



Effect of Rake Angle on Stress, Strain and Temperature on the Edge of Carbide Cutting Tool in Orthogonal Cutting Using FEM Simulation

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Abstract. Demand for higher productivity and good quality for machining parts has encourage many researchers to study the effects of machining parameters using FEM simulation using either two or three dimensions version. These are due to advantages such as software package and computational times are required. Experimental work is very costly, time consuming and labor intensive. The present work aims to simulate a three-dimensional orthogonal cutting operations using FEM software (deform-3D) to study the effects of rake angle on the cutting force, effective stress, strain and temperature on the edge of carbide cutting tool. There were seven runs of simulations. All simulations were performed for various rake angles of -15 deg, -10 deg, -5 deg, 0 deg, +5 deg, +10 deg, and +15 deg. The cutting speed, feed rate and depth of cut (DOC) were kept constant at 100 m/min, 0.35 mm/rev and 0.3 mm respectively. The work piece used was ductile cast iron FCD500 grade and the cutting tool was DNMA432 series (tungsten, uncoated carbide tool, SCEA = 0; and radius angle 55 deg). The analysis of results show that, the increase in the rake angle from negative to positive angle, causing the decrease in cutting force, effective stress and total Von Misses strain. The minimum of the cutting force, effective stress and total Von Misses strain were obtained at rake angle of +15 deg. Increasing the rake caused higher temperature generated on the edge of carbide cutting tool and resulted in bigger contact area between the clearance face and the workpiece, consequently caused more friction and wear. The biggest deformation was occurred in the primary deformation zone, followed by the secondary deformation zone. The highest stress was also occurred in the primary deformation zone. But the highest temperature on the chip usually occurs in secondary deformation zone, especially in the sliding region, because the heat that was generated in the sticking region increased as the workpiece was adhered by the tool and later it was sheared in high frictional force.

Keywords: *cutting force; deform-3D; effective stress; finite element method; orthogonal cutting; rake angle; total Von Misses strain.*

1 Introduction

Finite Element Analysis (FEA) technique was first introduced in 1960s and has been widely used in designing tools and forming processes. Based on the success of FEM simulations for bulk forming processes, many researchers developed their own FEM codes to analyze metal cutting processes during the early 1980s up to now (Marusich, et al. [1]; Cerenitti, et al. [2][3]; Xie, et al. [4]; Shet [5]; and Jawahir [6]). Cerenitti, et al. [2] assumed a rigid sharp tool and elasto-plastic workpiece, and defined a node separation criterion based on the geometry of the element approaching the edge of cutting tool. Cerenitti, et al. [2] used an early version of a commercial implicit FEM code DEFORM-2D™. This code uses four-node quadrilateral elements and is based on static Lagrangian formulation. Columbus [7] introduced DEFORM-3D™ code that has been commonly used by researchers and industry in machining simulation. Applications of FEM models for machining can be divided into six groups: a) tool edge design, b) tool wear, c) tool coating, d) chip flow, e) burr formation and f) residual stress and surface integrity. The direct experimental approach to study machining processes is expensive and time consuming. For solving this problem, the finite element methods are most frequently used. Mackerle [8] proved that modeling tool wear using FEM has advantages over conventional statistical approach because it requires less experimental effort and it provides useful information such as deformations, stress, strain and temperature in chip and the workpiece, as well as the cutting force, tool stress and temperature on the tool working under specific cutting parameter.

This paper presents the application of FEM simulation to predict the effect of rake angle on cutting force, effective stress, total Von Mises strain and temperatures on the edge of carbide cutting tool in the orthogonal machining process.

2 Methodology

Seven runs of simulation were conducted for various design of rake angles in positive rake angles (+15, +10, and +5 deg), 0 deg, and negative rake angles (-5, -10, and, -15 deg). The machining parameter, like the cutting speed, feed rate and depth of cut, were kept constant at 100 m/min, 0.35 mm/rev and 0.3 mm respectively as given in Table 1.

The work piece was ductile cast iron FCD500 grade and the cutting tool used was DNMA432 series (tungsten, uncoated carbide tool, SCEA= 0; and radius angle of 55 deg). This material was chosen as the workpiece material in this study because it was widely used in automotive component. Table 2 shows the composition of ductile cast iron FCD500 grade.

