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New in-situ vision-informed insights on the derivative deformation mechanisms during cutting with textured tools

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Abstract: Texturing on cutting tools is said to reduce tool-chip contact, and as a result, reduce forces and wear, and improve tool life. Though advantageous, the derivative cutting action between the chip and the walls of the texture as the chip enters and leaves the texture can increase forces and offset any potential gains. The evidence of derivate cutting is only indirect and is based on observing the underside of the chip and measuring forces. To provide direct evidence of derivative cutting, this paper reports on preliminary in-situ high-speed vision-based measurements of an orthogonal cutting process with textured tools. By processing images from video of the cutting process using digital image correlation, we observe the chip undergoes significant secondary deformation within the texture. Our observations provide new insights on happenings within the texture and can guide more detailed experiments to uncover the fundamental nature of material deformation mechanisms within the texture.

Keywords: Textured tool, derivative cutting, digital image correlation, material deformation

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1. Introduction

Texturing on cutting tools involves making patterns primarily on the tool's rake face to explicitly reduce the tool-chip contact. As a result of the reduced contact, forces and wear reduce, which improves tool life. Though advantageous, potential improvements depend on the method of making textures, the size of the textures, their location with respect to the cutting edges and each other, their features, i.e., if they are dimpled, grooved, or of some other shape, if cutting wet or dry, on the tool-workpiece material combination, and the cutting parameter regime [1, 2]. In addition to being dependent on so many parameters, it has been postulated that amongst the main reasons for textured tools not always improving cutting performance is the action due to derivate cutting [3, 4]. Derivative cutting occurs due to secondary shearing between the walls of the texture and the chip as the chip enters and leaves the texture. This secondary action can increase forces and offset any potential gains. Though the literature is replete with studies characterizing the influence of the many different texturing parameters influencing cutting performance, the evidence of derivate cutting is limited and is only indirect and is based on observing the underside of the chip and measuring forces. Providing direct evidence of the material deformation states within the texture is the main aim of this paper. We do so by observing the cutting process using high-speed video recordings and then processing that video to estimate deformation states from it.

In-situ vision-based observations of deformation states in machining processes are not new – for example, there are studies that reported on deformation in the primary shear zone and on chip flow [5, 6] and on burr formation [7]. However, there are no reports in the literature about using vision techniques to characterize material deformations when cutting with textured tools. Doing so is the modest new technical contribution of this paper.

To keep this study focused on the deformation mechanisms occurring in the texture, we limit our investigations to 2D orthogonal cutting. This is much like other such studies – see [5 - 7]. We cut steel with a relatively sharp carbide tool and make grooves that act as textures and that are parallel to the primary cutting edge. We cut at different depths of cuts and speeds. We record videos with a high-speed camera. The experimental setup and plan are detailed in Section 2 of the paper. To estimate deformations from video, we use the digital image correlation (DIC) technique. DIC is a standard technique used in experimental mechanics to estimate strains and strain rates [8]. The main idea in the scheme is to correlate displacements to how subsets within a pair of images correlate. And, if displacements can be estimated, strain and strain rates are easy enough to obtain from those displacements. To estimate displacements, strains, and strain rates, we use Ncorr - an open-source MATLAB DIC software [9]. The method of estimating deformations is discussed in Section 3 of the paper. Section 4 discusses the key results that confirm there to be significant secondary deformation within the texture of the tool, i.e., an indication of a derivative cutting action. Though our observations provide new insights on happenings within the texture, we report findings with limited experiments. We discuss this and other limitations of our setup that need to be addressed to plan more detailed experiments to uncover the fundamental nature of material deformation mechanisms within the texture.

