

Design and Analysis of Variable Micro-Geometry Tooling for Machining Using 3-D Process Simulations

Yiğit Karpat*, Tuğrul Özel¹, John Sockman**, William Shaffer**

* Manufacturing Automation and Research Laboratory, Department of Industrial and Systems Engineering, Rutgers University, Piscataway, NJ 08854

**Conicity Technologies, One Wildwood Drive, Cresco, PA 18326

¹Corresponding author: ozel@rci.rutgers.edu

Abstract

Emerging machining techniques such as hard turning, hard milling and micro-mechanical machining, set high standards for tooling. These techniques, where the uncut chip thickness and the tool edge dimension are in the same order of magnitude, require cutting edges, which can withstand high mechanical and thermal induced stresses during machining. Since it has been known that sharp tools are not suitable for these kinds of operations, tool manufacturers have introduced different types of tool edge preparations. A common approach is to provide uniform edge preparation. In this paper, uniform and variable edge micro-geometry design inserts are utilized and tested for 3-D turning process. In 3-D tool engagement with workpiece, the thickness of the chip varies from a maximum equal to the feed rate to a minimum on the tool's corner radius. The ideal tool edge preparation should possess a variable configuration which has larger edge radius at the primary cutting edge than at the trailing cutting edge. Here the key parameter is the ratio of uncut chip thickness to edge radius. If a proper ratio is chosen, for given cutting conditions a variable cutting edge along the corner radius can be designed or "engineered". In this study, 3-D finite element analysis based process simulations are utilized to predict forces and temperatures on various edge micro-geometry tools. Predicted forces are compared with experiments. The temperature distributions on the tool demonstrate the advantages of variable edge micro-geometry design.

Keywords: Variable micro-edge geometry tool design, machining, 3-D FEA

1. INTRODUCTION

Metal cutting operations still represent the largest class of manufacturing operations where turning is the most commonly employed material removal process. In advanced turning operations such as hard turning, PCBN cutting tools with edge preparation (honed, chamfered or waterfall edges) preferred to protect the cutting edge from chipping. Edge preparation should be carefully selected for a given application because it affects the surface properties of the workpiece in terms of surface integrity.

In recent years, finite element analysis (FEA) has become available to calculate and simulate the process variables such as cutting forces, temperature and stress distributions during machining. There are numerous studies on finite element analysis of orthogonal machining which provide essential information about the mechanics of cutting but the studies on 3-D machining is limited. 3-D FEA based process models is needed to study practical machining operations. Ceretti et al. (2000) developed a 3-D FEA model for turning to predict cutting forces, temperature and stress distributions for the machining of aluminum alloys and low-carbon steels under orthogonal and oblique cutting configurations. Guo and Dornfeld (1998) presented a 3-D FEA model to simulate burr formation when drilling stainless steel. Guo and Liu (2002) proposed a 3-D FEA model for hard turning of AISI 52100 steel using PCBN tools. The model was used to predict the temperature distribution over the cutting edge, the residual stress distribution on the machined surface and cutting forces. In a recent study, Liu and Shih (2006) compared the predictions of a 3-D FEA model with experimental measurements for turning of titanium. They also investigated the effects of edge preparations on process variables and observed that increasing cutting speed increases tool temperature, decreases cutting forces, increasing edge radius, decreases tool temperatures and increases cutting forces. In their simulations they were also able to demonstrate serrated chip formation in machining of titanium.

2. MECHANICS OF 3-D TURNING

For turning of alloy steels, typically low depth of cut and feed rates are used, chip load is shown in Fig. 1. It must be noted that the thickness of the chip varies along tool corner radius. A practical ratio of uncut chip thickness to edge radius is found to be around 2 by Endres and Koutanya (2002) after tool wear tests. This ratio may depend on the work and tool material. Ren and Altintas (2000) performed tool wear tests by using chamfered tools and showed that there is an optimum chamfer angle and chamfer height which makes the cutting the most efficient for a given depth of cut. Karpat and Özel (2006a, 2006b) introduced the slip-line field based models to identify friction factors for chamfered, honed and waterfall edge design tool in machining 4340 steel, which was utilized in modeling tool-chip friction in this study.

