Role of Forming In Micro- And Nano-Scale Material Removal Mechanisms During Surface Machining of Ductile Materials

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Role of Forming
In Micro- And Nano-Scale Material Removal Mechanisms During Surface Machining of Ductile Materials

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Abstract. The material detachment mechanisms of ductile metal surfaces are studied experimentally during dry grinding operation in a simulated experiment with near single grit contact with the surface. The spectra of the cutting and thrust forces are recorded and analyzed. It is found that the thrust force changes its direction from a compressive to a tensile mode. The ratio between the thrust and cutting force is consistently found to be greater than 1. In the grinding process, the chip is found to be much shorter and thicker than those predicted by traditional continuum cutting theories. From the analysis of chip dimensions and cutting forces, we speculate that the cutting process during a grinding operation comprises of three phases as follows: (i) lifting up of the surface ahead of the abrasive particle, (ii) segmentation through shear instability, and finally (iii) chip tearing from the surface. Accordingly, the heating cycle is much longer with a lower mean temperature, compared to those of macro machining. In addition, the proposed deformation field leads to loss of constraints ahead of the cutting grits, and possibly reducing the thrust to cutting force ratio. This suggests that forming took place prior to material detachment in grinding.

INTRODUCTION

Ultraprecision machining is becoming the backbone in several advanced industries, such as micro and opto-electronics, optical components and Microelectromechanical systems (MEMS), among many others [1, 2]. Fine grinding, lapping or chemically active slurry polishing usually produces the required high quality surface with tight tolerance. These processes share the utilization of abrasive particles either in free or bounded form to provide the cutting points. The machining process becomes similar to macro metal cutting, except with extreme negative rake angles and the possibility of cutting nose radius in the same order of the depth of cut. In macro machining, the ratio of the depth of cut to tool nose radius is of the order 50-100. As the depth of cut is reduced, the ratio of the depth of cut to the effective tool (abrasive particle) nose radius approaches 0.1 to 0.01. Thus the local field around the cutting nose is found to significantly affect the profile and dimensions of the entire chip deformation field, as well as the relative magnitudes of different components of the resultant cutting force. In such case, a very high down force is needed, resulting in thrust force, F_t that is about twice the cutting force, F_c [3, 4]. Here we will attempt to provide a mechanistic understating of the deformation process during fine grinding operation.

The extensive work on material removal and deformation under single abrasive has shown distinct material deformation modes, linked to the bluffness of the grit and the angle of attack [5-7]. These modes of deformation includes micro-machining, unstable prow ahead of the grit forming wear debris and the final

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mechanisms is ploughing with no net material removal. These investigators among many others have indicated that if the attack angle is less than a critical value, then the process is essentially one of ploughing or rubbing contact and virtually all the displaced material appears in ridges left in the wake of the tool.

As for grinding, while the process employ the same bluff grits and should be within the ploughing regime, instead, the angular trajectory of the cutting grits relative to the surface leads to surface micro-machining. Two primary phenomenological mechanisms have been proposed and are depicted in Fig. 1. The first is by Shaw [8, 9] wherein ductile materials are extruded ahead of the cutting tip nose. The other mechanism is by Komanduri [3, 4] wherein the grinding process is assumed to resemble machining with a high negative rake angle. While these two mechanisms are phenomenologicaly plausible, they are physically almost impossible since the material has to undergo extreme deformation with a singular deformation field at the apex of the formed chip and the free surface ahead of the deformation process. Such singular field "in the authors opinion" cannot be supported without externally imposed geometrical constraints.

