The Characterization of The Geometry of Monocrystalline Diamond Contouring Tools

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The diamond cutting tools used for producing extremely precise contoured surfaces are themselves highly accurate devices. Recent advances in the manufacture of these tools have made it possible to generate the tool tip geometry within a few micro-inches of perfection. In order to generate parts with contour accuracies of a few micro-inches, the geometry of the cutting tool must be known to a similar degree of exactness. This paper will show one method by which the geometry of a diamond cutting tool may be fully characterized so that a tool path can be calculated that will precisely generate a predefined workpiece.

Diamond tools, like other cutting tools, are often characterized by stating a value for the tool radius. This value, along with the top rake angle, the clearance angle, and the sweep angle, are considered to fully identify the tool characteristics. This information is not adequate to properly define the tool.

The clearance angle on a contouring tool may be generated by forming a cylindrical surface on the nose of the tool at an angle to the intended cutting plane[1] or, it may be formed by generating a conical surface with an axis perpendicular to the cutting plane. Each of these techniques has advantages and disadvantages.

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[1] The cutting plane is defined as the plane which passes through the axis of the work spindle at the surface of the finished workpiece and is parallel to the travel of the X and Z axes. The top rake angle is measured from the cutting plane.

A tool with a cylindrical clearance face has the advantage that its radius does not change when the top face of the tool is relapped. Cylindrical clearance tools are claimed to be somewhat more rugged than conical clearance tools. The disadvantage of a cylindrical clearance is that the clearance angle decreases as the cut moves away from the axis of the tool, eventually approaching zero degrees.

A conical clearance tool has the advantage that the clearance angle remains constant as the cut moves away from the axis of the tool. A major disadvantage is that each time a conical clearance tool is relapped, its radius will change and must therefore be requalified.

The tool radius is a more interesting subject. What is the tool radius? Most, diamond tools are elliptical rather than round. This can easily be seen in figure 1, which illustrates a zero degree top rake, cylindrical clearance tool with a 10 degree clearance angle. In this common configuration it can be seen that the top rake face of the tool lies in the cutting plane and intersects the clearance cylinder at an angle of 10 degrees. This produces an error in the tool radius of 0.000011 at a point 40 degrees off the tool axis. Except for the case where the top rake is equal to -1 times the clearance angle, all cylindrical rake tools are ellipses. Even in this case, when the cutting edge of the tool is projected into the cutting plane, it forms an ellipse.

Conical clearance tools which have a top rake of zero degrees are obviously circular, however it is interesting to note that conical clearance tools which have a top rake equal to -2 times the clearance angle are also circular, although when the cutting edge is projected onto the cutting plane, its projection is also an ellipse.

If the words "tool radius" should be used within quotes, how then should this feature of the tool be characterized? The common method used to measure the tool radius is to use a diamond tool analyzer to rotate the tool under a microscope, while adjusting both the position of the microscope and the position of the tool relative to the center of rotation. First the edge of the tool is centered, and then the center of the circle which best fits the edge. The difference between these two positions is the radius of the best-fit circle. It is this value which is given as the tool "radius". When this measurement is made, the tool is tipped so that its top rake surface is in the plane of rotation. This assures that the edge of the tool is in focus throughout the full range of rotation. It is essential that the angle through which the tool was rotated be noted along with the tool radius.

