# Bluntness of the tool and process forces in high-precision cutting

# Bluntness of the Tool and Process Forces in High-Precision Cutting

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The influence of bluntness of the cutting tool edge is considerable when making smaller cuts, particularly in high-precision cutting. In this paper its influence on the process forces is investigated. It has been approximated by a rounded tool edge. In that case, Abdelmoneim's model for determining the tool forces when cutting with a rounded tool edge, is applicable.

Rough cutting experiments have been carried out using tools ground with large edge radii. Force measurements have been compared with the theoretical results from Abdelmoneim's model. In addition the model has also been used for high-precision cutting experiments.

KEY WORDS: Cutting, Cutting forces, Tool wear

## 1. Introduction

The edge of the cutting tool is of great importance in high-precision machining. In the past, several researches have been carried out in order to determine the relationship between tool edge geometry and the obtained surface roughness. It is generally recognized that tool sharpness is of great importance in the burnishing process.

Besides its influence on the surface roughness it is obvious that a less sharp tool also leads to higher cutting forces. This will lead to more power dissipation, more heat development and to thermal expansion. More heat development when cutting with a worn tool has been measured by Moriwaki [6]. Cutting with a blunt tool will therefore decrease machining accuracy.

The size of the tool edge bluntness with respect to the dimensions in high-precision cutting can be illustrated by figure 1. In this figure the geometry of the uncut chip cross-section in single point diamond cutting is drawn. With a tool nose radius of 0.5 mm, a nominal depth of cut of 5 μm and a feed rate of 5 μm/rev, it can be calculated that the chip-tool contact length is 73 μm and the mean chip thickness is 0.3 μm. For smaller cuts the chip will even get thinner.

Freshly ground high-precision diamond tools are available with tool edge radii up to 20 nm. However, when cutting the edge bluntness will increase rapidly due to tool wear. With respect to the mean chip thickness, this bluntness can be considerable.

In this paper the influence of the tool edge bluntness on the cutting forces in high-precision diamond cutting is investigated. The tool edge bluntness has been approximated by an edge roundness. Flank wear is assumed to be negligible. Cutting experiments, with tools previously ground with large edge radii, are carried out starting with rough cutting and, in addition, high-precision cutting. The experimental results are compared with the theoretical results obtained from the work of Abdelmoneim. Theoretical and experimental observations are restricted to the situation where the depth of cut is less than the tool edge radius.

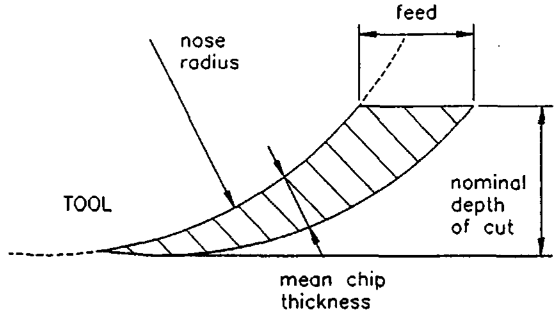


*Figure 1: Geometry of the uncut chip cross-section in single point diamond cutting*

## 2. *The tool force model*

The theory proposed in this study is based on the work of Abdelmoneim [1,2]. He suggested the existence of a small stable dead-metal zone beneath the rounded tool edge as shown in figure 2.

Part of the material is assumed to slide past a small build-up edge and then to traverse a plastic region around the tool base, called the rubbing region. The rest of the material will flow past the front surface of the build-up and is removed in the form of a chip. The front and bottom side of the build-up are called the cutting region.

The so-called 'stagnation point' at the tip of the build-up determines the height beneath which no cutting action occurs. This height is determined by the stagnation point angle Θ. Experiments using negative rake tools have indicated that the value of Θ is approximately 14°.

Furthermore it is assumed that:

- the workpiece material is ideal rigid plastic.
- the workpiece material beneath the stagnation point is subjected to a rubbing action and a plastic region of circular shape exists beneath the tool base.
- the chip leaves the rounded part of the cutting edge at the same vertical position as that of the uncut surface.
- sticking friction conditions will prevail at the tool edge.
- the chip does not flow to either side (plane strain).