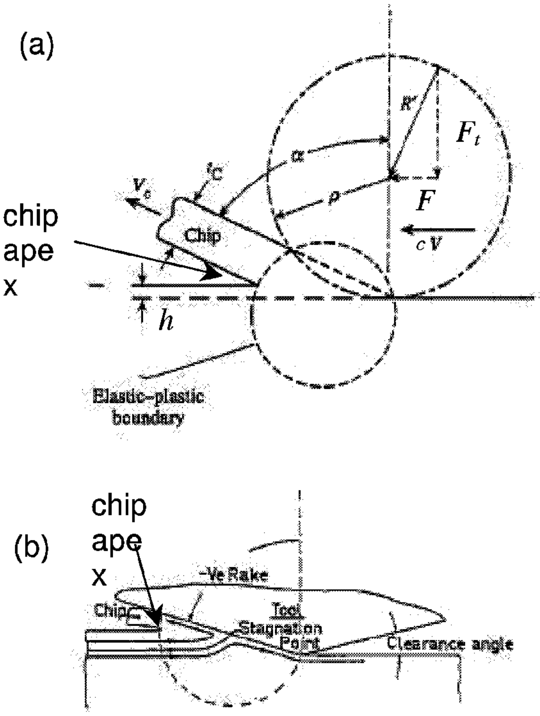


FIGURE 1. (a) Shaw's grinding mechanism employing ductile extrusion ahead of the grit [8, 9]. (b) Komanduri's model for grinding similar to machining with a high negative rake angle [3, 4].

On the other hand, the classical phenomenological grinding theory [10] describes the grinding operation as a milling cutter having cutting edges spaced evenly at the cutting radius, each of the cutting point cuts at the statistical mean chip.

In this work we will attempt to understand the deformation mechanisms associated with fine surface grinding, under dry conditions. A unique experimental protocol is developed to correlate the thrust and cutting forces spectra obtained from near single grit interaction of the surface to the profile of the formed chip. The gained insight is utilized to describe a physically based phenomenological model of the chip formation process in grinding and its implication on the evolution of the thermal field and the quality of the machined surface.

EXPERIMENT

A Reid precision surface grinder (model 618 HYD) is retrofitted with a DC speed control to provide step down nominal operational speed of 250-500 rpm and adjusted by a strobe light. The reduced speed is required to resolve the signature of individual abrasive grit at a suitable bandwidth of the data acquisition system. The nominal table speed is about 10mm/s and is controlled by a limit switch and oscilloscope. A 7`` fine silicon carbide soft grinding wheel (Norton SG 5SG100-KVS) is utilized. The microstructure of the grinding wheel is shown in Fig. 2, where it has an average grit size, d =150 µm and grit spacing pitch, m=400µm. The depth of cut is controlled by the grinding machine, which has a resolution of 1.27 µm. While every care is taken to eliminate the feed screw backlash, the reported depth of cuts has an uncertainty of about +/-20%.

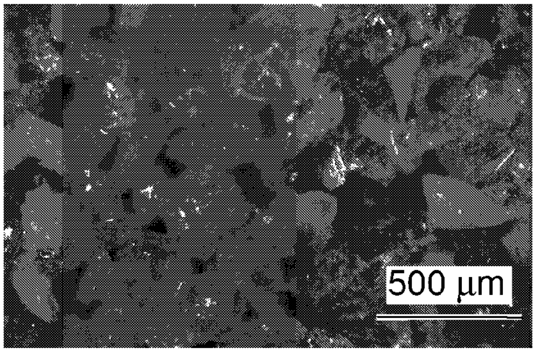


FIGURE 2. Optical image of the grinding wheel (class 100, Norton SG 5SG100-KVS). The opaque particles are the SiC grits with about 100-150µm diameters and about 400µm spacing pitch.

Specimen design

A normal dry grinding operation is performed except the specimen thickness is selected to be less than the range of the average grit spacing pitch of the grinding wheel. Such selection would ensure almost single grit interaction within the width of the specimen at any moment. The selected material system is a thin sheet of stainless steel 304, with varying thickness of 254 and 762µm. This range of thicknesses would ensure covering the range below and above the wheel pitch and to provide approximately single grit-surface interaction.

Measuring force Spectra

A micro-specimen holder (Fig. 3) is devised to measure the thrust and cutting forces under the grinding wheel. The setup has two piezoelectric load cells (PCB-model 208C01, 10-lb capacity) for measuring the applied normal and tangential forces. The specimen post has rotational degree of freedom about z-axis to provide orientation control. The force profiles are recorded with a dynamic data acquisition system (DAQ: ACE model DP104 FFT Analyzer, 20kHz bandwidth). The response of the load cells is calibrated first with step input as a function of position. The spatial calibration function is used to estimate the cutting and thrust force over the whole specimen length. The test parameters are selected to provide approximately a data point for every 100µs and thereby mapping each grit-surface interaction by at least 10 data points.