Table 1 Input parameters in the simulation process.

Parameters	
Cutting speed	100 m/min
Feed rate	Kept constant at 0.35 mm/rev
Depth of cut (DOC)	Kept constant at 0.3 mm

Table 2 Composition of ductile cast iron FCD500 grade.

Element percentage (%)											
C	Si	S	P	Mn	Ni	Cr	Mg	Cu	Mg	Al	Co
2.77	1.26	0.11	0.036	1.24	0.26	0.27	0.09	0.18	0.127	0.063	0.073

Source: Sirim, 2008

Figure 1 shows the geometry and schematic of orthogonal cutting condition model for the rake angle of +15 deg. The flow stress model used was the equation given by Oxley [9] as shown in Table 3.

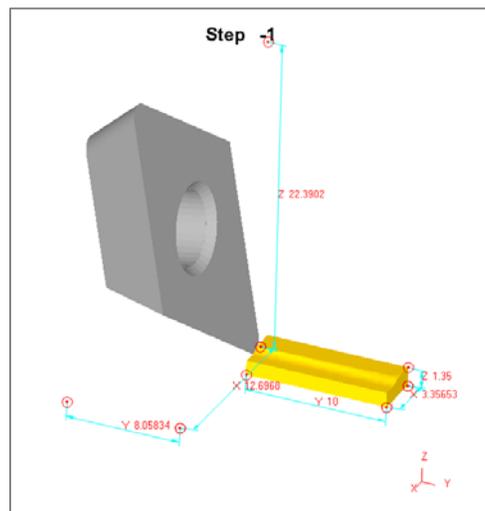


Figure 1 Geometry and schematic of the orthogonal cutting condition model for rake angle of +15 deg.

In these simulations, the tools were defined to be an elastic body and isothermal, so the mechanical and thermal properties and also boundary condition for simulation model are given in Table 4.

Table 3 Flow stress models used in simulation.

Material Model	Equation for flow stress σ models	Material constants	Variables
Oxley model	$\sigma = \sigma_1 \epsilon^n$	$\sigma_1, n = f(T_{mod})$	$\epsilon, \dot{\epsilon}, T$

Table 4 Mechanical and thermal properties and boundary condition for the simulation model.

Tool geometry of DNMA432 (WC as base material, uncoated carbide tool)	
Rake angle (deg)	-15 -10 -5 0 5 10 15
Nose angle (deg)	55
Tool properties	
Modulus Young (GPa)	500
Modulus of elasticity (GPa)	641
Poison ratio	0.26
Boundary condition	
Initial temperature (°C)	20
Shear friction factor	0,5
Heat transfer coefficient at the workpiece-tool interface (N/s. mm°C)	45
Workpiece geometry (ductile cast iron FCD500 grade)	
Depth of cut	0,3
Width of cut (mm)	3,4
Length of workpiece	10

The chosen cutting tool insert carbide was DNMA432 series that has a nose angle of 55 deg and without use of coolant. Using deform 3D, seven model of cutting tools were set up in positive rake angle (+15, +10, and +5 deg), 0 deg, and in negative rake angle (- 5, -10, and -15 deg) as shown in Figure 2.