Using the concept of a circular surface of velocity discontinuity, an upper-bound solution for the plastic flow of material beneath the rubbing region may be developed in terms of an specific force (force per unit

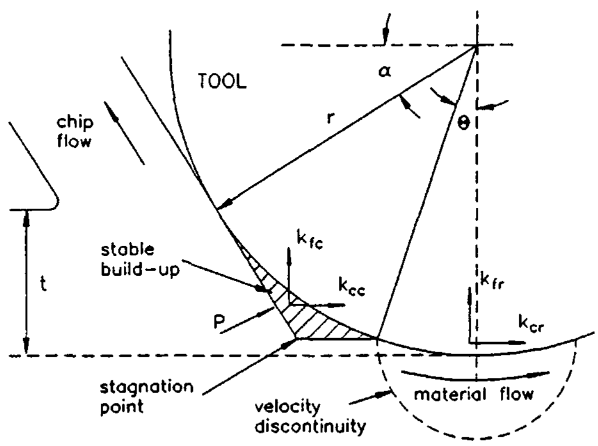


*Figure 2: Cross-sectional view of the cutting area according to Abdelmoneim's model*

area of cut). It can be shown that the best solution, i.e. that giving the least value for the specific cutting force, is (for a depth of cut equal to $r\cdot(1-\cos\theta)$)

$$k_{cr} = \tau \cdot \left\{ \frac{2\theta/\cos\theta + \pi \sin\theta \tan\theta}{1 - \cos\theta} \right\}$$

with $\tau$ : yield shear stress
r : cutting edge radius

The specific feed force in the rubbing region (for a von Mises material in which the normal stress is equal to $\sqrt{3}\cdot\tau$) is given by the expression

$$k_{fr} = \tau \cdot \left\{ \frac{2\sqrt{3}\,\sin\theta}{1 - \cos\theta} \right\}$$

For the cutting region it can be shown that the specific cutting force

$$k_{cc} = \tau \cdot \frac{r}{t} \cdot \left\{ \left(\frac{t}{r} - 1 + \cos\theta\right) \cdot \left(\frac{P}{\tau} - 2\tan\alpha\right) + \cos\alpha - \sin\theta \right\}$$

with t : depth of cut
$\alpha$ : chip flow angle

P is the pressure acting on the chip side of the stable build-up. Assuming an uniform pressure distribution, a slip-line technique was adopted to estimate the value of P.

$$P = \tau \cdot \left(1 + \frac{\pi}{2} + 2\alpha\right)$$

The specific feed force in the cutting region is given by the expression

$$k_{fc} = \tau \cdot \frac{r}{t} \left[ \left(\frac{t}{r} - 1 + \cos\theta\right) \cdot \left(\frac{P}{\tau}\tan\alpha - 1\right) + \right.$$
$$\left. + \sqrt{3} \cdot \left\{ \cos\alpha - \left(\frac{t}{r} - 1 + \cos\theta\right) \tan\alpha - \sin\theta \right\} \right]$$

Combining the specific forces for the cutting and the feed direction leads to

$$k_c = k_{cc} + k_{cr} \cdot \frac{r}{t}(1 - \cos\theta)$$

$$k_f = k_{fc} + k_{fr} \cdot \frac{r}{t}(1 - \cos\theta)$$

The chip flow angle is determined by the depth of cut and the cutting edge radius

$$\alpha = \arcsin\left(1 - \frac{t}{r}\right)$$

It follows from the analysis outlined here that the specific cutting force and feed force are both determined by the material yield shear stress $\tau$ and the value of the ratio t/r, but not by the values of t and r independently.

Figure 3-A shows the dimensionless values of $k_c/\tau$ and $k_f/\tau$ plotted against the dimensionless value $t/r$. This relationship looks very alike the one that Furukawa [3] observed. When these values are plotted logarithmically, approximately linear relationships are evidenced (figure 3-B).

