up the original intersection (see Figure 6). By connecting all these points, the surface profile left in the workpiece after M passes of N grits each is obtained. The program had to be flexible enough to accommodate the three scenarios: all intersection points fall above the surface line (grits do not touch the workpiece), all intersection points fall below the surface line (full indentation), and the general case where some intersection points will fall above the line and some below the surface line. Finally, a database with all line equations (piecewise by intervals) involved in the final surface profile was built and stored for descriptor calculation.

Once the resultant surface was generated and characterized, the final step was to perform discrete sampling over the evaluation length (thus mimicking a profilometer) and store the readings in a vector. Figure 7 shows an example: four grits/row, two rows, 35Â° attack angle, 0.3 units of indentation, and 0.1 units of sampling resolution.

As can be seen in Figure 7, the sampling algorithm consisted in stepping from the lower limit of the evaluation length, by an amount equal to the sample resolution, and intersecting the surface profile with the appropriate line equation from the piecewise database until reaching the upper limit of the evaluation length. Once the profile was sampled, the data was stored in a vector and the corresponding calculations were performed for estimating R_a, R_q, R_{sk}, R_v, R_p, and R_t. These surface roughness descriptors were calculated following the ASME B46.1 standard (ASME).

Experimental Validation

For the purpose of model validation, a customized experimental apparatus was constructed and aluminum specimens were prepared. The abrasive tooling consisted of an engineered abrasive belt that is commercially available. The attack angle on these belts is always 35Â°. The verification experiments included scratching polished aluminum samples with strips cut out from the belts and under controlled loads. The two attack angles considered in this study were 0Â° and 35Â°, as they were the two configurations most easily measured and set up with minimal error. Once the tooling was set up in position, the attack angle was verified by applying ink to the grits and pressing the belt against paper. The idea was then to produce samples at these two angles and for identical loads and number of passes, and subsequently compare the trends from this experiment with those obtained from the model. A phase-shift interferometric microscope (wavelength 550 nm) was used to assess the surface topography and descriptors. The area of sampling was 500 Âµm Ã? 500 Âµm. The CRT resolution was 480 pixels Ã? 480 pixels. The output from the interferometric microscope included 3-D maps, intensity maps, 2-D traces, as well as area averaging and 2-D descriptors.

The testing apparatus (abrader) was custom designed and built. It was intended to hold a specimen in position while a variable but controlled load was applied over a known area. It also had to be stiff enough to withstand the dynamics of an abrasive strip sliding between the workpiece and the lever mechanism with minimal lateral movement. Figure 8 shows a picture of this apparatus.

The device consisted of a lever mechanism with a titanium shoe that pivots about a shaft. This allowed for a more localized pressure and for easier calculation of the area of contact. The specimens were mounted on a manually driven microstage. The area of contact was measured and found to be 1.16 cm^2. There were six steel weights available for a combined total weight of 1350 grams.

The specimen preparation involved machining of aluminum 2024-T351 bar stock down to a specimen size of 1 x 1 Â¾ x Â¾ in. and prepared into the best possible surface so that the abrasive scratches from the experimental setup correlate as closely as possible to the results from the computer model. Twelve specimens were cut and faced in a vertical machining center. Following this, the specimens were run through a sequence of two grit sizes (P-1200 and P-2500) in a bench belt grinder and then processed in a polishing wheel with a 6 Âµm diamond paste thinned with a Buehler paste extender. This was followed by a polishing operation in a wheel with 1 Âµm Al^sub 2^O^sub 3^ slurry. This preparation sequence produced a mirror finish on all specimens.

A correlation between the load applied and the indentation amount was developed for the material of interest. This was accomplished by a series of controlled Vickers microhardness tests with a 136Â° diamond indenter. The microhardness experiment showed a very linear relationship between the load applied and the depth of penetration between 50 and 1350 grams. Because the pyramid angle in the Vickers indenter is slightly different from that in the abrasive grit, this approximation had to be based on the assumption of equal energy required for displacing dislocations in the material by both pyramidal indenters. Finally, the abrasive tooling utilized was silicon carbide A-110 [equivalent to a P180 FEPA (3M)].

Scanning electron microscopy was utilized for performing metrology on the pyramids, documenting chemical composition, as well as for illustration purposes. The metrology for base width was performed by processing the nontilted image with measurement software. The average measurements from 28 pyramids yielded an average base of 843 Âµm and pyramid height of approximately 415 Âµm. This yielded a base-height ratio of approximately 2:1. Additionally, the SEM documentation of the belt included secondary/backscattered electron images, X-ray mapping, and compositional imaging.