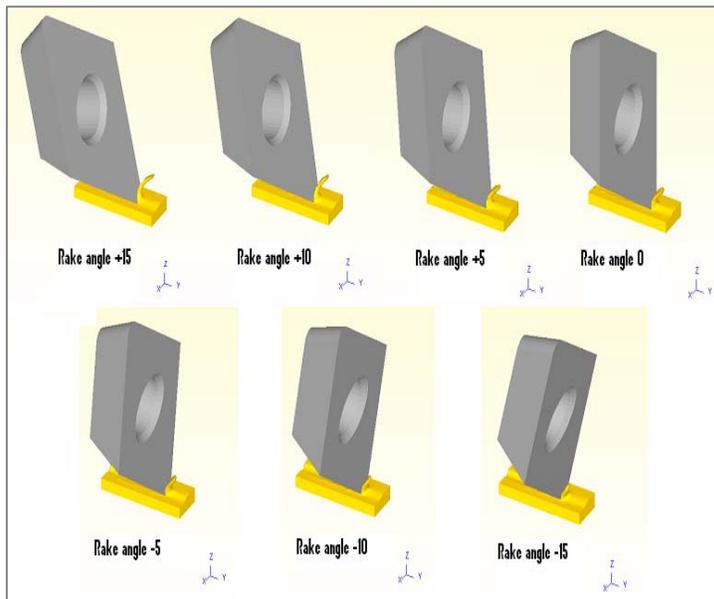


Figure 2 Various set up of rake angles in positive section (+15,+10, and +5 deg, 0 deg, and negative section (-5, -10, and -15 deg).

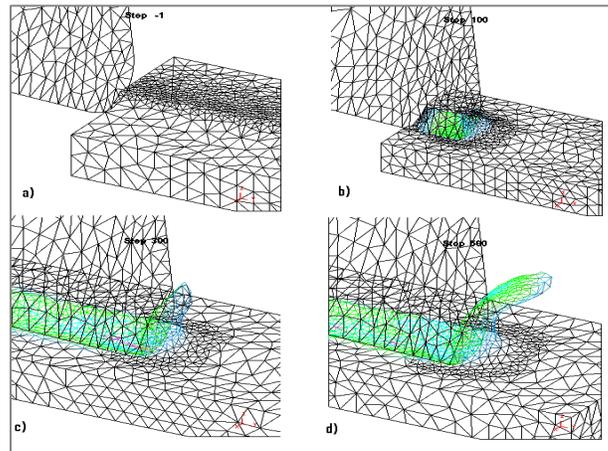


Figure 3 (a) Initial mesh and tool indentation, (b) Chip formation at step 100, (c) Chip formation at step 300, (d) Developed continuous chip at step 500.

The chip formation from initial mesh and tool indentation in the beginning of cutting process until the developed continuous chip formations at step 100, 300 and 500 are as illustrated in Figure 3a, 3b, 3c and 3d respectively.

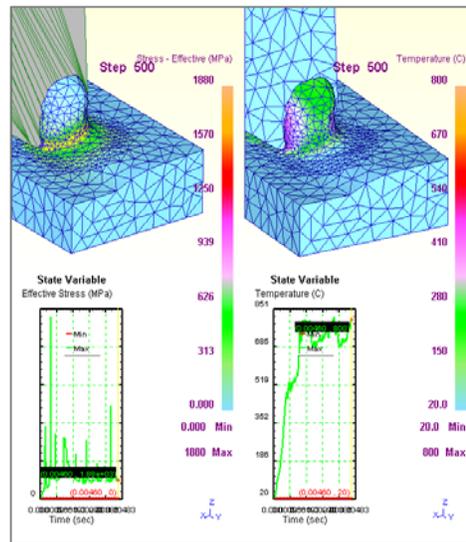


Figure 4 Example of the transient simulation result for the cutting speed of 100 m/min and rake angle of +5 deg (after running in 500 steps).

The workpiece and the tool are characterized by non uniform mesh distribution in the simulation. Very small element is required in the contact area between tool and workpiece because of very large temperature gradient and stress that will be developed in this region during the simulation. Figure 4 shows an example of transient simulation result for rake angle of +15, the cutting speed of 100 m/min, feed rate of 0.35 mm/rev and DOC of 0.3 mm, at 500 steps of simulation running. The simulations were done in two series. First, simulations were carried out to investigate and analyze the tool stress, strain and temperature on the edge of carbide cutting tool. Second series, simulations were performed to investigate the workpiece and chip deformation. The results of these simulations were the stress, strain and generated temperature on chip formation and workpiece. Both series of simulation results, cutting force, the effective stress, strain and generated temperature were studied and analyzed.

3 Results and Discussion

3.1 Effects on Stress, Strain and Generated Temperature on The Edge of Carbide Cutting Tool

Figures 5 and 6 show the effective stress and the total Von Misses strain on the edge of carbide cutting tool for a rake angle of +15 deg; cutting speed of 100 m/min, feed rate of 0.35 mm/rev and depth of cut of 0.3 mm. The highest effective stress of 266 MPa was reached at contour line I, followed by 233 MPa at contour line H, and reduced to minimum value of 33.3 MPa at contour line B, then followed by other areas around the carbide tool that experienced the effective stress of 0 MPa (Figure 5).