2. In-situ vision-based experimental setup and plan

Experiments were performed on an AMS make ACER 3-axis CNC vertical milling machine. The setup is shown in Fig. 1(a). Dry orthogonal cutting experiments on this machine were performed by mounting the tool in a holder that was in turn mounted in a locked spindle and by moving the table relative to the spindle. The table speed controlled the cutting speed. We used a 16 mm diameter solid carbide tool that was ground to ensure its cutting-edge radius was less than 10 μm. The rake angle and the clearance angle were fixed to be 10^0 each. The width of the tool at 9 mm was made to be greater than the 6 mm width of the wall of the AISI 1045 steel workpiece that we cut. This was done to try and ensure that plain strain conditions that are assumed in orthogonal cutting are met. The tool's overhang from the face of the holder was kept low at 25 mm such as to minimize the tool's deflections influencing material deformation during cutting.

For cutting with textured tools, we used tools with the same geometry as non-textured tools. For textures, we made grooves on the tool parallel to the main cutting edge. The first groove was placed 150 μm away from the cutting edge. The width of the grooves was 250 μm, and the center-to-center distance between the adjacent grooves was maintained to be 400 μm. The textures were made by electrical discharge machining. Texture features and the method of making textures were based on recommendations in [1, 2]. Details of the textured tool's features are shown in Fig. 1(b).

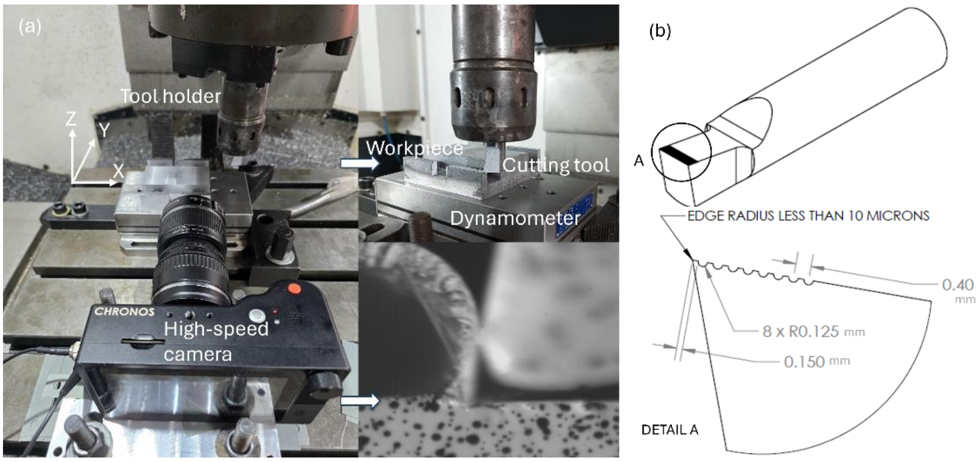

Fig. 1. (a) Orthogonal cutting and video capturing setup; (b) Geometric details of the textured tool.

With the non-textured and textured tools, we cut at two speeds, 4 m/min and 8 m/min. The maximum cutting speed in our experiments was limited by the maximum positioning feed-speed of the table in the G01 mode. At each speed, we cut at two depths of cut, 0.1 mm and 0.2 mm. Each experiment was repeated at least once. This made for a total of 16+ experiments.

To monitor the cutting process, we used a Chronos 2.1 high-speed camera. We recorded with a resolution of 800 x 600 pixels at a framerate 4352 frames per second. We used our prior experience with image magnification using extension tubes and a reverse mounted lens [10] to obtain a per pixel spatial resolution of 1.43 µm per pixel. This pixel size ensures that we can track small material motion and deformation. The camera set up with the extension tubes and lens is shown in Fig. 1(a). Since the DIC scheme works best when there are random speckle patterns on the object whose motion is being tracked, we sprayed a speckle pattern on the tool and on the workpiece. The speckle pattern is visible in a frame from the video of the cutting process shown within the inset of Fig. 1(a). To ensure the cutting zone was properly illuminated to make tracking for motion registration easier, we used a 100 W Godox SL-100D LED DC light source. And, to corroborate our observations with vision, we measured forces by fixing the workpiece onto a Kistler 9257B dynamometer. The dynamometer is also shown in Fig. 1(a).