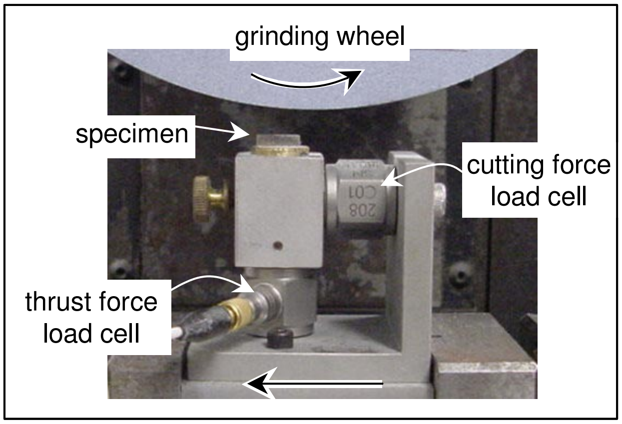


FIGURE 3. Experimental setup showing the cutting and thrust force load cells, and the specimen mount.

RESULTS

Atypical force measurements are shown in Fig. 4 and 5 for specimen thickness of 762 and 254µm respectively. Figure 4 is recorded at a table speed, v=10.87mm/s, grinding wheel rpm=251 and depth of cut, h=12.7µm. For these conditions, the average grit-surface contact is about 0.64 ms with an average pitch time of 0.17ms. In Fig. 4 there are multiple time cycles that range between 0.2-0.8 ms, which is indicative of the variability of the grit sizes and their depth of cut. In addition, a single prevailed frequency is not clear due to the interference of multiple grit contact with the surface. At the relative peaks, the ratio of F_t /F_c ranges from 1-3. The interesting feature is that F_t increases instantaneously to a tensile value. At few instances, F_c changed sign to reach a tensile value, which seems counter intuitive.

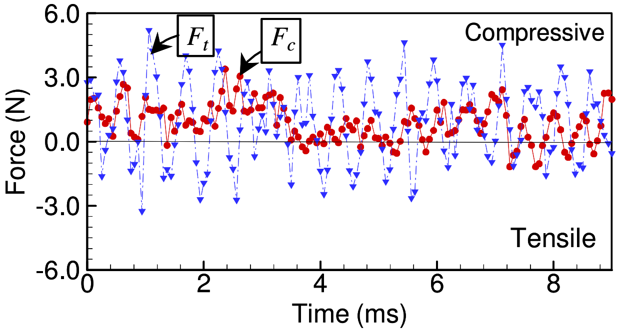


FIGURE 4. Thrust and cutting force traces for the 762 µm thick specimen. The deformation period does not have a relatively repeated period.

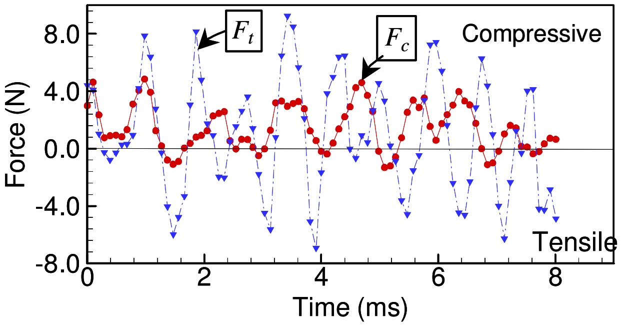


FIGURE 5. Thrust and cutting force traces for the 254 µm thick specimen. A relatively uniform deformation cycle is observed (~ 0.84ms) with the thrust force changing sign from compressive during the main deformation to tensile at the end of the deformation cycle.

Figure 5 shows a better correlated time period for the near single grit grinding. For this test, the table speed is 11.59mm/s, grinding wheel rpm=251 and depth of cut, h=12.7µm. The average deformation cycle is about 0.84ms, out of which the thrust force remained compressive for about 0.6 ms, and switched to a tensile value at the end of each cycle. There is no evidence that each grit on the wheel perimeter is in contact with the surface, instead, it seems that one in four or five grits comes in contact with the surface as there is no prevailed loading cycle with a time constant equals to the pitch time constant. The ratio of F_t/F_c ranges again between 1-3.

Figure 6 shows optical micrographs of atypical chips, collected after the grinding operation. The chip length is about 160-200 μm and thickness of 10-20μm. The chip has a very non-uniform initiation point with bulged segment that spanned about quarter to a third of the chip chord length. It should be noted that from classical grinding theory, wherein the process is assumed to resemble the milling operation, the chip length should be about 1500μm and thickness of about 2.2μm.