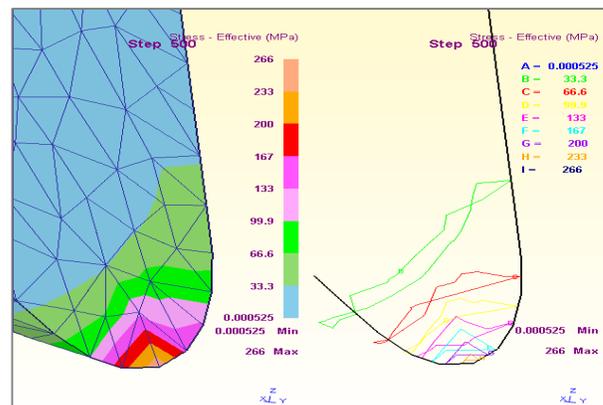


Figure 5 Effective stress at the edge of carbide cutting tool for rake angle of + 15 deg, cutting speed of 100 m/min, feed rate of 0.35 mm/rev and DOC of 0.3 mm.

Similarly, the highest of total strain von misses of 0.000386 mm/mm was reached at contour line I and followed by 0.000338 mm/mm at contour line H etc., the minimum of total Von Misses strain was 0.0000483 mm/mm at contour line B, followed by other areas around the carbide tool that had zero value of strain (Figure 6).

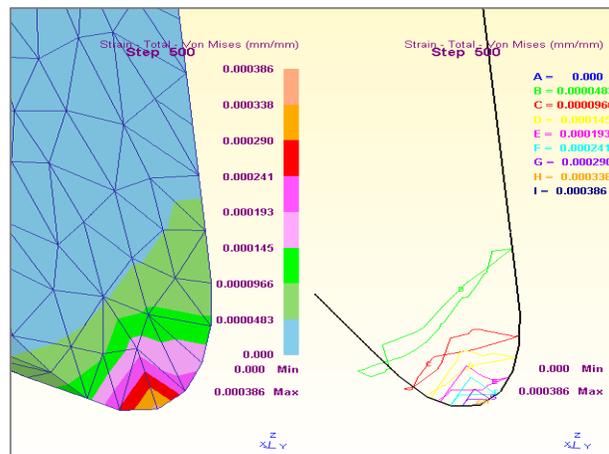


Figure 6 Total Von Mises strain at the edge of carbide cutting tool for rake angle of +15 deg, cutting speed of 100 m/min, feed rate of 0.35 mm/rev and DOC of 0.3 mm.

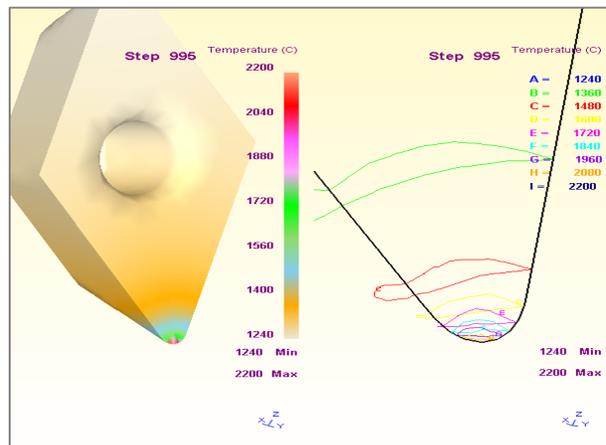


Figure 7 Generated temperature on the edge of carbide cutting tool for rake angle of + 15 deg, cutting speed of 100 m/min, feed rate of 0.35 mm/rev and DOC of 0.3 mm.

The reasonable temperature occurred on the edge of carbide cutting tool were found by running at steady state simulation until 1000 steps. The temperature distribution is shown in Figure 7 where the highest of temperature occurred at the end of the cutting edge around 2200°C (contour line I), followed by contour line H around 2080°C etc., and the minimum temperature was 1360°C (contour line B), followed by other area of the carbide tool at temperature of 1240°C.