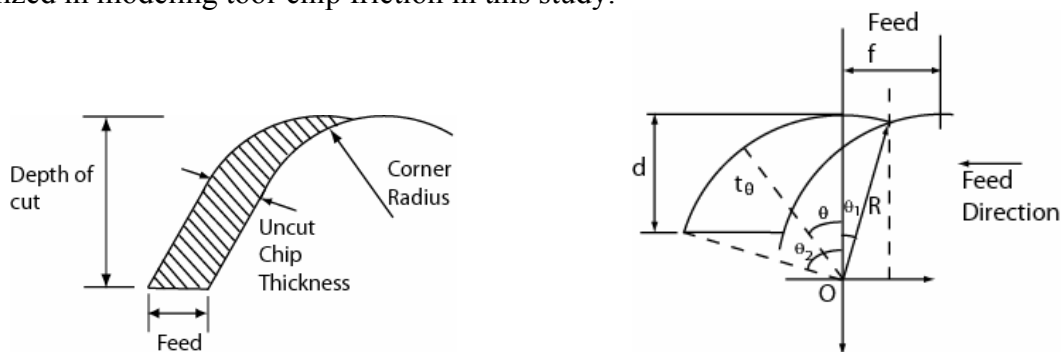


Fig. 1: Chip load in typical turning operation with a corner radius tool

Assuming zero rake and inclination angle, maximum uncut chip thickness along the chip can be calculated as:

$$\theta_1 = -\sin^{-1}\left(\frac{f}{2R}\right)$$

$$\theta_2 = \cos^{-1}\left(\frac{R-d}{R}\right) \quad (1)$$

$$t_\theta = R + f \sin \theta - \sqrt{R^2 - f^2 \cos^2 \theta} \quad \text{when} \quad \theta \leq \tan^{-1}\left(\frac{R \sin \theta_2 - f}{R-d}\right)$$

$$t_\theta = R - \frac{R-d}{\cos \theta} \quad \text{when} \quad \theta > \tan^{-1}\left(\frac{R \sin \theta_2 - f}{R-d}\right)$$

Fig. 2 shows the chip thickness with respect to sweep angle θ for a given cutting condition. The distribution of chip loads on the insert can be determined as a function of angle θ along corner radius of the tool. Uncut chip thickness becomes very small for a considerable range of angle θ along corner radius.