Results

The model output for a configuration of 40 grits/row, 40 rows, 34 Âµm indentation depth, 843 Âµm pyramid base width, 415 Âµm pyramid height, and 0.05 Âµm sampling resolution is shown in Table 1.

The same configuration was set up in the abrader and run twice for each setting. Because the mathematical model used a 2-D projection of the profile to calculate the descriptors, it was necessary to use a 2-D approach (line scans) for validation with the interferometric microscope. Figures 9 and 10 show two of these scan lines from the actual specimens.

From Table 2 it can be seen that the computer model and the experimental results agree within the experimental error.

Analysis

According to Table 1, the computer models estimated the configuration at 35Â° attack angle to produce a better surface across the board. This was expected as the 0Â° attack angle configuration presented all grits aligned with respect to the feed direction, therefore completely overlapping their projections. The R^sub q^ and R^sub a^ descriptors were approximately 47% better and the peak-to-valley about 30% better when machining at 35Â° than in the 0Â° case. Additionally, the maximum possible peak-to-valley amount (equal to the indentation level) of 34 Âµm was logically obtained in the 0Â° configuration.

From Table 2, it can be seen that the same trends were observed during experimentation: the configuration at 35Â° produced better surface than at 0Â° across descriptors, especially when looking at the summary descriptors such as R^sub q^ and R^sub a^.

Some of the possible explanations for such divergence in the results can be related to the difference in probe size. The mathematical model reads points from the theoretical surface without considering any physical interference at all. This is, if the sampling interval is such that a particular reading takes place in the very bottom of a deep and narrow valley, the model would obtain the result without problem. In reality, there is an effective probe size for most instruments (i.e., stylus profilometer 3-10 Âµm; optical profilometer 0.1 Âµm) that would not permit either the physical probe to go all the way in or the light to come out. This causes the theoretical model to produce higher (rougher) descriptor values than those produced by the profilometer. A second line of reasoning was the imperfections in the abrasive and slight variations in geometry. In some cases, the abrasive did not necessarily present a perfect pyramid. Figure 11 shows SEM micrographs of two different grits in a brand-new belt.

As can be appreciated in Figure 11, some of the abrasive tips suffered some damage even prior to their utilization. This could be due to several causes: during the casting process, during the belt handling, etc. These events caused differences in geometry and obvious departure from theoretical values. Additionally, dissimilarities in the proportions can also be partially attributed to the material used. The model assumes a perfectly flat and homogeneous material. However, and although a great deal of effort was put into polishing the specimens, there were peaks and valleys (roughness) initially present in the original sample. Figure 12 depicts this situation.

From these pictures, it can be seen that initial roughness of the specimens played some role in the final descriptors. For instance, in the area reflected in Figure 12, a peak-to-valley distance of 21.4 Âµm would explain why the R^sub t^ obtained doubled the amount of indentation. Not considered in this study, but adding to the experimental noise, is the fact that the material is not perfectly homogeneous and could present hard spots and other irregularities that would locally affect the abrading or polishing processes.

Finally, the fact that the material removal mechanisms are not 100% efficient also distorts the values somewhat. Larsen-Badse (1968) found that approximately 15% of the groove volume is removed to form a chip, and that the remainder forms ridges on the metal surface. Also, Gahlin and Jacobson (1999) reported that the relative bluntness of a non-ideally sharp tip decreases with increasing penetration depth. Regardless of the load and penetration depth used in this study, it is very likely that in most cases the pyramid did not behave like an infinitely sharp tip and did not completely form a sharp-bottom groove in the metal. Finally, the equal energy indentation assumption that allowed for extrapolation of the Vickers test is not perfect, as the geometry of the two indenters was slightly different.

With respect to the individual effects of parameters, the computer model made it possible to estimate the individual effect of design factors. Figures 13 through 16 show these.

As can be seen from Figure 13, the effect of pressure for the three descriptors considered increased linearly from 10 Âµm to approximately 25 Âµm. From then on, the descriptors reached a plateau or asymptote and stabilized. The initial increase in the descriptors is due to the fact that, initially, for small indentation depths, the grits are barely scratching the surface. This leaves untouched areas, which is obviously undesired, but roughness is low because the initial surface was ideally flat. The reason can be geometrically described as having all the intersection points between the projections of different grits taking place above the surface level. Also of interest, is the fact that after reaching a certain level of indentation, further pressure did not result in a better surface (as all the intersection points were below the surface level and additional pressure did not generate new surface profiles). This is consistent with the findings of Taylor, Carrano, and Lemaster (1999) in which the surface roughness did not improve when increasing the interface pressure from 0.50 psi to 0.75 psi in a stroke-sanding operation and indicates that the grits are fully engaged.

