

Single Point Diamond Turning of CVD coated Silicon Carbide

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ABSTRACT

Scratching experiments, using diamond styli and single point diamond tools, were performed to simulate Single Point Diamond Turning (SPDT). The results of these experiments were used to determine if a ductile response is possible, and then to determine the critical depth of cut or penetration depth for the ductile to brittle transition (DBT). The depths of the scratches produced at different loads were measured and correlated to the ductile and brittle response of the material. The DBT depth for Chemically Vapor Deposited (CVD) coated Silicon Carbide (SiC) samples was determined. The analysis for the critical depth (DBT) did confirm the possibility for SPDT of CVD coated SiC in the ductile regime. These results were further used for SPDT of CVD SiC.

Post experimental analysis of the machined surface did reveal a final surface roughness of 8-20nm, successfully demonstrating ductile regime machining of CVD coated SiC.

INTRODUCTION

Machining of brittle materials has reached a level where the focus is turning towards commercial applications. CVD SiC is an excellent reflective optics material, exhibiting superior polishability with low scatter. Since optics applications are a high priority for this material, the surface roughness of the finished CVD SiC should be less than 60 nm. This level of surface roughness is achievable by processes like polishing and lapping. A problem that persists with polishing or lapping is the resultant figure error, primarily flatness or form error deviations. The larger the diameter or size of the piece, the more difficult it is to maintain the flatness with traditional processes. Hence to overcome the limitations of these processes (polishing and lapping) investigation of single point diamond turning (SPDT) was pursued and is reported in this paper.

Determination of the DBT depth of CVD coated SiC (from Poco Graphite) using scratching tests (simulated machining), preceded the actual machining experiments. The detailed explanations of scratching experiments have been divided into different sections corresponding to the experimental plan and materials. Two major sets of experiments were performed to determine the DBT depth

using an instrumented micro tribometer. One experiment involved scratching using a diamond stylus and the second one used an inclined plane experiment in which a flat nose diamond tool was used to make a scratch. The inclined plane experiment was conducted only on the Poco Graphite sample.

A comparison was made between the resultant surface (ductile/brittle) and the force data derived from the tribometer. The speeds of the scratches were kept slow at 0.005 mm/sec to minimize thermal effects. Our primary goal was to demonstrate that SPDT of brittle materials like SiC is possible. Hence a 6 inch diameter SiC piece was machined and reported on herein. The piece was supplied by Poco Graphite Inc.

These experiments were executed using a Universal Multi System Tribometer (UMT) from CETR Inc. Unlike precision lathes, a tribometer is typically used for experiments concerning tribological applications. One difference between precision lathes and the tribometer is that precision lathes are displacement based machines and tribometers are load based devices. Chemical mechanical polishing (CMP) fluid was used as a cutting fluid for these experiments to reduce tool wear. The single crystal diamond tools used for SPDT of CVD coated SiC did not show appreciable wear on their cutting edges. The use of the CMP slurry as a cutting fluid most likely provided this positive benefit, i.e. the fluid acted as a lubricant and possibly provided some chemical enhancement. Future work will involve higher cutting speeds to investigate productivity capabilities and enhancements. The post experimental analysis, which primarily included depth measurements of the scratch, used a white light interference microscope (Wyko RST). The data shown for x and y profiles within the Wyko image were averaged for completely ductile scratch profiles. The DBT and the brittle fracture profiles are not averaged as they have the presence of both ductile and brittle behavior.

PRE-SCRATCHING PROCESS

The CVD coated SiC as received from Poco Graphite Inc) had a very high surface roughness as shown in Table 1. Initial calculations for DBT depths for CVD SiC revealed the

critical depth to be approximately 40 nm. Hence scratching a rough surface to find a DBT depth of 40-50nm was difficult if not impossible for the as received sample (with surface roughness > 500 nm, i.e. more that 10x the estimated DBT depth). Secondly, imaging was a problem with the high surface roughness, as it is difficult to image dull surfaces under white-light microscopes, which we were using for determining the scratch depths and confirm/determine the DBT. Thus polishing of these CVD coated SiC samples was done to improve the starting surface roughness (polishing performed by RAPT Inc). The resultant surface roughness values for both samples are also shown in table 1.