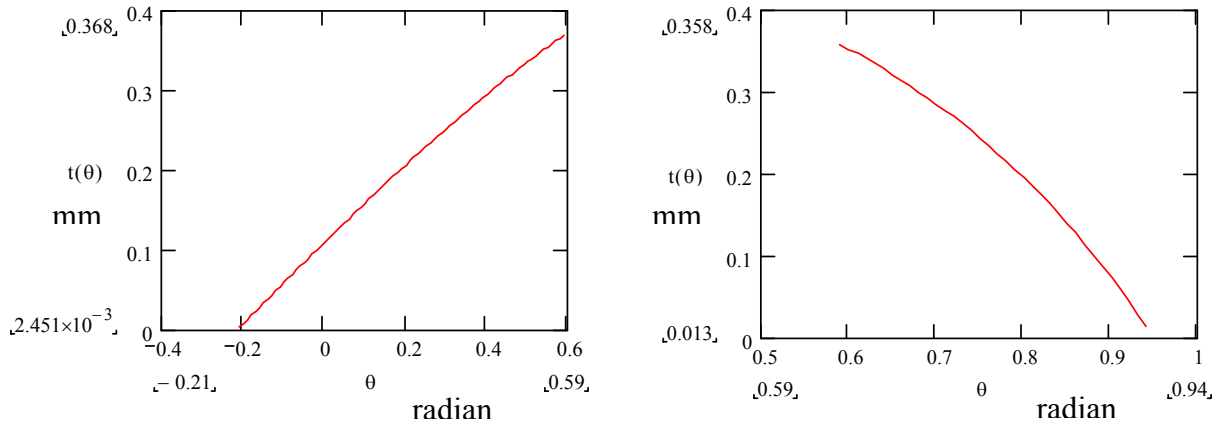


Fig. 2: Variation of uncut chip thickness

3. ADVANCED CUTTING TOOL MICRO-GEOMETRY DESIGN

Edge preparation enhances tool life but at the same time makes cutting less efficient especially when the ratio of uncut chip thickness to tool radius decreases. This is especially true when friction factor increases with decreasing uncut chip thickness to edge radius ratio. The work material is trapped near end of the uncut chip geometry along the corner radius. Inefficient cutting results in increased strains in the workpiece which in turn increases mechanical and thermal loads and results in high temperatures. This phenomenon becomes extremely important in hard turning. In order to explain this in detail, let us consider Fig. 3 which demonstrates the chip load of a uniform edge insert during cutting. As shown, the thickness of the chip varies from a maximum equal to the feed rate to a minimum on the tool's corner radius. If a uniform edge radius applied to the tip of the cutting tool, around that area cutting efficiency will be low due to small ratio of uncut chip thickness to tool edge radius. Three critical sections A-A, B-B and C-C are indicated in Fig.3. In Section A-A, uncut chip thickness is greater than the edge radius. In Section B-B, the uncut chip thickness is equal to the edge radius where the rubbing action becomes more dominant than shearing. In Section C-C the edge radius is larger than the thickness of the uncut chip and work material is rubbed against the workpiece. This rubbing action will result in increased temperatures on the tool and workpiece surfaces and hinder the performance of the tool.

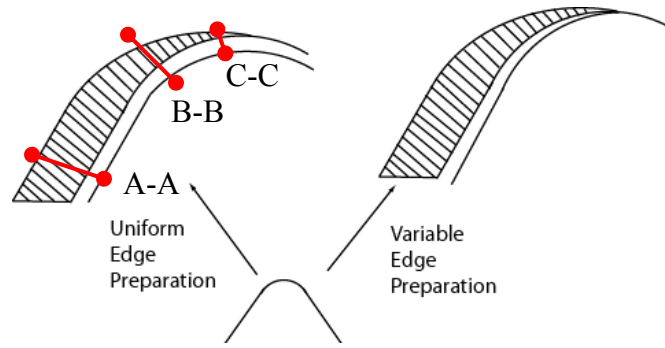


Fig. 3: Uniform vs. variable edge design on a tool insert

Computer controlled brushing devices enable the production of cutting tools with engineered micro-geometry or cutting tools with variable edge preparation where the edge radius along the corner radius of the cutting tool changes as a function of the thickness of the chip (Conicity Technologies, 2006). A CAD model of a variable edge design tool insert is given in Fig. 4. This figure shows the tip of a cutting tool with variable edge preparation. The edge radii at point A and B are 0.05 mm and 0.01 mm respectively.

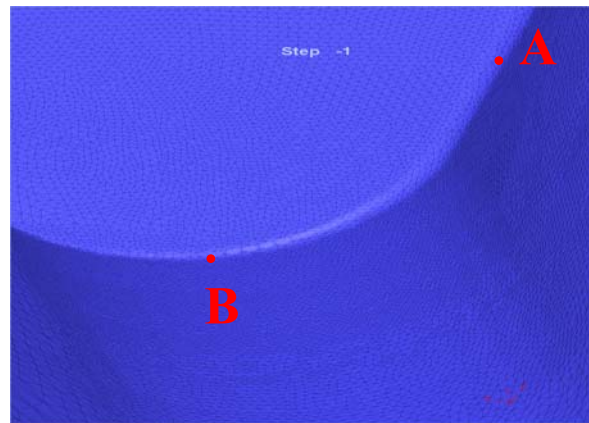


Fig. 4. The tip of the variable hone micro-geometry insert.

The purpose of this design is to eliminate the rubbing action at trailing edge of the tool by decreasing the edge radius towards the tip of the tool. This will reduce the unwanted excessive heat generation at the trailing zone and increase the performance of the tool. Proper tool edge design for the process in hand can be made only when tool-chip friction and heat generation mechanisms at the tool-chip and tool-workpiece interfaces are understood.

In variable edge design, the key parameter is the ratio of uncut chip thickness to edge radius. As mentioned earlier, the proper ratio is believed to be between 2 and 3. If this ratio is known, for a particular cutting condition a variable cutting edge can be designed. Variable edge preparation is not limited to honed micro-geometry inserts. Chamfered and waterfall type micro-geometry inserts can have variable edge preparation. As for variable chamfered edge design, the goal will be to calculate optimum chamfer angle and chamfer height for given uncut chip thickness along the cutting edge as detailed in Klocke and Kratz (2005). The purpose of continuously changing the chamfer angle along the corner

radius is to alter the locations of high temperature zones and reduce the possibility of a crater wear formation.