With respect to the attack angle (Figure 14), the general individual effect was a decrease in the two descriptors of consideration when increasing the angle. This is because the model is based on the 2-D projection of the pyramids (removed area) and, when rotating them toward 45Â°, the projected area increases. It is not a monotonie decline because the inter section points occurred at different places for each angle, thus producing different roughness. The best possible point was obtained at 45Â°, which is the maximum projected area ([the square root of]2 times larger than at 0Â° attack angle), but this was not considered because of the obvious overlap of subsequent rows (this happens at 0Â° and any n Ã? Ï?/4), which would translate into inefficiency in the removal as more grits are added. The other tail of the plot presented the worst performances, being 0Â° and 5Â° the extremes for both R^sub q^ and R^sub t^. The R^sub t^ descriptor shows a more abrupt behavior as it depends on whether the sampling interval is such that it captures the highest peaks and lowest valleys. Two high rises interrupt the quadratic descent of the R^sub q^, and those were at 20Â° and 35Â°. The latter is precisely the configuration found in the commercial belt. The points to consider for further observations were 25Â°, 30Â°, and 40Â°. Therefore, detailed inspection of the interval [20Â°, 45Â°] was performed by running the model for every degree in such an interval and with a better sampling resolution (0.01 Âµm). The average and standard deviation were then calculated for each of the three angles (plus the commercial configuration of 35Â°) in consideration by pooling 10 observations in the neighborhood (five before and five after) and via parameter perturbation. These are presented in Table 3.

From this table, it can be seen that the configuration at 40Â° presents not only the best average but also the smallest standard deviation. This means that this is the most robust configuration against perturbations in the angle. These perturbations can arise from the abrasive manufacturing process itself or from belt tracking problems during the use of the belt.

The individual effect of pyramid height (Figure 15) was as expected. An increase in the height produced an increase in the descriptors R^sub q^ and R^sub t^ until it reached a point where it stabilized. The initial increase was because a shorter pyramid with a relatively large base width produced a large angle at the tip of the pyramid. This caused the intersection points to take place close to the tip, therefore producing better finishing. This continued until it reached the point where the intersections occurred beyond the surface level.

The individual effect of pyramid width (Figure 16) is, surprisingly, negligible in the interval observed. A possible explanation might be the fact that if between these limits the intersection points already occur below the surface line and further widening does not lower these intersections enough to overcome the increase in the total projected area, then the roughness should not change much. For the interval observed, this parameter showed a very robust behavior, so the current commercial width (843 Âµm), which is located in the middle of this region, seems appropriate.

Conclusions and Future Work

The advent of engineered abrasives has allowed for a new approach to abrasives modeling to be considered-that of a deterministic multi-grit model. This approach is now possible because the size, shape, and relative placement of the abrasive grits are known and can be definitively modeled geometrically. A computer model has been developed to show, predict, and analyze the behavior and individual geometric characteristics of engineered abrasives. It was possible to validate the model with actual experiments conducted in a controlled environment and with commercial abrasives. Further investigation with the model allowed for a more developed understanding of the individual effects of geometric features such as pyramid height, width, and attack angle. It was also possible to optimize attack angle configurations, which presumably can be easily changed in the abrasive manufacturing process. However, this model does not currently include elastic/plastic effects, such as ploughing, but rather assumes a 100% cutting efficiency (Abede and Appl 1988; Dornfeld 1981; Lin et al. 1996b; Buttery and Hamed 1978). Additionally, it does not include any provision for abrasive grit wear or breakage throughout the process (Sin, Saka, and Suh 1979; Jiang, Sheng, and Ren 1998). These two major assumptions must be taken into account when considering the model and its merits. Nonetheless, the potential of such a modeling tool has been established and will be the subject of more detailed work. Future work will focus on incorporating the elastic/plastic effects of ploughing, grit wear, and breakage into the model, as well as modeling the workpiece roughness prior to machining.

Acknowledgments

This research was partially funded by USDA grant no. 99-03035 and the Furniture Manufacturing and Management Center at North Carolina State University. The authors also thank Dr. Richard Lemaster from the Wood Machining and Tooling Research Group at NCSU for his contributions to this work.

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