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Influence of cutting edge geometry on force build-up process in intermittent turning

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Abstract

In the intermittent turning and milling processes, during the entry phase the cutting edges are subjected to high impact loads that can give rise to dynamical and strength issues which in general cause tool life reduction. In this study the effect of geometrical features of the cutting tool on the force generation during the entry phase is investigated. Cutting forces are measured by a stiff dynamometer at a high sampling frequency. In addition, the chip load area is analyzed and related to the measured cutting force. The results show that micro-geometrical features, in particular the protection chamfer, significantly affect the force generation during the entry phase.

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Keywords: cutting; force; edge; chip; turning; dynamic.

1. Introduction

The cutting process can be divided into four important phases: entry phase, steady state cutting, exit phase and work-free phase. In the majority of intermittent cutting applications, the cutting tool edge is subjected to impacts and high loads that occur during the entry phase. The purpose of this research is to identify the influence of cutting edge features, such as rake angle and protection chamfer, on the force build-up process in the intermittent turning.

The general theory of the mechanics of metal cutting and derivation of cutting force model is explained in [1]. The force build-up process in the entry phase of intermittent turning has been investigated in [1], [2]. A 2-D approach has been employed and the growth of the cutting force has been investigated with focus on the engagement angle which is dependent on the cutting tool and workpiece geometry.

An analytical model for the cutting force simulation in the case of milling has been developed in [3]; however, that model only incorporates the micro-geometry of the cutting edge through the force coefficients (mechanistic approach) and does not model the effect of the micro-geometry on force build-up during engagement.

In this study, the geometrical analysis of rake angle and protection chamfer is conducted and a mathematical expression for the growth of the projected chip load area is developed for these particular cutting geometries. The magnitude and the growth of the cutting force in the tangential and feed direction from the cutting force measurements is evaluated and related to the calculated chip load area. The correlation between force build-up and chip load area rate is shown.

2. The tool and cutting geometries

The primary task of this study is to find the influence of the rake angle γ and protection chamfer length (b_n), see Fig. 1, on the cutting force build-up process. The inserts utilized for the cutting force measurements are DNMG150608 turning inserts.

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Three cutting geometries with different rake angles and protection chamfers are analyzed. All cutting edges have the same edge radius, 0.05 mm. The effective clearance angle α is 6° for all cutting geometries. The toolholder geometry corresponds to a PDJNL type toolholder.

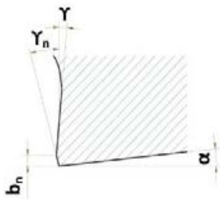

Fig. 1. Cross section of cutting edge.

Cutting geometries utilized in the experiment are defined in Table 1.

Table 1. Cutting geometries and geometrical characteristics.

Cutting geometry	Rake angle, γ [°]	Chamfer angle $γ_n$ [°]	Chamfer width b_n [mm]
A	0	0	0
B	5	-15	0.15
C	10	-10	0.12

3. Experimental set up

A turning machine is utilized for the experiment. The cutting geometries are run at various cutting data in a special workpiece. The experiments are conducted at three cutting speeds (50, 150, and 200 m/min) and three feeds (0.14, 0.2 and 0.25 mm). The cutting speed of 50 m/min is only employed at feed 0.25 mm, so in total, 21 experiments are carried out.

3.1 Cutting force dynamometer

The cutting forces are measured by a dynamometer that utilizes built-in strain gauge sensors connected in three electrical bridges and allowing the deformation of toolholder in three mutually perpendicular directions due to the influence of cutting forces to measure. General view of the toolholder and scheme of its clamping is illustrated in Fig. 2. The signals from the bridges were acquired by CompactDAQ NI-9223 with sampling rate of 1 MHz, amplified and recorded on the computer. Later the signals in [V] were converted into forces [N].