A methodology is proposed for advanced cutting tool micro-geometry design as shown in the flowchart in Fig 5. For a given cutting condition values of suggested tool corner radius can be obtained from tool manufacturers. The edge radius must be selected in accordance with tool corner radius. It should be noted that the friction identification method for micro-geometry tools proposed by Karpas and Özel (2006a, 2006b) is at the heart of this design methodology. Cutting conditions and workpiece material affects the friction conditions and this information is built into 3-D finite element model by using different friction factors at specific locations of the cutting tool depending on the geometry. The field variables obtained from 3-D process simulations such as temperature and stress distributions, forces etc. are utilized in assessing the performance of cutting tools or selecting cutting conditions for a given edge preparation.

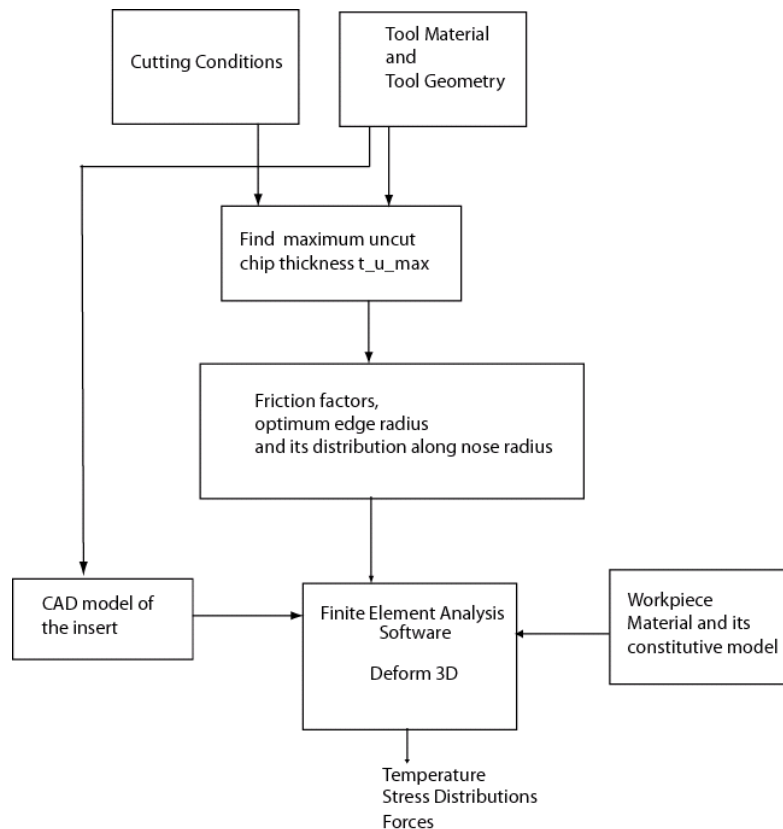


Fig. 5: Flowchart of advanced cutting tool micro-geometry design.

In order to investigate the performance of cutting tools with various edge preparations, tools with uniform and variable edge preparations provided by Conicity Technologies have been used in machining tests. These tests were performed at Manufacturing Automation and Research Laboratory of Rutgers University. The results of the experiments are expected to reveal the tool wear characteristics of edge preparations and their effects on surface roughness and surface integrity of the workpiece.

4. EXPERIMENTAL PROCEDURE

In this study, turning of AISI 4340 steel using PCBN inserts with three different micro-geometries (uniform chamfer with 0.1 mm chamfer height and 20° angle, uniform hone with 0.050 mm edge radius, variable hone with $r_A=0.05\text{mm}$, $r_B= 0.01$ mm edge radii, see Fig. 6) was considered.