Vendor	Original Surface Roughness (nm)	Final surface Roughness after polishing (nm)
Poco Graphite Inc.	1200	<100

Table 1. Surface roughness details of CVD coated SiC samples

SCRATCHING USING A 5µm DIAMOND STYLUS TIP

A 5µm radius diamond stylus was used for making scratches on the surface of CVD coated SiC. This diamond stylus was moved over a span of 5mm on the sample with continuously increasing loads using the load control mode in the tribometer. The loads were varied from 10 to 25 grams for the Poco Graphite sample.

RESULTS FROM SCRATCHING USING A 5µm TIP

The maximum ductile scratch depths that the Poco Graphite sample achieved were 700nm, which can be seen in figure 1. It is revealed from the peaks seen in the X-profile (upper right image) of the Wyko images that depths beyond this would be brittle, as the material is seen breaking up and moving out of the surface. The Y-profile (lower right image) is taken in the ductile region of the scratch, before the DBT is reached. There are two areas on the surface of a sample where ductile to brittle transition can take place. One is in front of the tool (at lower depths) and one is behind the tool (at higher depths). The DBT depth (approx. 700 nm) shown in this sample certainly is behind the tool as the material is pushed up above the surface-in the wake of the tool.

The large peak (encircled region) seen in the X-profile of figure 1 suggest the occurrence of brittle fracture in this region of the scratch. If the scratch is ductile there is usually material piled up on both sides of the scratch (as shown in fig 1, Y-Profile) unlike brittle fracture where the material moves above the surface of the sample unevenly. The forces (normal and tangential) were also measured along with the acoustic emission data using the tribometer. These data are shown in figure 2. The AE sensor was mounted on the tool holder away from the contact point of the diamond stylus and the surface of the sample. Hence it was difficult for the AE sensor to pick up signals from the brittle fracture. The forces shown are not for the entire scratch. The force plot exactly corresponds to the region of the scratch shown in figure 1. It is difficult to determine any difference in force values as the

brittle fracture occurred behind the tool. Typically fracture behind the tool is not seen in the force plots, as it is outside the sensor’s measurement loop. To measure the force impulse from a major fracture event behind the tool usually requires additional sensitivity and/or instrumentation.

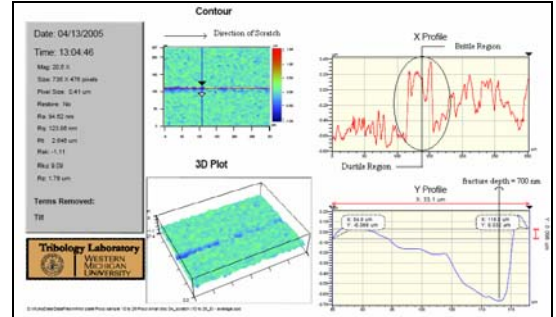


Figure 1: Wyko image showing DBT depth behind the tool for Poco Graphite sample using 5µm diamond stylus

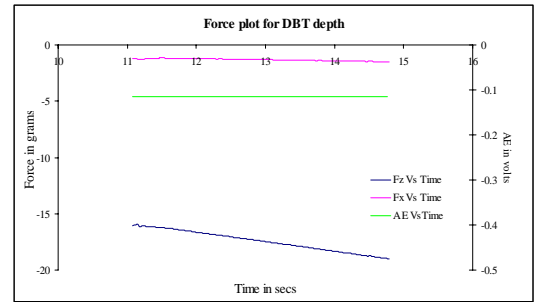


Figure 2: Force and Acoustic Emission (AE) data for Poco Graphite sample Further experiments were performed to determine the DBT depths (in the wake of the tool) after polishing the surface roughness down to <10nm RMS.

SCRATCHING USING A 12.5µm STYLUS TIP

The Poco Graphite sample which was used for scratching with a 5µm tip stylus showed a brittle fracture behind the tool at 700 nm. Thus the DBT depth was likely to be with < 700 nm for the Poco Graphite sample. Hence to determine the actual DBT depth the scratching experiment for Poco Graphite sample was also revisited. The 12.5 µm diamond stylus was also used for this experiment, with a load range was 80-120 grams.

