The effect of diamond geometry and wear on rotogravure engraving

Andy Clist, Mark F. J. Bohan and Tim C. Claypole*

Keywords

Gravure, Engraving, Process Control

Abstract

The geometry of the diamonds used in engraving of the rotogravure cylinder effect on the shape and volume of the cells engraved. The angles of the diamonds have previously been measured using a projected shadow technique. The volume of the cells is estimated by measuring the width of the open area and assuming the cell geometry. No allowance is made for diamond wear or subtle variations in geometry. The effect of machine variation in the engraving of gravure cylinders is part of a research programme on gravure printing in the Welsh Centre for Printing and Coating. White light interferometry was used to measure the precise shape of individual diamonds and hence the condition of the diamond, in terms of its angle, the condition of its face surface, the wear of edges and the wear of the tip.

Despite the hardness of the diamond and the inherent softness of the copper, the diamond was found to wear over the engraving of a number of cylinders. Although the wear was small, when considered against the cell depth in engraving, the change is significant. The diamond was wearing at the tip with the characteristic wear patterns normally associated with metal machine tools. The stylus angle was also found to decrease with use compared with the rear surface of the diamond, which was used as a reference, as it is not subject to any abrasion during the cutting process. The effect of wear on cell volume and its implications for engravers is discussed in the paper.

Introduction

One of the most common methods of manufacture of cylinders for rotogravure printing is electromechanical engraving using a diamond stylus to peck the cells

*Welsh Centre for Printing and Coating, Swansea University

in the copper layer to produce the desired image. The angle of the stylus determines the internal geometry of the cell. The external dimensions of the cell are determined by the screening and the need to eliminate Moiré. The selection of a stylus angle will depend on many parameters. Small stylus angles produce larger cells (due to their more pointed nature), which will transfer more ink, and are used where the transfer of the maximum amount of ink possible is desirable (for the strongest, most vivid colours). Larger stylus angles last longer and produce smaller cells, minimising the amount of ink that is required to print the image.

The volume of the cells can be estimated by measuring the width of the open area, the depth and assuming the cell geometry. The engraved cell is assumed to be an inverted truncated pyramid whose angle is identical to the stylus angle, θ (Fig. 1). As stylus angle is increased, solid density decreases. This is largely due to the reduction in volume, which occurs as stylus angle increases. The effects of varying stylus angle on cell volume whilst keeping cell width and length constant are shown in Figure 2. As the stylus angle is increased, the volume and cross sectional area of the cell decreases significantly, with a 140° stylus engraving a cell with only approximately half of the cross sectional area of a 110° stylus and two thirds of the volume.

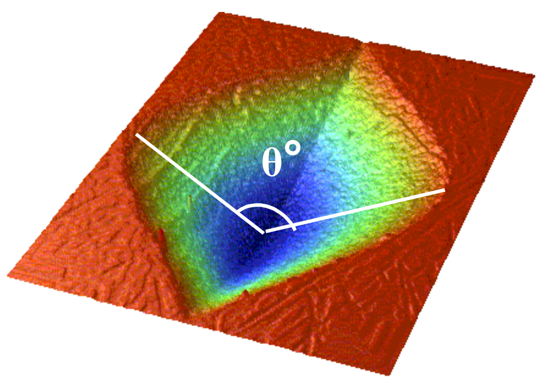


Figure 1. Typical gravure cell measured by white light inteferometry

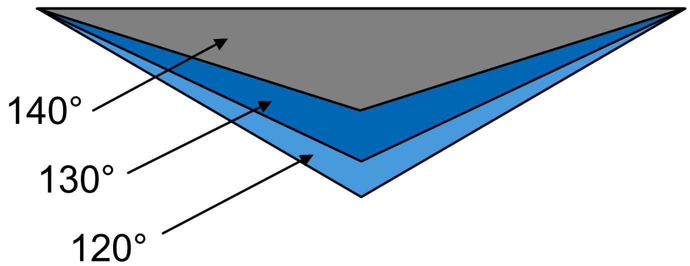


Figure 2. Schematic of the effect of stylus angle on maximum cross sectional area