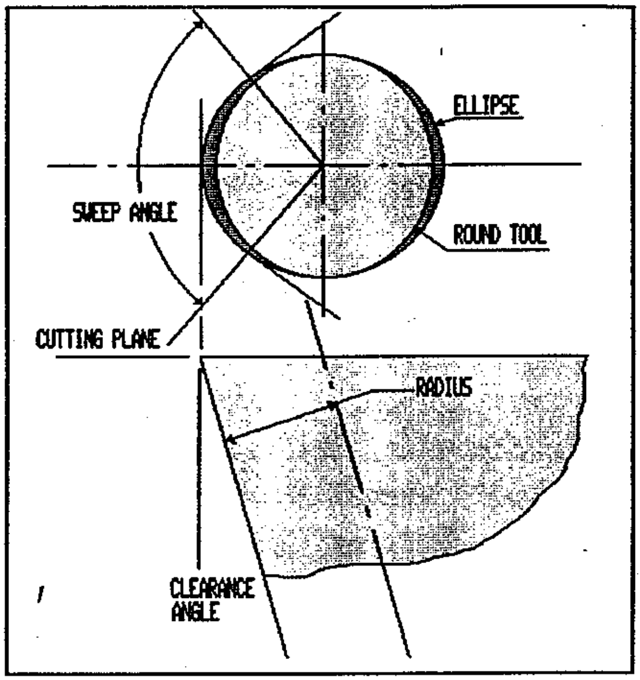

Figure 1. Even a tool with a zero degree top rake is an ellipse which differs significantly from the circle which is commonly used to approximate it.

Referring to figure 2, which shows a negative rake, conical clearance tool, the length of line J, which is one axis of the ellipse, is:

(1) $$J = L \tan \alpha$$

(2) $$L = \frac{J}{\tan \alpha}$$

From this, K, which is the other axis, can be stated to be:

(3) $$K = \frac{L \sin \alpha}{\sin(90-\alpha-\beta)}$$

The formula for the ellipse is:

(4) $$Y^2+(1-e^2)X^2 = 2pX$$

Solving this expression for p:

(5) $$p = \frac{Y^2+(1-e^2)X^2}{2X}$$

The eccentricity of the ellipse, e is:

(6) $$e = (1-(\frac{b}{a})^2)^{1/2}$$

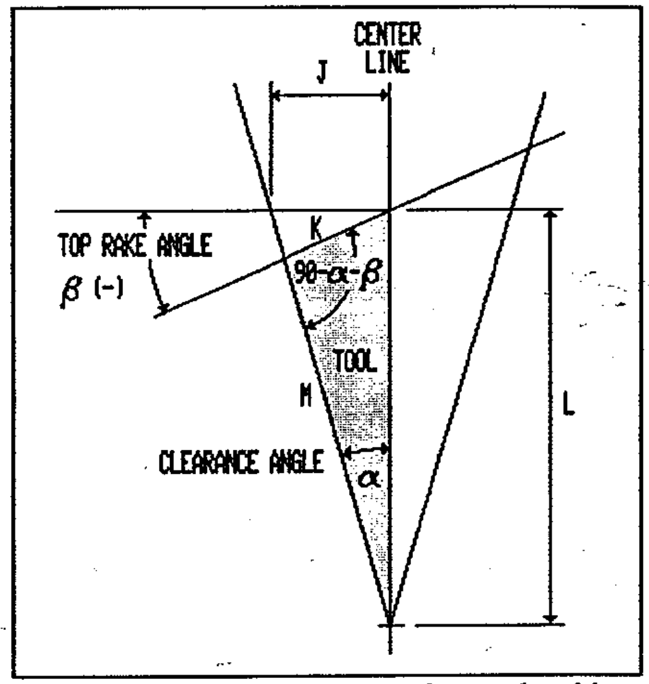

Figure 2. A negative top rake tool with a conical clearance angle. The tool is shown as a cross section taken along its axis of symmetry.

In equation (6), b is the minor axis of the ellipse, and a is the major axis. Substituting K for a and J for b, we find that the fraction a/b contains only functions of the angles α and β. If, upon evaluating (7), we find that its value exceeds 1, we know that J, rather than K, is the major axis of the ellipse. If this is the case, before solving (6) for e, we must invert expression (7) so that its value is less than 1.

(7) $$\frac{\mathrm{Tan}(\alpha)\mathrm{Sin}(90-\alpha-\beta)}{\mathrm{Sin}\ \alpha}$$

This may be simplified as follows:

(7a) $$\frac{\mathrm{Cos}(\alpha+\beta)}{\mathrm{Cos}\ \alpha}$$

In order to solve equation (5), we must obtain values for X and Y. These values come from the best-fit circle which was found using the diamond tool analyzer. If, for example, this circle was fit to the tool using ±35 degrees of sweep, it is tangent to the tool at its axis and intersects the ellipse 35 degrees either side of the center line. The coordinates of the intersection are as follows:

(8) $$X = R(1-\cos(\sigma))$$

(9) $$Y = R\ \sin(\sigma)$$

Where σ is equal to one half of the total sweep angle of the tool.