The transfer function of the toolholder – dynamometer system has been dynamically simulated with FEM modelling and measured experimentally. The extensive and detailed description of the dynamometer is given in [4]. The lowest resonant frequency is 5.5 kHz in the axial direction, and the resonant frequency in the tangential direction is 7.5 kHz [4]. The forces are measured in tangential and feed directions while the radial force is neglected in this study. Since the load rate during the tool entry into the workpiece has an impact nature, the dynamic behaviour of the "tool-workpiece-machine tool" system is also determined by the vibrations of machine tool units. Experimental examination of the dynamic system employed shows that the dominant vibration mode has a frequency around 2.6 kHz due to the low stiffness of tool post and tool clamping mechanism. As the only parameter that changes in the setup is the cutting geometry, it is assumed that the influence of the cutting geometry will be captured by the measurement system. The evaluation of the force magnitudes and rise times is explained in Chapter 6.

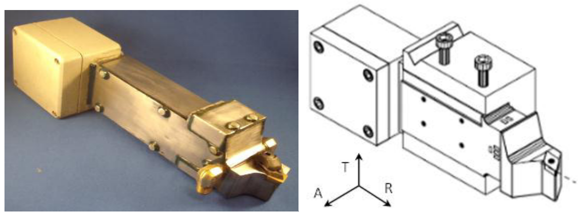

Fig. 2. A cutting force sensor (Center In Line) for measuring dynamic cutting forces with a bandwidth of approx. 7.5 kHz in the T-direction, 5.5 kHz in the A-direction and 12.5 kHz in the R-direction.

3.2 Workpiece

The workpiece is a solid cylinder with four slots. One side of each slot is coinciding with the center axis of the work piece. The set up generates impact loads every time the cutting edge enters the workpiece. The workpiece material used for the experiments is AISI 1045 steel.

Fig. 3. Section of the work piece and the set-up utilized in the measurements.

The inclination angle of the insert – toolholder system together with the entering angle of the slot in the workpiece results in the effective entering angle which in this particular case is λ = 6° (Fig 4). The combination of these two angles is of vital importance for the force build-up process as it directly affects the time necessary for the cutting edge to penetrate the workpiece. However, these angles are kept constant, and their influence is not in the scope of this study.

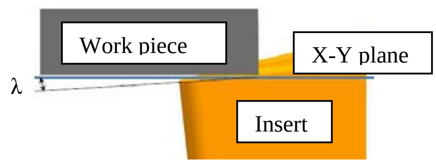

Fig. 4. Position at entry of cutting edge into work piece.

4. Theoretical considerations

Depending on the cutting edge geometry, the growth of the cutting force and the time necessary for the cutting edge to get into workpiece are different. It is assumed that despite the very short period of time needed for the force to build up, the size and even the shape of the chip load area during its growth affects the force build-up process. The potential development of the forces due to the increase of the contact area on the rake surface, and initiation of chip sliding on the rake face, as explained in [1], is not taken into account in this study. Thus, the chip load area is limited to the size of the feed in the feed direction while the boundaries in the radial direction are the starting point of the nose and maximum depth of cut. Due to the projection on the X-Y plane, shown in Fig. 4, the final chip load area is equal for all geometries while its growth and duration is dependent on the rake angle and the protection chamfer of each insert.

A simplified expression for the cutting force is :

$$F(t) = C \cdot A(t) \quad (1)$$

$A(t)$ incorporates the growths of the chip load area in both directions while C is cutting resistance. The cutting resistance is a function of the cutting geometry so it directly affects the magnitude of the cutting forces.

The difference in the growth of the chip load area at the very entry for the three cutting geometries is illustrated in Fig. 5.

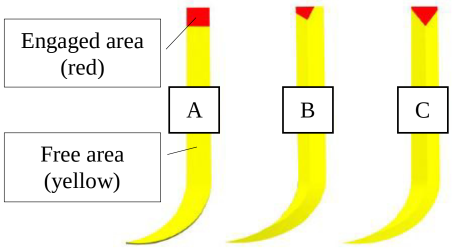

Fig. 5. Chip load area (red) at an early stage of entry.