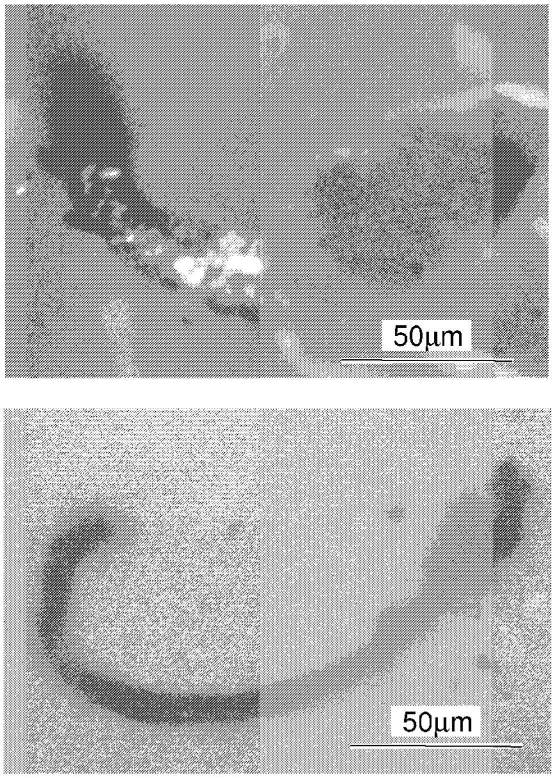
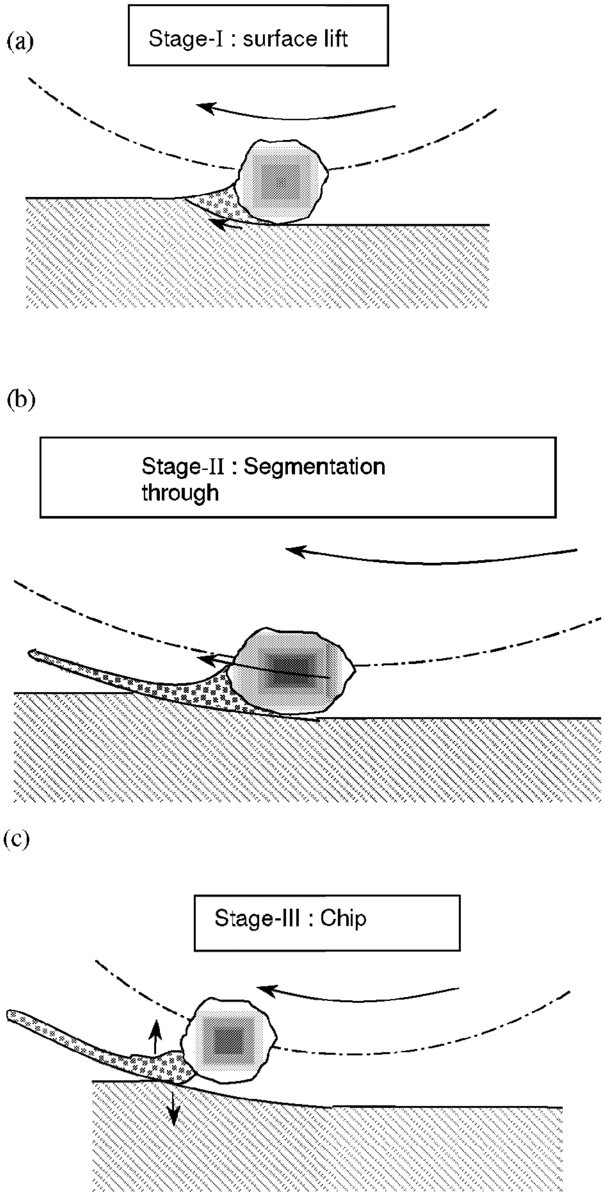


FIGURE 6. A typical grinding chip, showing the bulged front section, the thicker thickness and the shorter length.