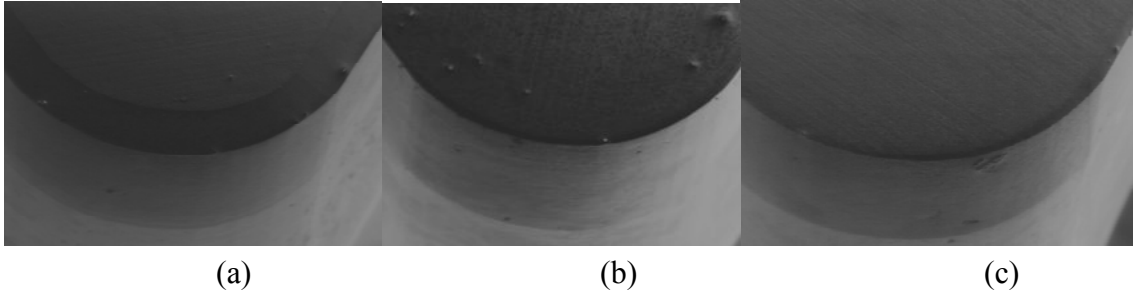


Fig. 6: Images of PCBN inserts at 50 times magnification obtained with scanning electron microscopy: a) chamfered, b) uniform honed with 0.05 mm radius, c) variable hone with 0.01 to 0.05 mm radius.

Bar turning experiments were conducted using a cylindrical bar specimen with a diameter of 2.8 inches (71 mm) and length of 12 inches (305 mm). Solid top CBN inserts (TNG-423) were used with a Kennametal MTGNR-123B right hand tool holder that provided 0° lead, -5° side rake, and -5° back rake angles. The cutting forces were measured with a three-component force dynamometer (Kistler Type 9121) mounted on the turret disk of the CNC lathe. The charge signal generated at the dynamometer was amplified using charge amplifiers (Kistler Type 5814B1), acquired and sampled by using data acquisition PCMCIA card and Kistler DynoWare software on a laptop computer.

Largest thrust force was measured when machining with the chamfered insert whereas variable honed insert resulted in lowest thrust force. Cutting and feed forces are measured to be almost the same for all three inserts.

5. RESULTS AND DISCUSSION

In this study, a Finite Element Analysis (FEA) software (Deform 3D) is used to study the effects of uniform chamfered, uniform honed and variable honed edge preparation. In 3-D FEA model, friction factors of 0.9, 0.85, 0.9 are used for the simulations with uniform chamfered, uniform honed and variable honed inserts respectively. The workpiece is modeled as rigid-perfectly plastic material where the material constitutive model of this deformable body is represented with Johnson-Cook material model where $A=1504$ MPa, $B=569$ MPa, $n=0.22$, $C=0.003$, $m=0.9$ are the parameters for AISI 4340 steel as given by Grey et al. (1994). The cutting tool is modeled as a rigid body which moves at the specified cutting speed. Thermal boundary conditions are defined accordingly in order to allow heat transfer from workpiece to cutting tool. Continuous adaptive remeshing is used for the separation of the chip from the workpiece. A fine mesh density is defined at the tip of the tool and in the cutting zone to obtain fine temperature distributions. The minimum element size for the workpiece mesh was set to 0.015 mm. All simulations were run at the same cutting condition (cutting speed of $V=125$ m/min, feed rate of $f = 0.15$ mm/rev, and depth of cut of $d=1$ mm).

The edge radius for the uniform hone insert is 0.05 mm which is one third of the feed rate. As for variable edge insert, the hone radius is decreased along the corner radius from 0.05 mm to 0.01 mm as shown in Fig.4. This provided an almost constant ratio of uncut chip thickness to edge radius.

The comparison of experimental and simulated forces (F_c , cutting force, F_t , thrust force and F_f , feed force) are shown in Fig. 7. The simulated thrust and feed forces for uniform honed insert are found to be close agreements with the experimental ones.