As the cutting edge moves into the workpiece, the chip load area grows until the tool completely engages to the workpiece. The feed movement of the cutting edge is neglected as it is much smaller in comparison to the movement in the tangential direction. The workpiece geometry and the cutting tool geometry in this particular set up cause the chip load growth from two directions, as the lower part of the nose radius of the insert hits the workpiece before the cutting edge fully penetrates it. That is a consequence of the workpiece and cutting tool configuration in this particular set up. The situation is illustrated in Fig. 6.

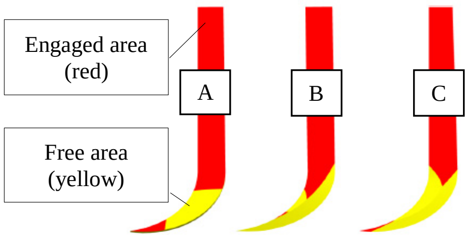

Fig. 6. Chip load area (red) after certain period of engagement.

5. Mathematical analysis

The chip load area is calculated for a number of increments from the position where the cutting edge has started the engagement to the position where the entry phase is completed. This results in a number of discrete values for the chip load area which are used for derivation of the mathematical relation between the cutting geometry and the chip load area. Using the curve fitting method, continuous functions are established that describe the growth of the projected chip load area for the given cutting geometries. The result of this analysis is illustrated in Fig. 7.

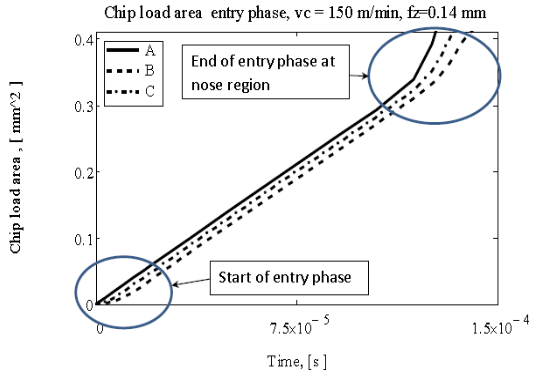

Fig. 7. Projected chip load area as function of time. A, B, and C refer to the cutting geometries introduced in Table 1.

The time interval for the entry phase is directly proportional to the cutting speed. From Fig. 7, where the projected chip load area is set as a function of time, a couple of observations can be made. Firstly, the rate of the chip load area is different for the cutting geometries in the very beginning of the entry phase. Secondly, the rate of the chip load area seems to be equal in the middle part of the engagement, and thirdly, the chip load area grows differently around the nose corner. In the middle section the chip load area increases linearly along the cutting edge.

6. Results and Discussion

From the cutting force measurement, as an example is shown in Fig. 8, the growth rate of the tangential force notably increases in the second part of the entry phase. This trend is typical for all cutting force measurements regardless of the cutting speed. The increase may be due to the growth of the chip load area, shown in Fig. 7.

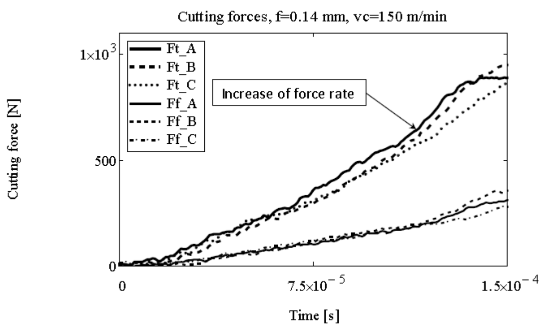

Fig. 8. Tangential and feed forces for A,B and C cutting geometries.

Even in the beginning of the entry phase, shown in Fig. 8, a certain difference in the force growth for the A, B and C cutting geometry can be seen. As a similar behavior is shown in the chip load area model, this indicates that the tangential cutting force is proportional to the chip load area in the entry phase.

The cutting force measurements for a single entry are evaluated for all cutting geometries. Two parameters are extracted from the force measurements, averaged force of the first vibration cycle and time to peak force as shown in Fig. 9.