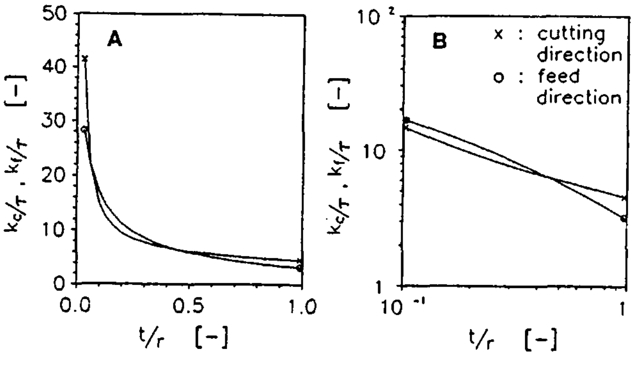


*Figure 3: The relation between the specific cutting and feed force and the ratio depth of cut/cutting edge radius*

Bearing in mind that for sharp tools $k_c/\tau$ and $k_f/\tau$ are approximately 2 to 3 respectively 1 to 2, it can be seen that, according to this theory, the specific tool forces can become more than 5 times higher because of tool edge roundness.

Notice that the theory, as outlined here, is only applicable for $t \le r$.

### 3. Rough cutting experiments

In order to verify Abdelmoneim's model, rough cutting experiments have been carried out using tools having varying degrees of edge roundness. Preliminary rough cutting experiments were employed since in high-precision cutting a defined edge roundness is very difficult to obtain and to measure. In rough cutting the edge roundnesses are much larger and easy to obtain.

On the other hand, the specific tool forces depend only on the value of the ratio $t/r$ for values of $t \le r(1+\sin\alpha)$ regardless of the tool geometry. The results obtained from the rough cutting experiments may therefore be applicable to the machining of materials with sharper tools, for instance in high-precision cutting.

The experiments have been carried out on a regular heavy-duty turning lathe. Cutting was performed on bars in longitudinal direction. The tool forces were measured using a Kistler type 9263 toolholder/ dynamometer.

The tools were ordinary Cermet tool inserts. Its geometry is shown in figure 4. Cermet has been chosen because of its high wear-resistance.

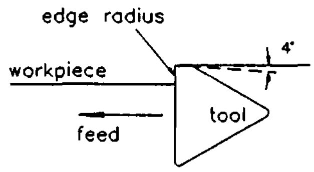


*Figure 4: The geometry of the tool inserts used in the rough cutting experiments*

Thus, the influence of flank wear can be neglected. The tools were ground with edge radii varying between 0.05 mm and 0.2 mm. The minor cutting edge was ground to remove the tool nose radius.

After grinding the exact value of the edge radius was measured using a roughness measuring instrument (Perthometer). This instrument has been used to scan the profile of the tool edge. The output of the instrument was sampled by a personal computer which estimated the tool edge radius using a least squares method.

Cutting was performed with feedrates varying between 0.04 and 0.2 mm, depending on the radius of the tool edge. The workpiece material was free turning brass (CuZn40Pb3).

The other operational settings were:

- tool rake angle: 0°, clearance angle: 7°.
- cutting velocity: 4 m/s.
- no usage of cutting fluid.
- nominal depth of cut: 1 mm.

The forces measured were divided by the area of uncut chip cross-section and the material yield shear stress and were plotted against the ratio $t/r$. Figure 5 shows the results for the cutting direction and figure 6 the results for the feed direction. The straight lines are the theoretical

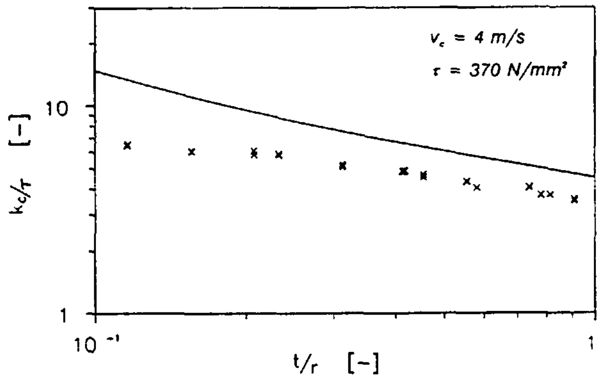


*Figure 5: The specific cutting force divided by the yield shear stress versus the ratio t/r for brass in rough cutting*