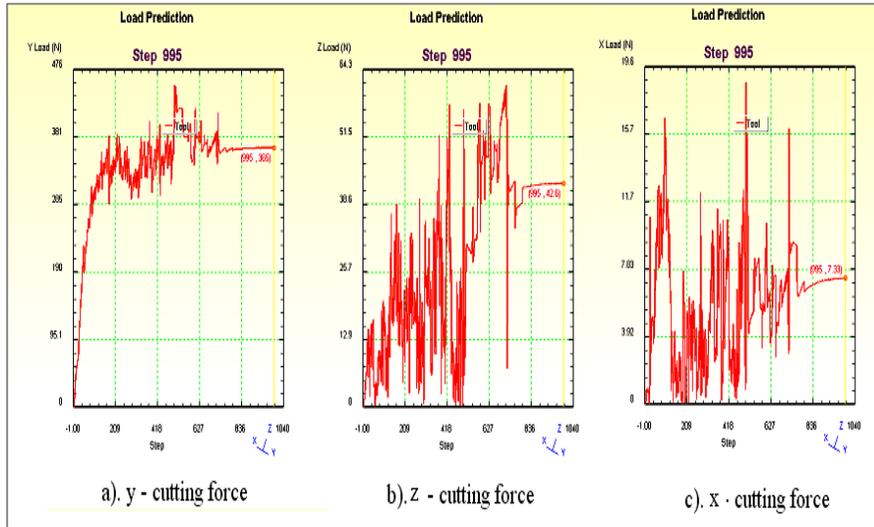


Figure 8 The generated main cutting force in three directions during the cutting simulation processes (rake angle of + 15 deg, cutting speed of 100 m/min, feed rate of 0.35 mm/rev and DOC of 0.3 mm. a) y-cutting force, b) z-cutting force, and c) x-cutting force.

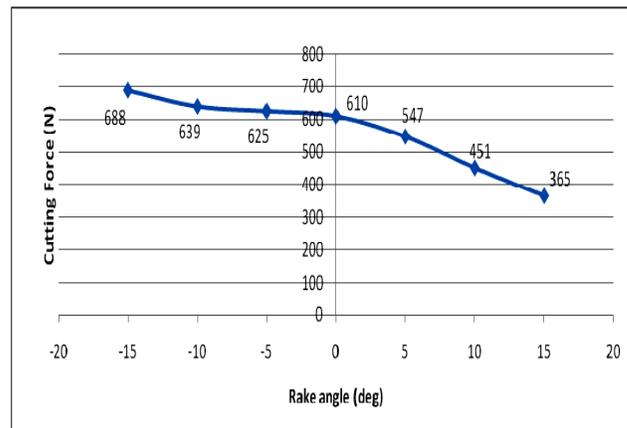
Figure 8a, 8b and 8c show the main cutting force generated in y, z and x-directions respectively during the cutting simulation processes for the rake angle of + 15 deg; cutting speed of 100 m/min, feed rate of 0.35 mm/rev and depth of cut 0.3 mm. The cutting forces were fluctuating in the transient simulation, and remained constant in steady state simulation (above 500 steps), the measured value in y direction was around 365 N and followed by z and x-directions of 42.6 N and 7.33 N respectively (Figure 7).

The other simulation results of the cutting force (in y-direction), effective stress, total Von Mises strain and generated temperature for other variations of rake angles are shown in Table 5.

Table 5 The cutting force in y axis, effective stress, and total Von Mises strain and generated temperature on the edge of carbide cutting tool in various rake angles.

No	Rake angle [deg]	Cutting speed [m/min]	Feed rate [mm/rev]	DOC [mm]	Cut. force [N]	Eff. Stress [MPa]	Total. Von Misses strain [mm/mm]	Temp [°C]
1	+15	100	0.35	0.3	365	266	0.000386	2200
2	+10	100	0.35	0.3	451	304	0.00041	1770
3	+5	100	0.35	0.3	554	357	0.000484	1560
4	0	100	0.35	0.3	610	554	0.000754	1170
5	-5	100	0.35	0.3	625	539	0.000735	1120
6	-10	100	0.35	0.3	639	666	0.000909	1010
7	-15	100	0.35	0.3	688	774	0.00105	981

The prediction of the cutting force, effective stress, total Von Mises strain and generated temperature on the edge of carbide cutting tool for various rake angles are shown in Figures 9, 10, 11 and 12 respectively.