RESULTS FROM SCRATCHING USING 12.5 µm TIP

The scratches made on the Poco Graphite samples were divided into three major parts, one is the ductile region (figure 3, 4 and 5), the second is the DBT region for both scratches, and the third is the brittle region after the transition occurred (figures 6, 7 and 8). Figure 6 shows the force and AE plot for DBT depth of the Poco graphite sample. The encircled region is where the AE plot shows a rise and the frictional/cutting force (Fx) values decrease, indicating brittle material behavior. The scratch beyond this depth was completely brittle, which is shown in figure 7.

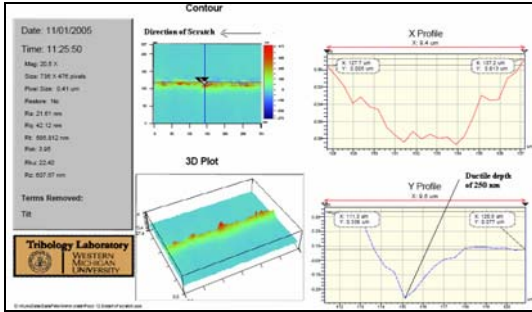


Figure 3: Wyko Image of starting (ductile) portion of the scratch on Poco Graphite sample using a 12.5µm stylus

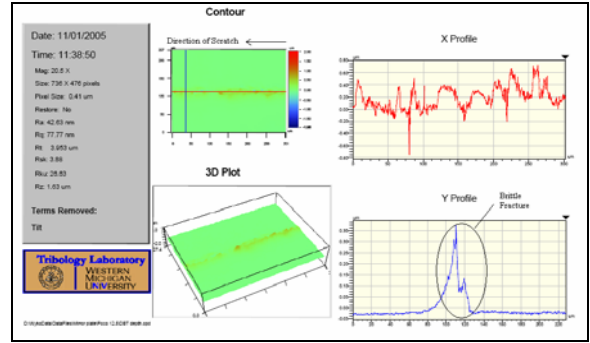


Figure 7: Wyko Image showing brittle fracture after the DBT region on Poco Graphite sample using a 12.5 µm diamond stylus

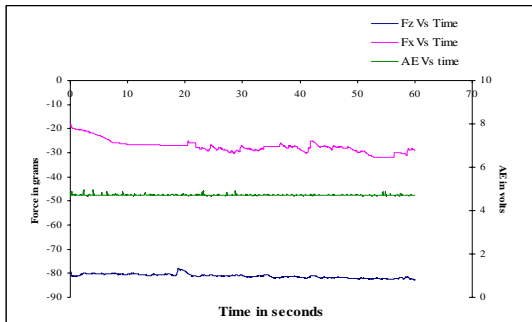


Figure 4: Force and AE plot for starting (ductile) portion of the scratch on Poco Graphite sample using 12.5µm diamond stylus

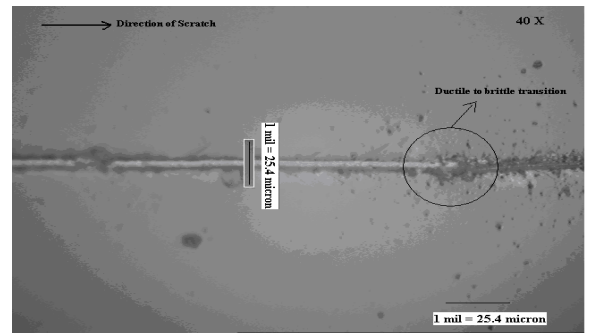


Figure 8: Optical image showing ductile to brittle transition of the Poco Graphite sample using 12.5 µm diamond stylus

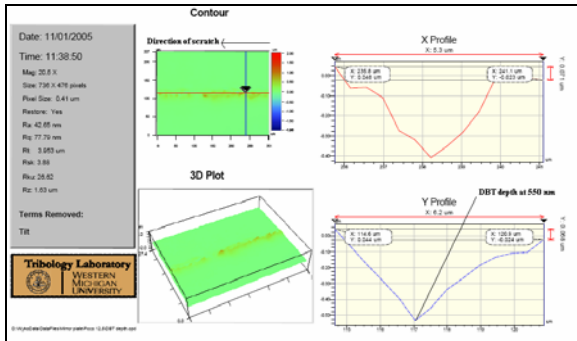


Figure 5: Wyko Image of DBT depth (550 nm) for Poco Graphite sample scratched using 12.5 µm diamond stylus