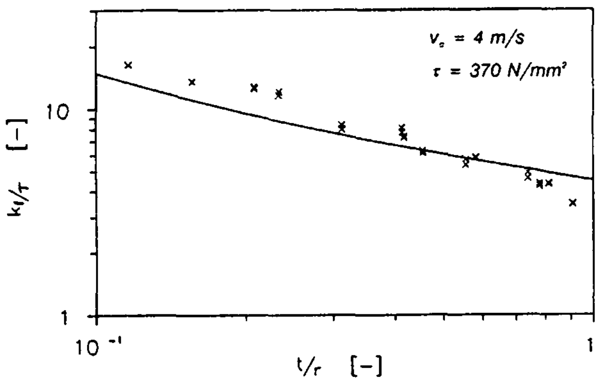


*Figure 6: The specific feed force divided by the yield shear stress versus the ratio t/r for brass in rough cutting*

results from Abdelmoneim's model.

The value of the yield shear stress $\tau$ was estimated in such a way that the experimental results approach the theory as much as possible. In this case its value is $\tau$=370 N/mm², which appears to be reasonable.

#### 4. High-precision cutting experiments

The high-precision cutting experiments have been carried out on a lathe with hydrostatic bearings. This machine is only suited for plain (longitudinal) cutting. The shaft of the spindle can make a travel in the direction of the rotation axis. The speed in this direction, which is the feed velocity, can be adjusted by variable flow-control valves.

The workpiece was divided into 5 sections by making grooves in it (figure 7). When cutting, the lathe was switched from one feed velocity to another between the sections. In this way it was possible to perform a cutting experiment with different feed velocities in one pass of the tool. Thus, variations of the nominal depth of cut are negligible. The feed velocity per section was calculated from the time required for the

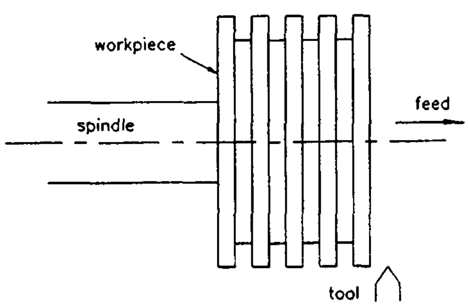


*Figure 7: The geometry of the grooved workpiece in the high-precision cutting experiments*

diamond tool to traverse the section.

The diamond tool was mounted in a tool holder containing a three component dynamometer (Kistler type 9251A). The induced signals were amplified and recorded on a multi-pen recorder.

The geometry of the diamond tool is drawn in figure 8. The tool was ground with an edge radius of approximately 15 μm. The cutting edge radius was determined by viewing the tool minor cutting edge through a

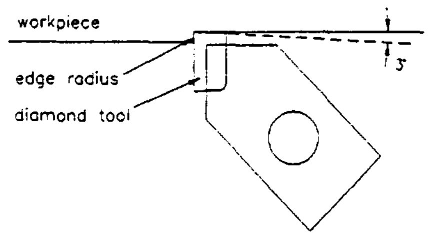


*Figure 8: The geometry of the diamond tool used in the high-precision cutting experiments*

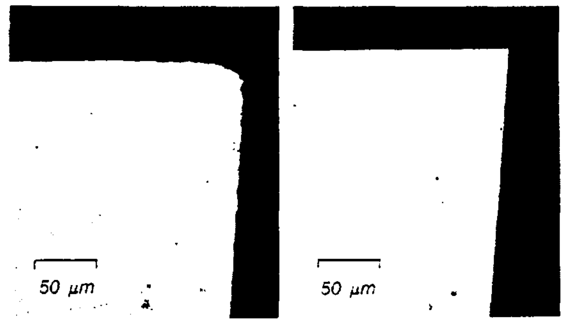


*Figure 9: Photographs of the rounded diamond tool edge (left, r≈15 μm) and, as a comparison, a sharp tool edge (right)*