Most on line quality assurance for engraving is based on measurement of the area of the cell. The depth and width of the cells are directly linked by the stylus angle of the diamond. Thus, the depth is inferred from the stylus angle/width correlation and volume by the stylus profile. This assumes there is no elastic recovery of the copper after engraving, the stylus angle of the diamond is fixed at its defined angle, and no wear has occurred. Thus, for the same cell width, the volume of the engraved cell is dictated by the stylus angle. If the stylus angle is not within specification or varies during production then the cell volume will not be as specified by the colour management system.

The lowest point in the cell is not precisely in the middle of the cell. The pivoting action of the engraving head serves to produce a cell with a characteristic offset of the deepest point (Fig. 3). The offset angle defines the angle between a vertical line from the bottom of the cell and the line joining the bottom of the cell to the geographical centre of the cell. The diamond is rotated into the copper about the pivot point. As a result, the diamond tip does not execute a straight line as it enters the copper, but a curve. This also affects the cutting angle of the diamond and wear on the cutting surfaces.

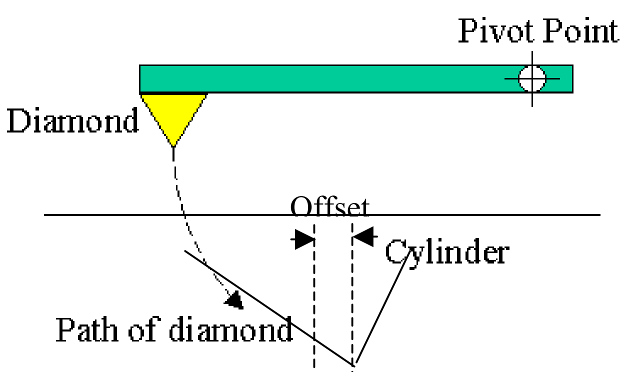


Figure 3. Asymmetry of gravure cell due to pivot and offset of diamond

Inherent variation in the diamond and changes due to wear are potential sources of differences between engravings. This paper describes the use of white light inteferometry to define the shape and hence the condition of the diamond. The variation in stylus angle for both new and stylus in service was evaluated and compared with the nominal values.

Methodology

A typical engraving diamond in its mount is shown along with an engraving head in Figure 4. Historically, diamonds have been examined in terms only of their angle, measured using a shadowgraph. This has limited accuracy and cannot resolve details of wear etc. White light inteferometry was used to measure the precise geometry of the engraving diamond and hence the condition of the diamond, in terms of its angle, the condition of its face surface, the wear of edges and the wear of the tip.

Figure 4. Engraving Head and Diamond

Stylus angles were calculated manually from interferometric measurements (Fig. 5). The alignment of the two sides of the cutting face (a and b), were measured manually. As well as cutting on the front face of the diamond, during the engraving process, the stylus head rotates pushing surface a into the copper. Surface b rubs on the surface of the engraved cell and dictates the shape of one side of the cell, but is subject to friction wear only. A second test examined the angle with reference to a fixed surface, c, of the diamond that never enters the copper surface of the cylinder, so should never experience wear, and therefore provides reference surface for comparison of the other sides. The angle φ was calculated and provides a reference over the life of the diamond. The repeatability was found to be 0.1˚