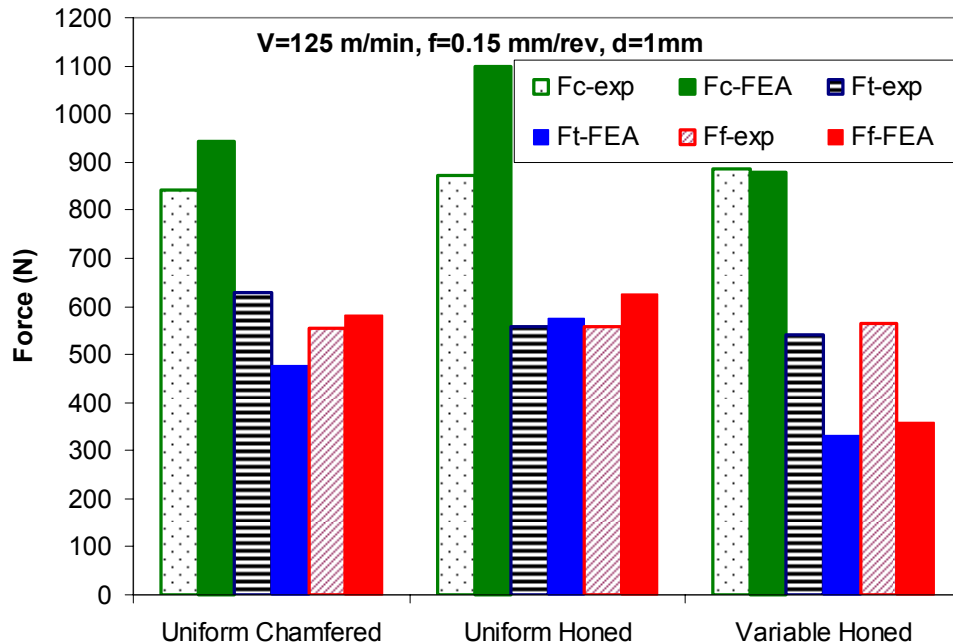


Fig. 7. Comparison of measured and simulated forces for various micro-geometry inserts

Predicted temperature distributions on the tool are shown in Fig. 8 for three different edge preparation inserts. These distributions depict that smallest hot zone formed on the variable honed tool and maximum temperatures of 730 °C, 783 °C and 719 °C were predicted for uniform chamfered, uniform honed and variable honed inserts respectively.

6. CONCLUSION

In this paper, a methodology for variable cutting tool micro-geometry design is explained. Cutting experiments and 3-D finite element analysis are performed to compare uniform and variable edge preparations. These results revealed that the variable edge preparation inserts perform better than uniform edge preparation counterparts if the variable edge is properly designed for the given cutting conditions. 3-D FEA based process simulations can be utilized for more detailed investigations in predicting tool wear and workpiece integrity. An experimental performance assessment of edge preparations in terms of tool life, workpiece surface roughness and integrity is left for future studies.