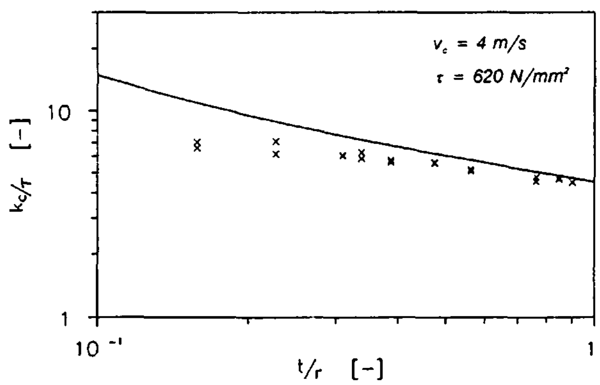


*Figure 10: The specific cutting force divided by the yield shear stress versus the ratio t/r for brass in high-precision cutting*

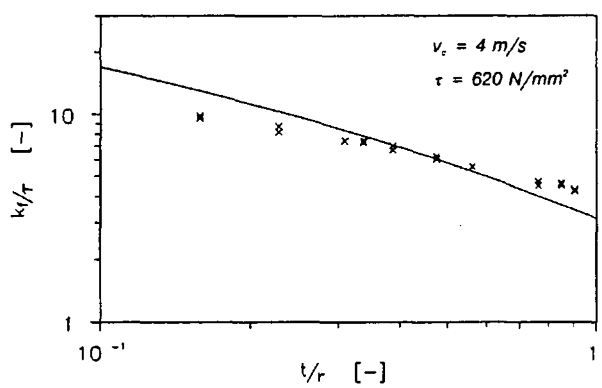


*Figure 11: The specific feed force divided by the yield shear stress versus the ratio t/r in high-precision cutting*

microscope. Photographs of the rounded edge and, as a comparison, a sharp tool edge are shown in figure 9. The grooves on the left photograph are a result of an post-grinding operation of the minor cutting edge. The grooves are very small with respect to the depth of cut, and may therefore be neglected.

The workpiece material was the same as for the rough cutting experiments (brass 58). The other operational settings were:

- feed rate: 2.4 - 13.5 μm/rev.
- nominal depth of cut: 30 μm.
- tool rake angle: 0°, clearance angle: 5°.
- cutting velocity: 4 m/s.
- no lubrication.

Results of the force measurements are drawn in the figures 10 and 11. In this case an estimation for the yield shear stress was 620 N/mm². This value is almost twice as high as the value estimated for rough cutting.

### 5. Discussion and conclusions

There is a fair agreement between the increase of the measured cutting forces, as result of an edge radius, and the theoretical predictions. It is clear that an increase of the tool radius, thus a decreasing ratio t/r, leads to much higher forces.

From the figures 5, 6, 10 and 11 it can be seen that the cutting force is rather low as compared to the feed force. This may be due to the fact that brass forms discontinuous chips. Therefore the chip-tool contact length may be smaller than assumed in the theory.

The value of the yield shear stress in high-precision cutting is almost twice as high as the value in rough cutting. An explanation for this difference is the presence of a higher strain rate in high-precision cutting. Because of the higher strain rate, the material yield strength is higher. This has also been measured by Lo-A-Foe [4]. Eventually, a cutting force measurement could be used to determine the material yield strength at very high strain rates ($>10^5$).

Except for the difference in yield stress, there are no distinct differences between the results of the rough and high-precision cutting experiments. This lends credence to the proposition in the beginning of chapter 3 that rough cutting measurements could be applicable to the machining of materials with sharper tools.

Despite the assumption in the model of Abdelmoneim that the chip does not flow to either side, it was observed during the tests that there was little side-flow. Possible deviations between the experimental and the theoretical results due to this side-flow have not been considered.

Results of this study could be used to formulate quality requirements, with respect to the cutting edge, for high-precision cutting tools. It may also be possible to determine the permissible amount of tool wear during cutting.


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