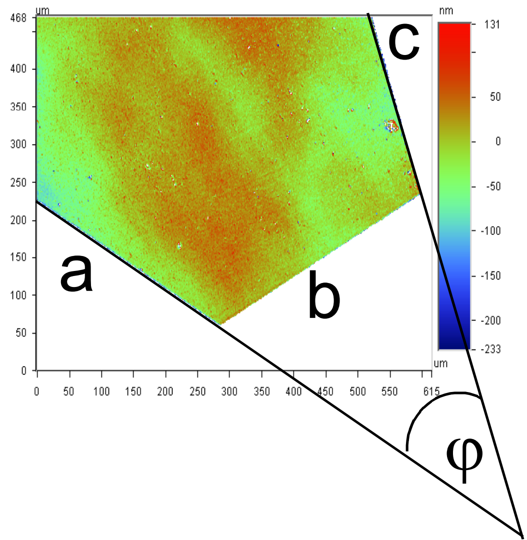


Figure 5. Profile geometry of the engraving diamond

An initial assessment was made of the inherent variation in the angles of new diamond styli. 5 diamonds were measured with a nominal 125° stylus and tolerance of ±0.5° (Figure 6). Two were found to be outside of the specification. Applying Hartley's theory to estimate the standard deviation based on the range (i.e. the difference between the largest and the smallest value for a sample size of 5), the standard deviation, $\sigma = 0.5$. On this basis, only 68% of the new diamonds would be within tolerance. Thus, the only way to ensure the diamonds met the specification would be 100% inspection, i.e. measure each one.

Typical profiles for new and used diamonds are shown in Figure 7. The new diamond has straight sides and a well-defined, clear tip, whereas the used diamond has evidence of wear on both the sides and to the tip. In preliminary measurements, for a nominal stylus angle of 120° stylus, the new diamond had an angle of 120.4°, the angle increased to 121.1° after engraving 6 cylinders, changed to 121.0° after 12 and eventually 117.9˚ at which point the diamond had to be reground. This decrease in angle probably represents the effect of wear on the tip itself.

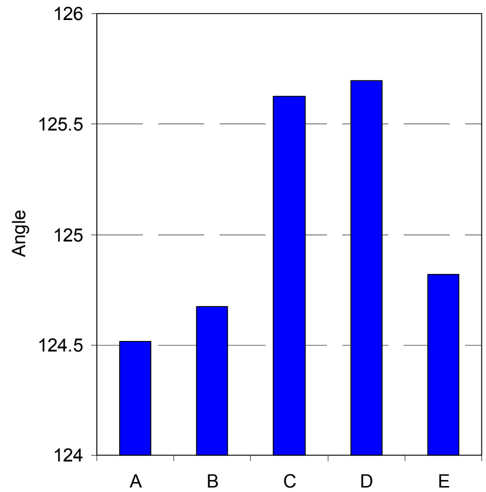


Figure 6. Measured angle of 5 new diamond styli

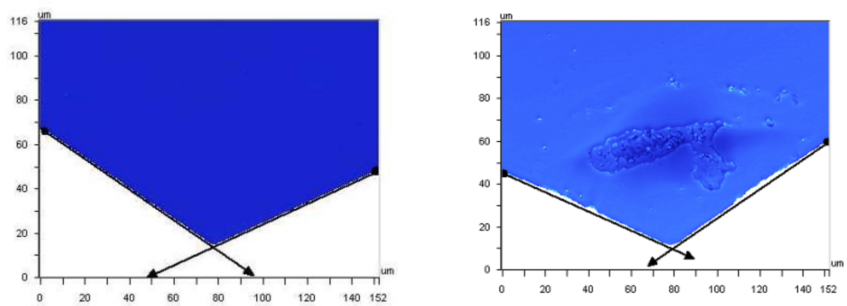
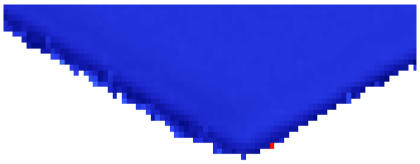
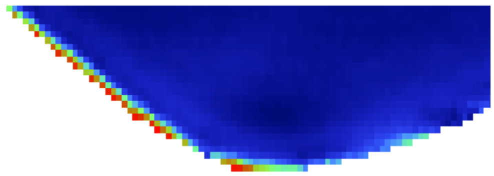