DISCUSSION AND DEFORMATION MECHANISMS

The detailed force measurements of near single grit contact with the surface have revealed several interesting and counter intuitive features about the deformation mechanisms in fine grinding operation. (i) The chip profile is quite different from those predicted by classical grinding theories. While the chip volume is preserved, the chip cord length is at least an order of magnitude shorter while its thickness is an order of magnitude thicker. (ii) The chip has interesting bulge at its start, which may conceivable become the last contact point with the surface as indicated in Fig. 7. (iii) The thrust force change from compressive to tensile for at least a quarter of the deformation cycle. (iv) Not every grit on the grinding wheel surface is engaged in the surface cutting operation, since the prevailed deformation cycle encompasses about 4-5 grit time constants. These observations cannot be rationalized in terms of the proposed grinding models by Shaw [8, 9] and Komanduri [3, 4]. Instead a combination of these models could be the actual representation of the deformation process.



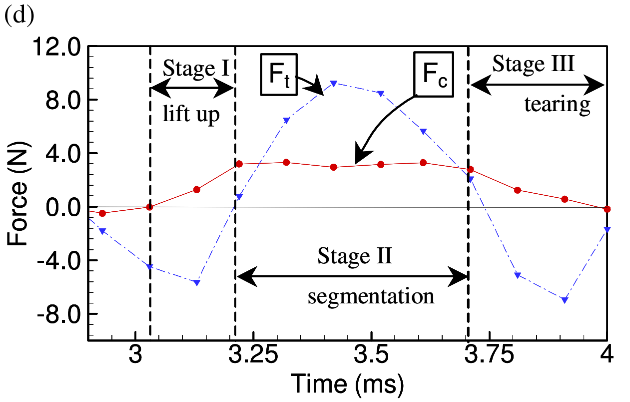


FIGURE 7. (a-c) The proposed three-stage mechanism for chip formation during fine grinding. (d) The corresponding cutting and thrust force variation during a single deformation cycle, indicating the three stages of deformation.

We propose a three-phase deformation to capture these trends as illustrated in Fig. 7. (i) Lift up of the surface ahead of the abrasive grit commenced at the initial contact of the grit and the surface. This would lead to formation of a prow ahead of the grit. This phase lasts for about quarter the cycle (300ms in the current experiment). Such deformation mechanism can be also envisioned to be similar to the Shaw extrusion model [8, 9]. (ii) A steady segmentation through micro-shear instabilities. In this regime, a shear band is formed deep beneath the grit and tunnels to the surface away from the formed prow. This process progresses with the circular grit motion for more than half the deformation cycle (about 400-500ms), resulting in a very thick chip. This deformation mechanism can be also envisioned as similar to that of Komanduri [3, 4] for micro-machining operation with a negative rake angle. (iii) Chip tearing phase commences near the end of the deformation process. During this phase, the chip has mostly curled away from the surface but still adhered to the grit. A tearing processed is commenced to separate the chip from both the surface and cutting grit, resulting in switch of the thrust force to a tensile mode. At this instant, the cutting force is almost vanishing. This phase of deformation lasts for less than a quarter of the deformation cycle. It is evident that the proposed three-phase deformation cycle will be longer than the dwelling of single grit on the surface due to the added tearing process. Such process would result in having intermittent cutting process wherein not every grit on the surface becomes active in cutting. Instead, the percentage of the active cutting grits would be approximately given by the ratio of the pitch time constant divided by the deformation cycle time constant.

The proposed the deformation mechanism has several implications on the quality of the ground surfaces, the heating cycle and thermal softening as well as on the role of cooling and lubrication fluid. The intermittent deformation zone should provide longer period for transient cooling and thereby reducing the mean temperature within the process zone. Such effect has more implications on the kinetics of subsurface grain annealing, recrystallization and growth. The role of transient heating is under further investigation utilizing infrared imaging [11]. The role of the lubricating fluid would be to reduce the adhesion between the grit and the formed chip, and thereby reducing the probability of the final chip tearing stage and the quality of the machined surface. Further studies are needed to assert the proposed tearing model and its influence on the nature of the formed chip as wheel as its dependence on the cooling fluid. Furthermore, the role of thermal softening has to be also addressed at the full grinding speed.

CONCLUSION

Detailed force measurement has been carried out during near single grit fine grinding of ductile surfaces. The force spectra and the chip configuration indicated a three-phase deformation process during each grit interaction with the surface. These are, prow formation, segmentation, and chip tearing. There are several implications of such deformation mechanisms on the thermal cycle within the process zone, the quality of the surface finish and the role of the cooling fluid.

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