Since it was not possible to synchronize measurement of forces with the video recordings, we recorded forces for durations longer than the video. We began force acquisition at rates of 51200 kHz before the tool entered the cut and recorded till the tool exited. Force was acquired using MATLAB's signal processing toolbox. The video was recorded by remotely triggering the camera just before the tool entered the cut and recording for some portion of the 35 mm length of cut. Video was saved on an SD card and then transferred to a desktop that had Ncorr installed in MATLAB for all subsequent processing.

3. Estimating deformations from video using DIC

To estimate deformation states from video, we used Ncorr – a MATLAB GUI-based DIC code. DIC works on the principle of estimating displacements by correlating regions within a pair of images. As such, the selection of the region of interest to correlate is important. In our case, we select the region of interest as the region encompassing the primary shear zone and at least one texture along the rake face of the tool.

And since DIC scans a subset within this region in one image with subsets on the other image, the radius of the subset too is important. Furthermore, since the subset has to be scanned over the region of interest, the step size, i.e., the spacing of the subset as it moves around the region of interest too is important. We leveraged our prior experience with Ncorr and DIC to conduct parametric analysis to find the correct choice for the subset radius and the subset spacing. We tried three radii: 20, 40, and 60 pixels, and found that the displacement fields were distorted with smaller subset radii. We hence fixed the radius as 60 pixels for analysis herein. For the subset size, we tried a spacing of 1, 3, and 5 pixels, and found that higher spacing tended to smoothen the displacement field. We hence fixed the spacing to be 1 pixel for analysis herein. Another parameter that could influence results is the radius of the strain field – that, however, was not found to be significant in our analysis.

Though deformations are captured by strain fields, estimates for strains vary with the image pairs under consideration. For example, the strain estimated between the first image and the second will be less than the strain estimated between the first image and the tenth. Since more time has elapsed for the material to flow between the first image and the tenth as compared to the time between the first and second image pairs, and even though we report strains, we prefer to use strain rates as a measure of absolute comparison between non-textured and textured tools. Since strain rates are normalized by the framerate, estimates of strain rates are independent of the image pairs used for the DIC analysis. We apply the above procedure to estimate strain and their rates for all 16+ experiments conducted.

4. Main results

Estimates for shear strain fields for a representative case of cutting with a non-textured tool and for three representative cases for cutting with textured tools are shown in Fig. 2.

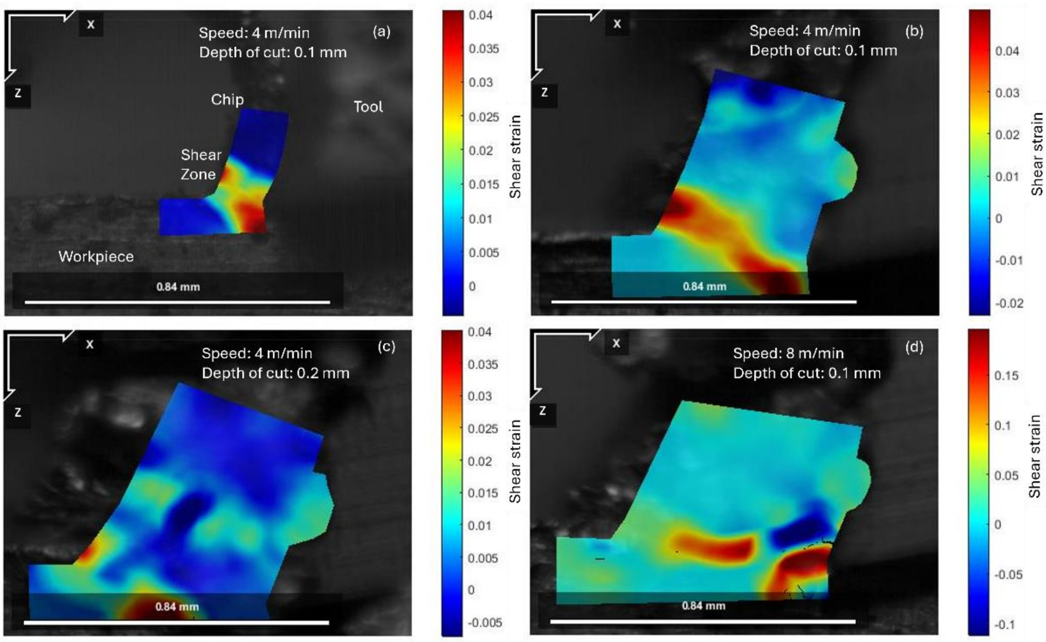

Fig. 2. Shear strains for representative cases of: (a) cutting with non-textured tool; and (b - d) cutting with textured tools.