Substituting these values into equation (5) will allow it to be solved for p. Once p is known, the values for K, L, and J can be found as follows:

(10) $$K = \frac{p}{(1-e^2)}$$

(11) $$L = \frac{K\ \sin(90-\alpha-\beta)}{\sin\alpha}$$

(12) $$J = L\ \tan\alpha$$

If expression (7) is greater than 1, which will be the case for negative rake tools with a top rake angle less than twice the clearance angle, the minor axis of the ellipse will lie along the axis of the tool. For this case the ellipse formula is:

(13) $$p = \frac{X^2+(1-e^2)Y^2}{2X}$$

In this case:

(14) $$J = p$$

And:

(15)
$$L = \frac{J}{\text{Tan } \alpha}$$

And:

(16)
$$K = \frac{L \text{ Sin } \alpha}{\text{Sin}(90-\alpha-\beta)}$$

If the tool in question has a cylindrical clearance angle, as is shown in figure 3, the major axis of the ellipse always lies along the axis of the tool. The calculations are similar to those just discussed, differing only in the calculation of e.

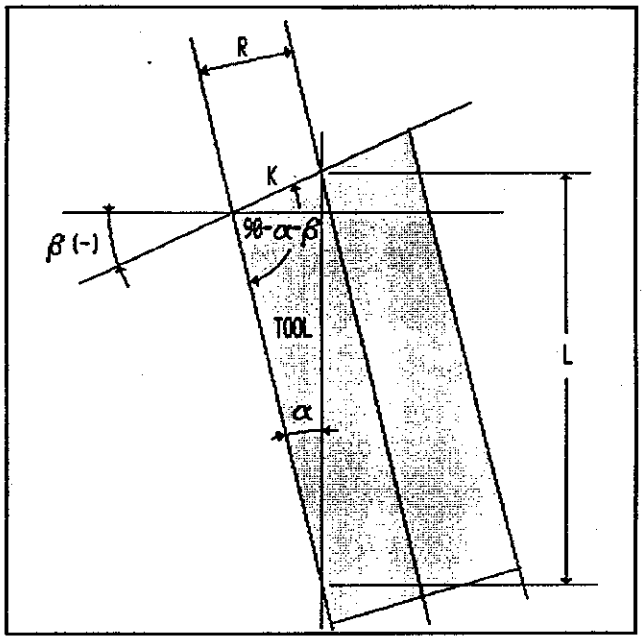

Figure 3. A tool with a negative top rake and a cylindrical clearance angle.

(17) R = Radius of the clearance cylinder

$$J = R = L \text{ Sin } \alpha$$

(18)
$$K = \frac{L \text{ Sin } \alpha}{\text{Sin}(90-\alpha-\beta)}$$

(19)
$$\frac{J}{K} = \text{Sin}(90-\alpha-\beta)$$

(20)
$$e = (1-(\text{Sin}(90-\alpha-\beta)^2)^{1/2}$$

Having determined the value of e, solve equation (5) for p and continue to find the values for K and J.

(10) (Repeated)

$$K = \frac{p}{(1-e^2)}$$

(21)

$$J = K \, \mathrm{Sin}(90-\alpha-\beta)$$

Having now characterized the ellipse formed by the nose of the tool, the next step is to project this ellipse into the cutting plane of the machine tool. To project the tool nose into this plane, The K dimension must be foreshortened by the cosine of the top rake angle, β.

(22)

$$K = K \, \mathrm{Cos} \, \beta$$

Now that the projection of the tool shape into the cutting plane is known, there is one further point to consider. For all tools which have a top rake other than zero, the point on the tool which is actually cutting the workpiece lies outside of the cutting plane by an amount which is a function of the tool orientation angle, the instantaneous slope of the work, the slope of the work at its center of rotation, the top rake angle β, and tool tip dimensions J and K. The errors caused by this are small, but corrections should be built into the tool path to account for the consequences of this geometry. As the detailed treatment of this falls outside of the scope of this discussion, it will be left to the interested user to develop the method to be used to correct these errors.

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