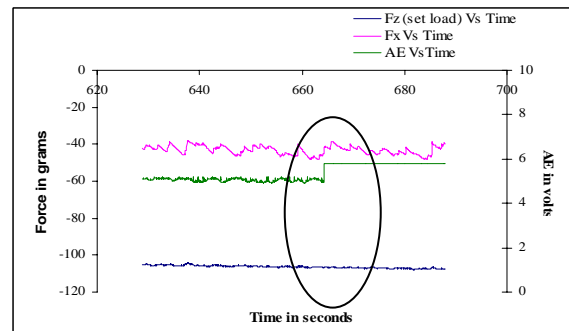


Figure 6: Force and AE plot for DBT depth (550 nm) in Poco Graphite sample using 12.5µm diamond stylus

Figure 8 above shows an optical image of the DBT of Poco Graphite sample using a 12.5µm diamond stylus.

PRE-MACHINING PROCESS

The 6 inch Poco Graphite sample was sent to, RAPT Inc. for polishing. The surface roughness of the sample was reduced from 700nm to less than 10nm (Ra). The sample was polished to minimize two major difficulties.: 1) to reduce tool wear, as significant tool wear was expected while machining larger samples, and 2). to reduce the machining time, as machining a polished surface would not require more than one pass to achieve the required surface roughness and demonstrate the feasibility of ductile regime machining of CVD SiC using SPDT.

MACHINING PARAMETERS

The speed for machining, i.e. the cutting speed, was kept slow at 0.001 mm/sec (60 rpm). The reasons for keeping the speed slow were:

- To avoid any thermal effects created at the contact point of the tool and CVD SiC
- The tribometer has a flexure design for the tool holders; at higher speeds the flexure is not stiff enough to sustain the forces generated during machining, therefore requiring slow speeds to avoid dynamic effects such as chatter.

The CVD SiC was mounted on a rotary spindle, which has a maximum speed of 5000 rpm. Trial experiments on single

point turning of aluminum were performed to measure the limitations of the tribometer. The experiments revealed that the tribometer was stable at lower spindle speeds, usable speeds being less than 100 rpm, to avoid tool chatter.

The tribometer is a load/force based machine. Calculations were done to predict the weight or load that should be programmed to achieve the desired depth of cut. Initial experiments did reveal the DBT transition depth for Poco Graphite CVD SiC as 550 nm. The tribometer's performance was limited to low speeds for stable operation as a cutting machine (note this is not the machine's intended use). Hence to keep the speeds low and also achieve ductile cuts, the final feed was selected to be 1 μm/rev, the spindle speed was 60 rpm and a maximum cutting velocity of 0.24 mm/sec, at an estimated depth of 500 nm,

EXPERIMENTAL SET UP FOR SPDT OF CVD SiC

SPDT of CVD SiC was done using the tribometer. A 500 gram load cell was used for the experiment. A single crystal diamond tool was used for this experiment. The nose radius for the tool was 3mm, rake angle of -45 deg and a clearance angle of 5 deg.

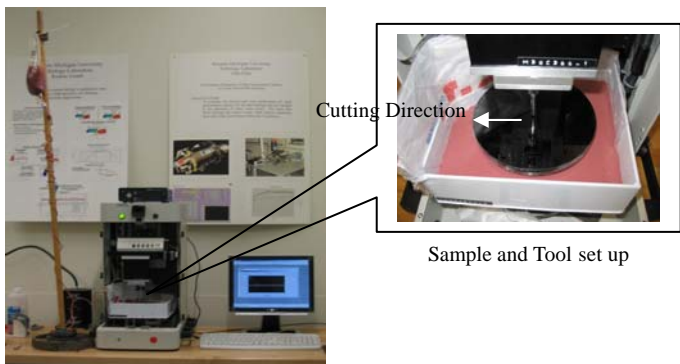


Figure 9: Experimental setup for SPDT

Chemical mechanical polishing (CMP) slurry was used as the cutting fluid (Buehler Inc. Master Polish 2, 40-6376-032). Figure 9 shows the experimental set up for SPDT of CVD SiC. The cutting direction was fixed from the center (inside) to outside. The coolant was deposited over the surface of CVD SiC sample using a drip system (similar to a thin film spin coating system).

RESULTS OF SPDT CVD SILICON CARBIDE

Machining Time:

The total machining time was 21 hours resulting from the fact that the feed-speed was slow at 0.001 mm/sec (1 μm/rev at 60 rpm), and the part was 6" in diameter.