As is evident from Fig. 2(a), for the case of the non-textured tool, the strains are highest in the primary shearing zone. This remains true even for the textured tools – see Fig. 2(b-d). However, in these textured cases, it is also clear that the chip has entered the groove and that the shear strain of the chip in the groove is almost half the value of the maximum shear strains in the primary shearing zone. This is clear and direct evidence of secondary deformation occurring in the formed chip due to potential derivative cutting action and also potentially due to the constrained area of the groove causing the material to further deform.

Blur observed in the images in Fig. 2 can be partially explained by the tool being wider than the wall of the workpiece being cut, and as such being closer to the lens than the chip and resulting is a defocus. It is also likely that there is some side spreading of material that takes place during cutting which also dynamically changes the depth of focus and causes distortions not just in the image but also in our estimates. Future work will consider constraining the side flow to ensure plain strain conditions are met.

Since Fig. 2 shows only representative results, a summary of our observations is tabulated in Table 1. The table lists averaged maximum strain rates and averaged tangential forces from repetitions of each experiment. As is evident, for both types of tools, i.e., for non-textured and textured, the strain rates and forces increase with increasing depths of cut and speeds. Forces increasing with depths of cut is expected. However, forces also increasing with increasing speeds run opposite to expectations. Usually, thermal softening due to an increase in speed reduces forces. However, since our speed changes only from 4 m/min to 8 m/min and since both these speeds are low and much lower than steel is usually cut at, we do not expect to see thermal softening and forces decreasing with an increase in speed. An increase in strain rates increasing forces is along expected lines as per most established constitutive models.

As is also evident from Table 1, we do not see a reduction in forces for cutting with textured tools. On the contrary, with the exception of cutting at 8 m/min with a depth of cut of 0.2 mm, the forces with textured tools are higher than the non-textured tools. This can be explained by the secondary deformation of the chip within the groove that likely increases forces. Interestingly, again with the exception of cutting at 8 m/min with a depth of cut of 0.2 mm, the maximum strain rates for textured tools are less than non-textured. This cannot be fully explained yet by our preliminary experiments and observations.

Table 1. Strain rates and forces for non-textured and textured tools

Cutting speed [m/min]	Depth of cut [mm]	Non-textured tool		Textured tool	
		Strain rate [s^{-1}]	Cutting force [N]	Strain rate [s^{-1}]	Cutting force [N]
4	0.1	294	565.6	217	756.2
4	0.2	495	761.7	220	784.6
8	0.1	665	975.2	537	1027.9
8	0.2	615	1116.4	1182	1072.8

5. Conclusions and outlook

This paper reported results from carefully curated orthogonal experiments that were monitored using high-speed imaging techniques to investigate the nature of deformation mechanisms prevalent during cutting with textured tools. Based on visualizing the chip flow and estimating the strain fields, we clearly observed secondary deformation of the chip within the texture confirming that derivative cutting can indeed happen when cutting with textured tools. Such direct evidence of the derivative cutting action is the main new technical contribution of this work.

We observed that forces in general increased for cutting with textured tools as compared to non-textured tools. Though this runs contrary to many reports on texturing, we think that the increase in forces can be attributed to the derivative cutting action. Oddly, we observed the strain rates to be lower for cutting with textured tools as opposed to non-textured tools. We cannot completely explain this yet. Since we observed some blur in our images that could distort our analysis, we think that future work should forcibly constrain the side flow of material. We also think that our findings can guide more detailed experiments to uncover the fundamental nature of material deformation mechanisms within the texture.

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