**Figure 9** The cutting force at the edge of carbide cutting tool in various rake angles of +15, +10, +5 deg (positive section), 0 deg, and rake angle of - 5, -10, and -15 deg (negative section).

As shown in Figure 9, the cutting force decreases while rake angles increases. Transition from the rake angle of -15 deg to +15 deg caused the decrease of the cutting force from 688 N to 365 N. In other words, the increase of the rake angle from 0 deg to +15 deg had reduced the cutting force from 610 N to 365 N, on the other hand, increasing the rake angle had increased the cutting from 610 N to 688 N.

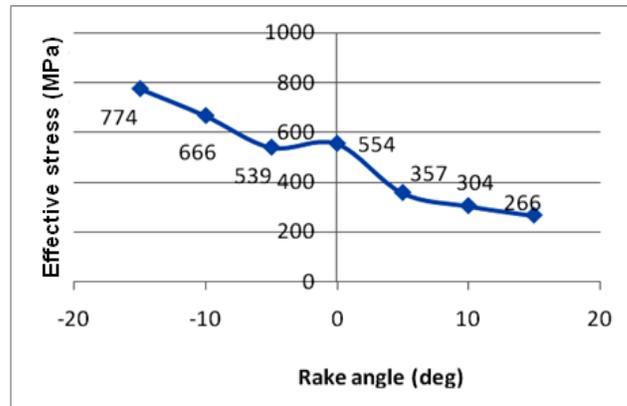


Figure 10 The effective stress on cutting edge in positive rake angle (+15, +10, and +5 deg), 0 deg, and negative rake angle (- 5, -10, and -15 deg).

This phenomenon is agreeable with the experiment done by Gunay, et al. [10]. According to him, the main cutting force was reduced by increasing the rake angle in positive direction and was increased by increasing rake angle in negative direction.

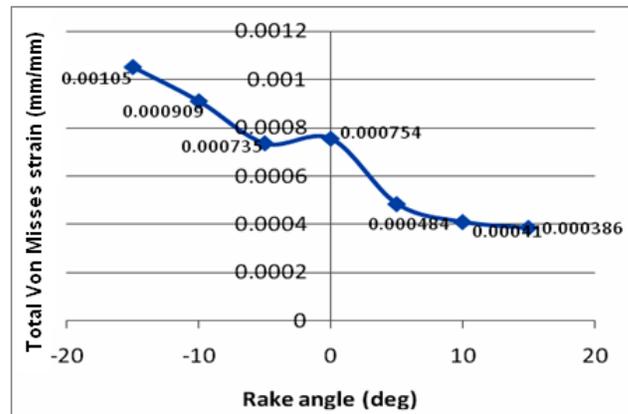


Figure 11 The total Von Misses strain on cutting edge in positive rake angle (+15, +10 , and +5 deg) , 0 deg, and negative rake angle (- 5, -10, and -15 deg).

Figures 10 and 11 show the affective stress and the total Von Misses strain on the edge of carbide cutting tool in negative rake angle (+15, +10, and +5 deg), 0 deg, and positive rake angle (- 5, -10, and -15 deg). The trend was similar for

effective stress and total Von Misses strain plots, i.e. increase the rake angle in positive direction had decreased the effective stress from 554 to 226 MPa and total Von Misses strain from 0.000754 to 0.000386 mm/mm respectively. Whereas, increasing the rake angle in negative section, had increased the effective stress to the maximum, i.e. 554 MPa to 774 MPa. Similarly for the total Von Misses strain that reached the maximum at 0.00105 mm/mm (at rake angle of -15 deg). This was agreeable with Lo [11] who found that the normal and effective stress acting on the edge of carbide cutting tool decreases with increases in rake angle from negative to positive value. According to him, the stress on the edge of carbide cutting tool decreases when rake angle increases. Figure 12 shows that the temperature on the cutting edge of carbide tool had increased from 1170°C to 2200°C when the rake angles were increased from 0 to +15 deg. The temperature were decreased from 1170°C to 981°C when the rake angles were increased from 0 to -15 deg. This is agreeable with theory about friction and contacted wear that will be explained later. In this simulation, the carbide tool was designed with constant geometrical model, whereas, the rake and clearance angles were varied accordingly.