Surface Roughness:

The surface roughness values were measured after machining using a Wyko RST white light interference microscope. Figure 10 shows the mirror finish achieved after ductile machining the CVD coated SiC. Post experimental analysis of surface roughness values using the Wyko RST is as shown as a CAD drawing in figure 11. The reason for having

more than one region of machined surface over the 6 inch CVD SiC plate was due to the machining process being temporarily interrupted about mid way through the machining operation to modify the coolant dispensing/collecting system. Wyko RST images, shown in figure 12, do compare well with the machining results, showing uniform feed marks for region 2 and a rougher surface (not as uniform) in region 1. The unmachined region is also shown for comparison of the surface before and after machining. In the final product, the feed marks (region 1 and 2) would be removed by a finish polishing operation to eliminate the fine surface texture generated during SPDT.



Figure 10: Picture showing the optical quality of surface finish on the machined CVD SiC sample

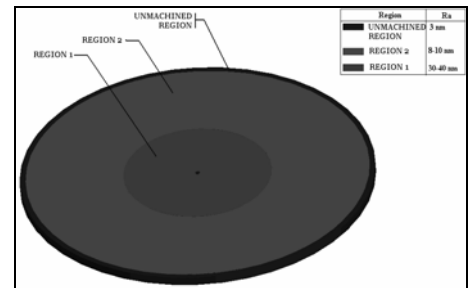


Figure 11: CAD model showing the surface roughness distribution on the 6inch CVD SiC plate

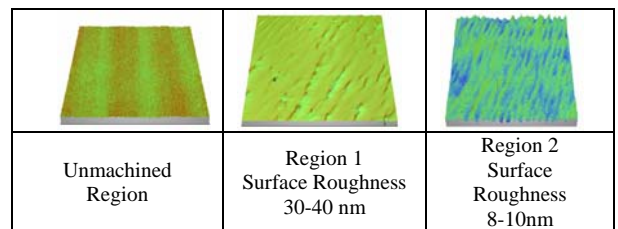


Figure 12: Wyko Images comparing before and after machining

Tool Wear:

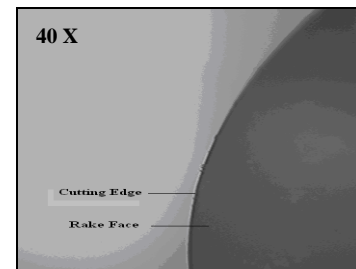


Figure 13: Optical microscope Image of tool edge after machining

Figure 13 shows an optical image of the tool edge used for SPDT of CVD SiC. There is no chipping or fracture on the cutting edge of the tool, and the abrasive wear is minimal. Due to minimal wear at the tool edge, the tool can be resharpened and used again for future experiments. Hence the usage of CMP slurry as the cutting fluid did seem to enhance the tool life to a great extent.

Depth of Cut:

Table 2 below shows the difference between estimated and actual depth of cut from machining.

Region	Expected Depth of cut	Actual Depth of cut
Region 1	500 nm	350 nm
Region 2	500 nm	200 nm

Table 2: Comparison of programmed and achieved depth of cuts

The tribometer used for SPDT of CVD SiC is a load/force based machine and it incorporates a flexure design for the tool/stylus holders. The flexure results in deflection in the sensitive direction (in-feed or depth) compared to a DTM, which are generally displacement based controlled. The tool was removed and repositioned between the region 1 and 2 cuts (to solve a coolant related problem). The difference in depth of cut and the resultant surface finish between regions 1 and 2 might be due to remounting of the tool. The calculations of the expected depth of cut (500 nm) were only estimates and did not include the effect of the cutting edge radius. At this time these effects have not been analyzed to the fullest, work is being done to fully characterize the cutting conditions.

Figure 14 compares the actual measured depth of cuts with the surface roughness values. Region 2 with a smaller depth of cut produced the better surface finish as would be expected. Region 1 with higher depth of cuts produced high surface roughness values.