Figure 7. New (left) and used (right) diamonds

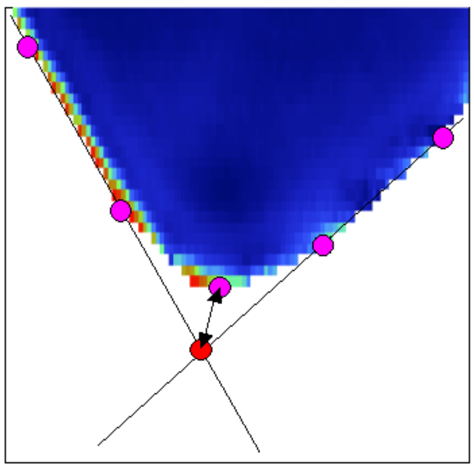
Wear of the diamond at the tip is shown in more detail in Figure 8. The tip has become rounded with use. To estimate how much the position of the tip has changed, the position of four points, two on each side of the diamond were measured, thus allowing a 'theoretical tip' point to be calculated. The 'lowest' point of the diamond was also be measured, and the distance between this actual tip and the theoretical tip calculated. The distance between the theoretical tip and the actual tip for a new diamond was measured in the preliminary work on 120° stylus and found to be 0.38µm. The distance increased to 1.26µm after 6 cylinders had been engraved, 2.40µm after 12 cylinders and 4.70µm at the point at which the diamond was taken off the engraving machine and reground.



8a – New tip



8b – Used tip



8c Geometry used to calculate tip wear

Figure 8 – Wear of diamond tip

This preliminary investigation showed that the diamond was wearing with use, with both the angle and the tip geometry changing during the life of the diamond. Thus, having identified that wear was occurring and that it could be consistently quantified, a systematic investigation of diamond tolerance and wear was undertaken, which is described in the next section.

Results

The stylus angle of 25 new diamonds were measured (Figure 9). These cover a range of nominal angles from 90˚ to 150˚. The graphs are colour coded with blue for within specification and red for outside specification. The majority are outside of the specification, this would suggest the standard deviation is higher than found in the preliminary work.