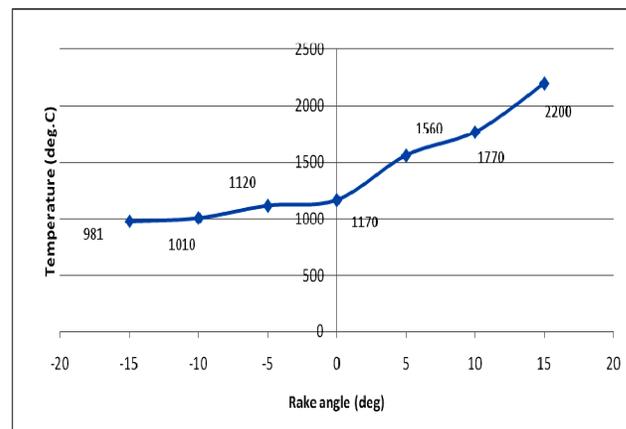


Figure 12 The generated temperature on cutting edge at positive rake angle (+15, +10, and +5 deg), 0 deg, and at negative rake angle (-5, -10, and -15 deg).

Change of the rake angle had caused the clearance angle to be changed accordingly, i.e. when the rake angle was increased to certain degrees, the clearance angle was also decreased with the same degree. For example, when the rake angle was increased from +5 to +10 deg, the clearance angle will accordingly also decreased from 15 to 10 deg as illustrated in Figure 13. In other word, as the rake angle was increased in certain degrees, the clearance

angle decreased in the same degrees. Smaller clearance angle caused more the area contact and friction between the clearance face and work piece, then caused more temperature on the cutting tool during cutting process with increasing rake angle (decreasing clearance angle).

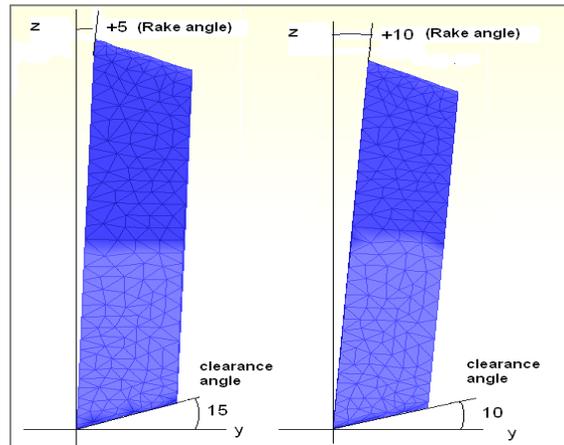


Figure 13 Change of the rake angle in 5 deg, cause the clearance changed conversely in 5 deg (The clearance angle changed, but shape is remained constant).

The larger the contact area between the clearance face and work piece, the more friction occur during machining, consequently more wear occurred that contribute to more temperature generated on the edge of carbide cutting tool. This was also agreeable with the theory that the smaller the clearance angle, the bigger the contact area between the clearance face and the work piece as found by Stephenson, et al. [12] and Yanda, et al. [13]. Coelho, et al. [14] found that small changes in clearance angle will greatly influence the wear mechanism and consequently the tool life.

Besides, this also agreeable with Cerenitti [15] who conducted the machining simulation for AISI 1045 in various rake angles from -5 to 50 deg. They said that the maximum temperature of the tool cutting increased with increasing tool rake angle while the chip temperature decreased with increasing tool rake angle.

3.2 Stress, Strain and Generated Temperature on Workpiece

The biggest deformation was occurred in the primary deformation zone, followed by the secondary deformation zone as shown in Figure 14. This also caused the higher effective stress occurred in this section, which reached 1920 MPa (contour line I). This result is agreeable with Kalhori [16] where the major

deformation during cutting process were concentrated in two region close to the cutting edge, and the bigger deformation were occurred in the primary deformation zone, followed by the secondary deformation zone.