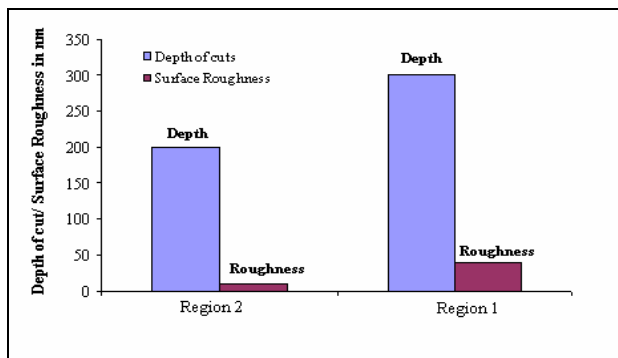


Figure 14: Comparison of depth and surface roughness data

Feed/ Rev:

The programmed feed/rev was 1 μm/ rev. Figure 15 shows the actual feed/ rev from machining in region 2 (figures

11 and 12), taken using an optical microscope. The scale on the image confirms that the actual feed/rev after machining was the same as the programmed feed i.e. there are 10 feed/marks per 10 μm distance.

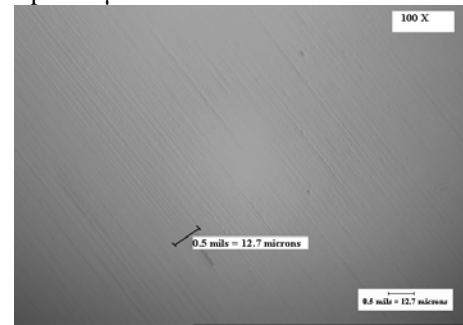


Figure 15: Optical image of the machined surface showing the actual feed/rev for region 2

DISCUSSION

The DBT depth for the Poco Graphite sample was found to be 550 nm. The calculated depth for the DBT (40 nm) did not correspond well to the actual DBT depth.. The difference in actual and calculated DBT depth might have to do with the fact that the grains in the CVD coated SiC are grown in a particular or preferential direction (the grains appear oriented normal to the surface). These grains most likely have directional properties similar to single crystal SiC, which might be a reason CVD SiC was ductile at 400 to 550 nm, as compared to the calculated DBT of 40 nm.

The surface roughness of less than 20 nm was achieved on the 6 inch CVD coated SiC disk. The machining speed was kept slow to minimize chatter and to nullify thermal effects between the tool and the material. Tool wear analysis was not an objective of this study; hence detailed tool wear analysis will be reported in future work. However, the tool wear did appear to be minimal and not substantial. The material removal calculations do suggest that the use of coolant has helped sustaining the cutting edge of the tool, even when machining a large diameter piece.

CONCLUSION

Scratching has proved to be a useful experimental basis for understanding qualitatively and quantitatively the ductile and brittle mode behavior of CVD SiC, and the resultant DBT, that are encountered in machining and other similar deformation processes. [9] The experiments also show the dependence of loads, surface roughness, and stylus geometry, relative to the quantities that characterize a scratch (load-depth profiles and the DBT). Ductile regime SPDT of CVD SiC was possible, achieving the required surface roughness value of less than 60 nm. Further optimization of the process parameters are required for enhanced machining of CVD SiC. The potential replacement of intermediate processes like grinding, polishing and lapping, by SPDT, would reduce the total manufacturing cost by increasing productivity and improving surface form accuracy.

ONGOING WORK

Presently work is being done on SPDT of unpolished CVD coated SiC samples from Poco Graphite Inc. and a laser machined sample from Mount Laser Inc. The chart below (figure 16) shows the number of passes made on the surface and the corresponding surface roughness achieved after each pass. The machining parameters used for SPDT of these samples are exactly the same discussed above for the 6 inch Poco Graphite sample. However, these cuts were all performed dry, without the benefit of a cutting fluid; and are thus considered “worse case” conditions. The estimated depths (based upon the programmed loads) of cut for the samples are 500 nm but the actual depths are 200-300 nm similar to that seen in the 6 inch sample. More details regarding the SPDT of these samples would be reported in future work.

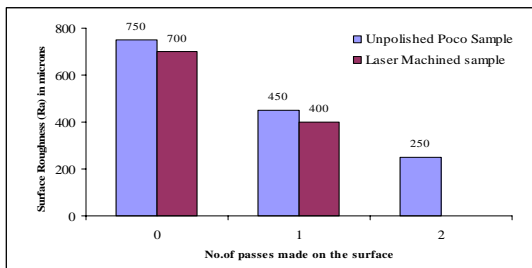


Figure 16: Chart showing surface roughness achieved for different samples after each pass of machining

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