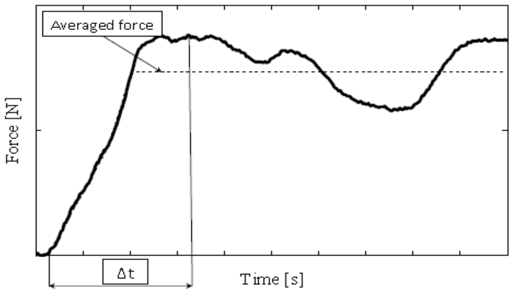

Fig. 9. Averaged cutting force and time period.

The average tangential and feed forces in the entry phase for the cutting geometries are shown in Fig. 10 in the left column, while the time to peak force is shown in the right column. The cutting geometry B creates the highest forces. The geometry B has a longer chamfer width compared to geometries A and C. The difference in comparison to other geometries is bigger on the feed force compared to the tangential force. This indicates that the protection chamfer plays an important role in the force build-up process. Another observation is that there is little difference between the force magnitudes for A and C geometries. The rake angle for C geometry is significantly greater than A geometry but even in the case of rather high feed, 0.25 mm, the cutting forces in the entry phase are quite equal. The effect of the bigger rake angle is highly reduced by the negative protection chamfer.

The time to peak force, shown in Fig. 9, exhibits good correlation with the chip load area model illustrated in Fig. 7 at low and moderate cutting speeds for the A geometry and its relation to the B and C geometry, while it shows the opposite result in a comparison between the B and C geometries. By increasing the rake angle or the protection chamfer angle, the force build-up process becomes longer at these cutting speeds. However, the effect of the increased rake angle and protection chamfer angle on the period of the force build-up process seems to vanish at higher cutting speeds. This effect might be caused by the insufficient frequency range of the measurement system at the higher cutting speeds.

7. Conclusions

- Protection chamfer in combination with the rake angle has a significant effect on the magnitude of the cutting forces at the entry phase.
- The effect of the increased rake angle on the cutting forces in the entry phase is significantly reduced by the protection chamfer.
- All deviations from a neutral cutting geometry, i.e. cutting geometry A with zero rake and protection chamfer angle seem to give longer duration of the force build-up process at low and moderate cutting speeds.
- The increase of the rate of the tangential cutting force might be explained by the sudden growth of the chip load area during the engagement of the nose corner.

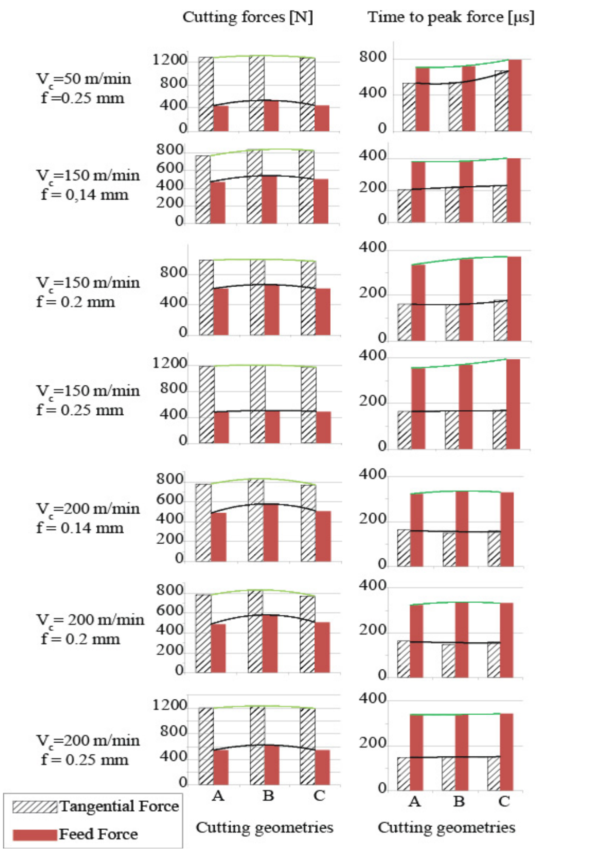

Fig. 10. Cutting forces in the entry phase in the left column, time to peak force in the right column for one of totally seven cutting data conditions.

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