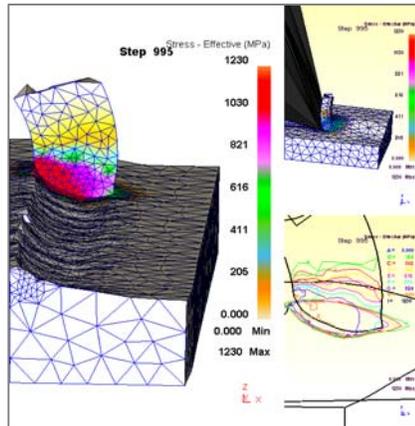


Figure 14 Effective stress in work for the rake angle of +15 deg, cutting speed of 100 m/min, feed rate of 0.35 mm/rev and depth of cut of 0.3 mm.

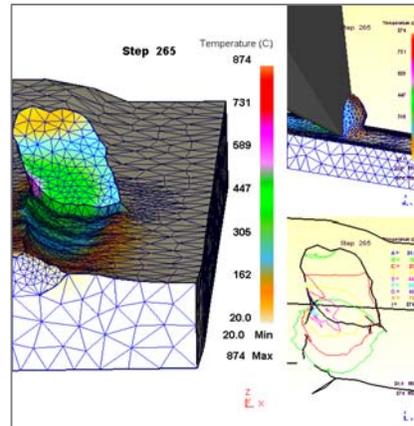


Figure 15 Generated temperature on chip formation for the rake angle of +15 deg, cutting speed of 100 m/min, feed rate of 0.35 mm/rev and depth of cut 0.3 mm.

The temperature on workpiece can be analyzed in detail based on the contour in Figure 14. A higher temperature of 874°C in contour lines I is obtained, followed by H (767°C), G (660°C) and etc. Figure 15 shows the contour of effective stress on workpiece and chip formation. The highest temperature on the chip usually occurred in this sliding region, while the heat generated in the sticking region caused the workpiece material to adhere with the tool. Later it was sheared which resulted in high frictional force, consequently high temperature was generated. These results are also agreeable with finding of Kalthori [16]. According to El-Hofy [17], theoretically, most of heat or generated temperature is carried away by the chip. The theory also tells that during the machining, it is assumed that all the cutting energy is converted to heat and, therefore, a considerable amount of heat is generated at the following three distinct zones, these are 1). Shear zone (75%); 2). Chip sliding on the tool face (20%); c). Tool sliding on the workpiece machined surface (5%) which neglected for perfectly sharp cutting tools. The maximum heat is produced at the shear zone because of the plastic deformation of the metal, practically all of this heat is carried away by the chip.

4 Conclusion

Based on the simulation results, it can be concluded that:

- a. Increasing the rake angle in positive section caused the decrease of the cutting force. On the other hand, increasing the rake angle in negative section, increases the cutting force.
- b. Increasing the rake angle in positive section decreasing the effective stress, and the total Von Misses strain, especially at the rake angle of +15 deg those values are minimum. On the other hand, increasing the rake angle in negative section increases the effective stress and total Von Misses strain. The minimum total Von Misses strain was obtained at the rake angle of +15 deg. Therefore, the optimum cutting force, effective stress and total Von Misses strain for this simulation is obtained at rake angle of +15deg.
- c. Increase of the rake angle caused to be reduced accordingly the clearance angle. Smaller clearance angles caused more the contact area and friction between the clearance face and the work piece, this also increased the temperature on cutting edge. The optimum temperature was obtained at rake angle of -5 deg.
- d. The biggest deformation (chip formation) was occurred in the primary deformation zone, followed by the secondary deformation zone. Therefore the highest stress was also occurred in this area. The highest temperature on the chip usually occurred in the sliding region, while the heat generated in the sticking region caused the workpiece material to adhere with the tool. Later, it was sheared which resulted the high frictional force and generated higher temperature in the sliding region.
- e. All of the results are agreeable with theory and some simulations and experimets in references.

Acknowledgment

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