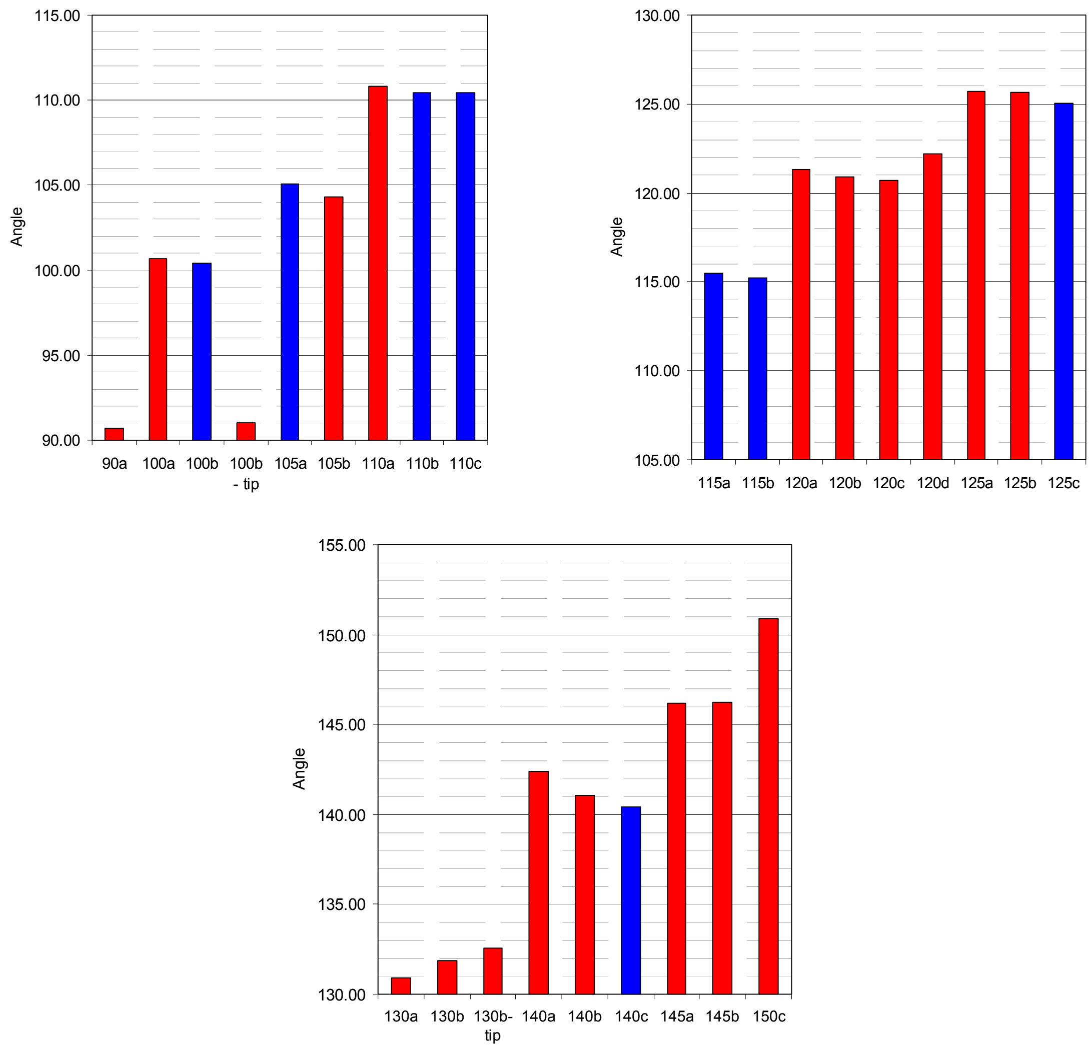


Figure 9. Measured stylus angle for nominal values from 90˚ to 150˚

Diamond wear was evaluated on three diamonds of 105˚, 110˚ and 120˚ that represent the mid range of those used. The diamonds were measured when new (set A) and then at two weeks and four weeks of continuous use (data sets B and C, Figure 10). There was a steady increase in angle with time of on average 0.4 degrees. The 105˚ was taken off the machine as it had become damaged and ceased to engrave before the end of the experiment.

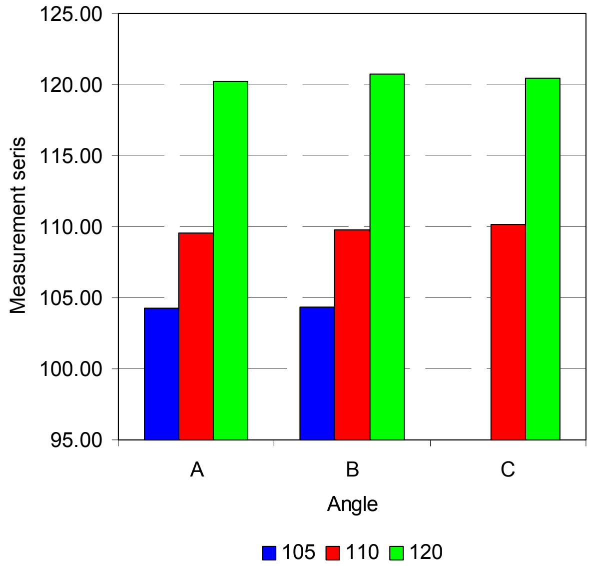


Figure 10. Change of stylus angle with use

A detailed view of a new diamond stylus is shown in Figure 11. The stylus comes to a well-defined point with straight sides. The front surface of the diamond is flat and shows the marks of the engraving process (parallel lines running across the face of the diamond. There are occasional defects, but on the whole these are fairly minor.