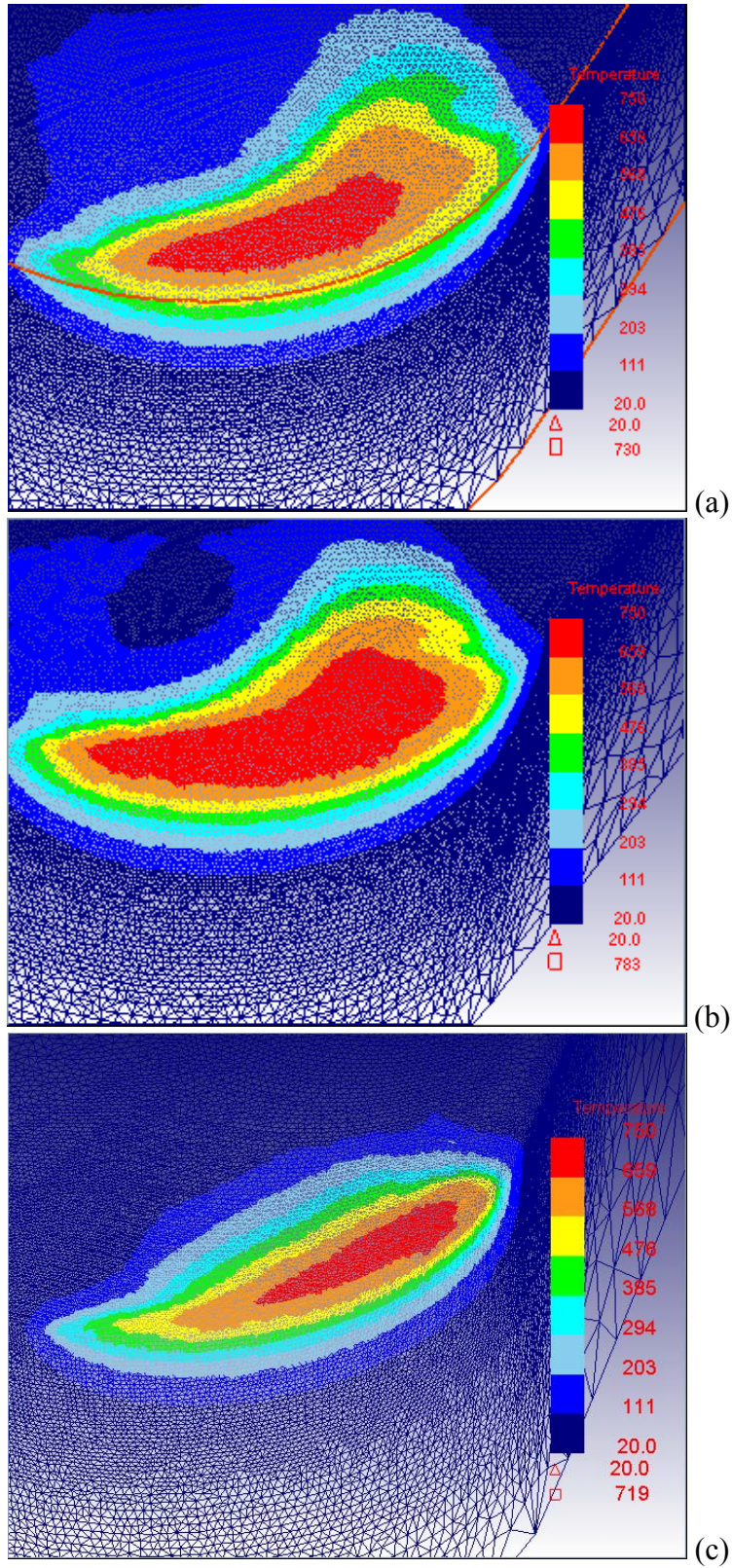


Fig. 8: Temperature distributions simulated for machining with (a) uniform chamfered, (b) uniform honed and (c) variable honed inserts.

References

- Ceretti, E., Lazzaroni, C., Menegardo, L., and Altan, T. (2000) "Turning simulations using a three-dimensional FEM code," *Journal of Materials Processing Technology*, Vol. 98, pp. 99-103.
- Conicity Technologies, (2006), www.conicity.com
- Endres, W.J. and Koutanya, R. (2002), "The effects of corner radius and edge radius on tool flank wear," *Transactions of NAMRI/SME*, Vol. 30, pp. 401-407.
- Guo, Y. and Dornfeld, D. A. (1998) "Finite element analysis of drilling burr minimization with a backup material," *Transactions of NAMRI/SME*, Vol. XXVI, pp. 207-212.
- Guo, Y. and Liu, C.R. (2002) "3D FEA modeling of hard turning," *ASME Journal of Manufacturing Science and Engineering*, Vol. 124, pp. 189-199.
- Karpat, Y. and Özel, T. (2006a) "An Integrated Analytical Thermal Model for Orthogonal Cutting with Chamfered Tools," *Transactions of NAMRI/SME*, Vol. 34, pp. 611-625.
- Karpat, Y. and Özel, T. (2006b) "Identification of Friction Factors for Chamfered and Honed Tools Through Slip-line field Analysis," *Proceedings of 2006 ASME International Conference on Manufacturing Science and Engineering*, Paper No. 21127, October 8-11, 2006, Ypsilanti, MI.
- Klocke, F. and Kratz, H. (2005) "Advanced Tool Edge Geometry for High Precision Hard Turning," *Annals of CIRP*, 54/1/2005, pp.47-50.
- Liu, R. and Shih, A. (2006) "Finite element modeling of 3D turning of titanium," *International Journal of Advanced Manufacturing Technology*, Vol. 29, No 3-4, pp. 253-261.
- Ren, H. and Altintas, Y. (2000) "Mechanics of Machining with Chamfered Tools", *ASME Journal of Manufacturing Science and Engineering*, Vol. 122, pp. 650-659.
- Gray, G.T., Chen S.R., Wright W., and Lopez M.F., (1994) "Constitutive Equations for Annealed Metals under Compression at High Strain Rates and High Temperatures," *Los Alamos National Laboratory Report*, LA-12699-MS.