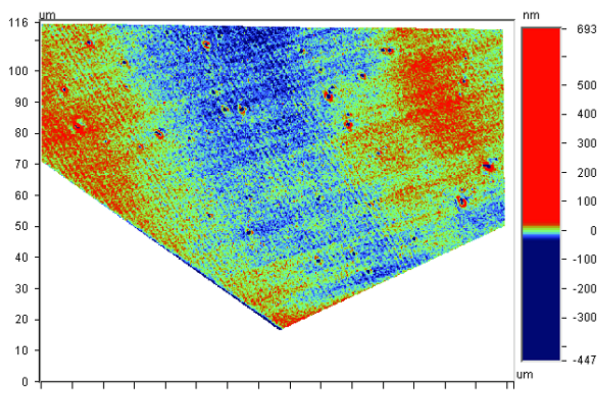


Figure 11. Surface profile of new diamond stylus

By contrast the edges of the worn diamonds (Figure 12), have irregular wear marks and are no longer straight. This reduction in angle and localised wear on the side faces will lead to the diamond removing less material in each peck and therefore the cells even if of the same width will be reduced in volume. There is evidence in figure 1 that the cell walls would appear to be ridged, representing a negative the image of the profile of the diamond being carved into the surface of the cell. All the grinding marks have been worn from the surface of the used diamond. There is also a crater formed behind the cutting edge (the hollow appearing dark blue on the contour plots).

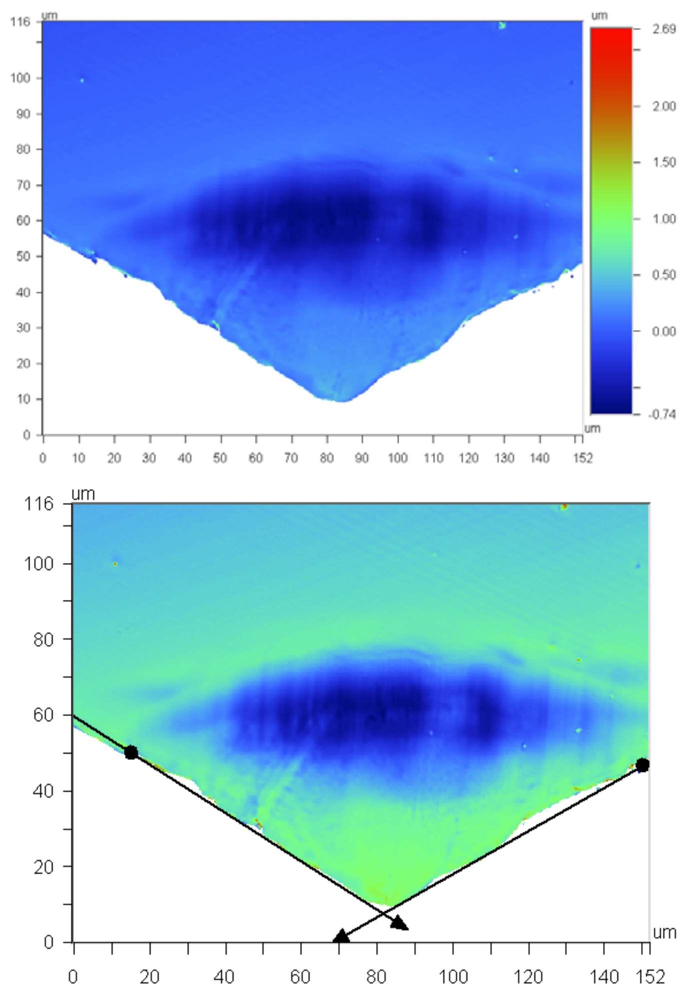


Figure 12 Contour plots of worn diamond styli

The edge wear occurs on both sides of the stylus (Figure 13). This is caused by the movement of the copper being cut over the surface. This is similar to flank wear in conventional metal cutting and is caused by the friction between the tool and the cut surface. It is reduced on the left hand side. This difference, observed on all styli, is a consequence of the pivoting action of the engraving mechanism, causing more force on one side than the other. There is a large increase in the wear on the flanks during the cutting of the first six cylinders and little change in geometry through the rest of the tool life. This may explain why in the preliminary work the angle increased initially, before decreasing with use.

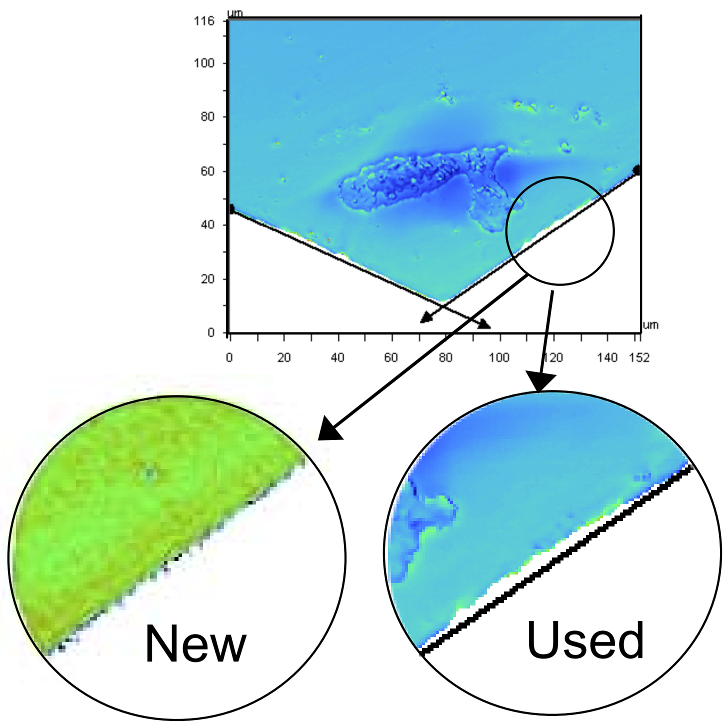


Figure 13. Comparison of new and used diamond flanks

There is a crater formed in the used styli that is set back slightly from the tip edge (Figure 14). This is a well-established phenomenon in metal cutting. The cutting process produces very high level of shear in the metal. The forces exerted at the tip are sufficient to cause the metal to shear in the body of the material. The very high friction induced between the metal and the stylus, means that at the tip the friction is very high and there is no relative movement between the tool and the metal adjacent to the surface. Therefore, with little or no relative movement, there is an area immediately behind the cutting tip where no wear occurs. However, slightly back from the tip, the friction force reduces and relative movement occurs between the stylus and the chip of metal removed in the engraving process. This leads to the formation of a wear crater. The crater increases with use, typically being 0.3μm deep after engraving 6 cylinders, 0.5μm deep after 12 and 0.8μm after 18.

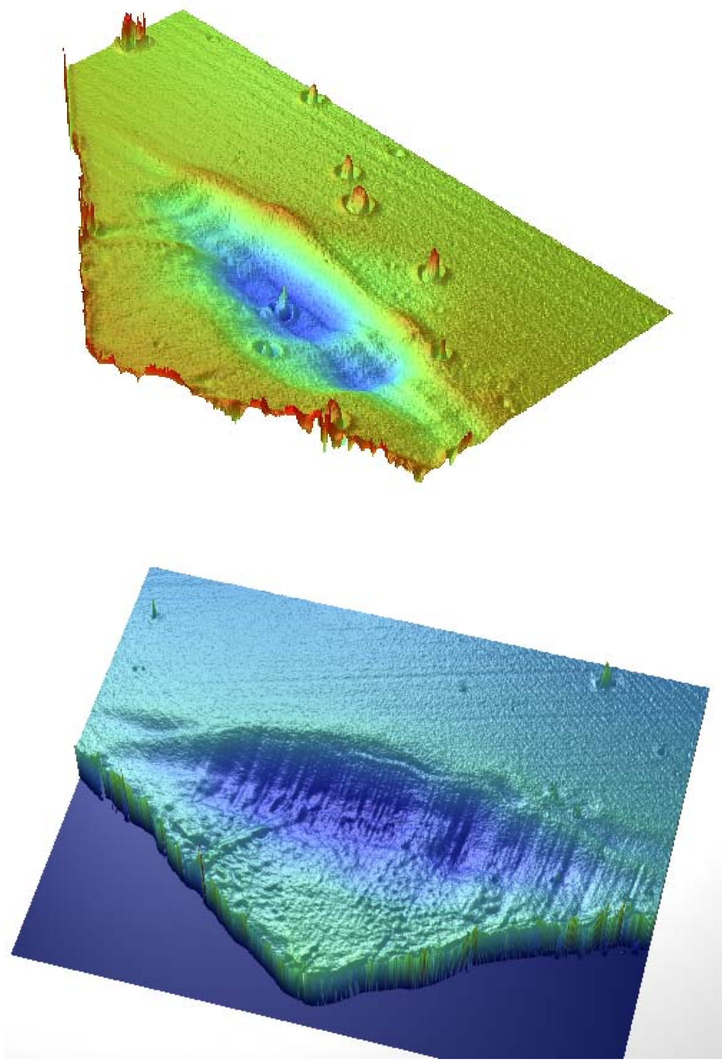


Figure 14. Worn diamond styli exhibiting crater wear and flank wear

As the tip wears, so the region of sticking friction, where no relative movement occurs between the tip and the metal moves backwards and so the crater wear also moves back. In time the crater wear becomes closer to the side of the stylus, probably leading to the failure of the diamond by chipping when the combination of crater, tip and flank wear lead to a region on the edge of the diamond that has insufficient strength to support the loads in the engraving forces.

While cutting theories have been developed under constant cutting conditions of depth and load, the nature of the engraving process means the cut depth is continuously varying during the engraving of each cell. As the diamond enters the material at the start of engraving each cell, the initial load on the cutting face will be relatively low, allowing sliding friction and wear at the tip. As the stylus enters further into the cylinder, then the conditions of sticking friction and sliding friction will produce less wear at the tip and crater wear in the sliding friction zone. The size of the crater will also be influenced by the depth of the cut. Except for coating rolls, the size of each cell varies continuously around the cylinder. Thus, quite a complex pattern of wear will build up on the surface. The only practical way to estimate the wear and life of the stylus will be by statistical methods, based on an extensive survey of diamonds during the engraving process.

Conclusions

The cutting surface of the diamond undergoes significant changes as a result of the engraving process. There were variations in the stylus angles both of new diamonds and those that had been in service. The cutting surface of the diamond undergoes significant changes as a result of the engraving process, despite the relative hardness of the diamond to the copper. This wear is inline with traditional metal cutting concepts. The stylus enters the copper on a curved path, which causes more load to be placed on one edge as the stylus enters the copper. This experiences a more even wear, while other the edge suffers from chipping. Both of these cause the angle of the stylus to decrease. The roughening of the edge of the diamond during engraving gives rise to the characteristic ridges observed on the internal surfaces of the cells. The tip also becomes rounded, further reducing the cell volume. Crater wear is observed on the front face of the diamond as the surface is eroded by the passage of copper across the surface.

Most engraving colour management assumes constant angle within tight tolerances and cell geometry. There has been a move towards using measurement of cell area as means of quality assurance. This assumes the styli are both within tolerance and that they remain the same throughout the cutting process. Therefore, the angle of each stylus should be measured before it is used to engrave a cylinder. Also throughout the use of the diamond stylus, wear will cause the stylus angle to increase leading to shallower cells with less volume that will hold less ink. The edge damage will increase the internal surface roughness and may affect ink release.

Acknowledgements

The authors wish to acknowledge the financial support of the Rotogravure Printing Technology Group, EPSRC and European Regional Development Fund for this work.