Paper Number: NTC-2009-004

MACHINING AND CUTTING SIMULATION: EFFECT OF RAKE ANGLE AND CLEARANCE ANGLE ON WEAR CUTTING INSERT CARBIDE

[1]Hendri. Y., [2]Jaharah A.G., [3]Che Hassan C.H.
Department of Mechanical and Materials Engineering,
Faculty of Engineering and Built Environment,
Universiti Kebangsaan Malaysia,
43600 Bangi, Selangor,
Malaysia
[1]*hyanda@eng.ukm.my*, [2]*jaharah@eng.ukm.my*, [3]*chase@eng.ukm.my*

Abstract

High production rates at minimum cost will also be achieved by selecting correct cutting tool geometry for a particular combination of work material and cutting tool. Problem facing in precision turning is how to minimize tool wear in order to obtain good accuracy of geometrical part and surface finish. In this study the effect of changing the insert carbide geometries of rake angle to the wear level was investigated. The tungsten carbide insert type of DNMA 432 was used as cutting tool. FCD 500, a ductile cast iron, was chosen as work material. The seven series of simulations using Deform-3D were carried out using various tool geometries, whilst the cutting speed, feed rate and depth of cut were kept constant at 200 m/s, feed 0.35 mm/rev, and 0.3 mm respectively. Some combination of carbide insert geometries were set up to produce -15,-10, -5 deg (negative rake angle), 0 and +5, +10, +15 deg (positive rake angle) using pre processor of Deform-3D. Changing rake (followed by change of clearance angle) resulted in changes in the cutting forces, therefore causes the change of the wear depth in the tool edge of carbide insert. The simulation results were agreeable with theory, where increase in rake angle, caused conversely decreasing clearance angle and will be bigger area contact between of clearance face and work piece surface, so this caused increase of tool wear.

Keywords: *tool wear, wear depth, rake angle, stress force, finite element analysis*

1. Introduction

To increase the efficiency of cutting, carbide tool insert geometries are continually being improved. Thought their cutting distance to life can only be determined by cutting tests under real operating conditions, model wear test are useful for the preselection of tool geometries [1].

Gunay. M et al [2] wrote that the main cutting force was reduced by increasing rake angle in positive and was increased by increasing rake angle in negative value.

The simulation as one of model test is particularly important because cutting test is very expensive and need more rush time. Testing and simulation of this can be done by using Finite Element Analysis.

The aim of the investigations was presented of finding in a one part of ongoing research results in modeling and simulation FEM of machining processes. In this study, some model wear tests were applied to investigated how the wear depth happened when geometries, especially rake angle (α) of DNMA's insert carbide are changed in case of orthogonal turning cutting machining.

During cutting, the rake and flank faces of the cutting tool slide against the surface of the work piece material (Figure 1). In this study, the rake angle was changed in some combination from -15 to +15 deg. The clearance angle was also change in following the change of rake angle Finite Element Analysis (FEA) technique was the first introduced in 1960s and has been widely used to analyze 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 [3], [4], [5], [6] and [7].

Cerenitti et al [3] assumed a rigid sharp tool and elasto-plastic work piece, and defined a node

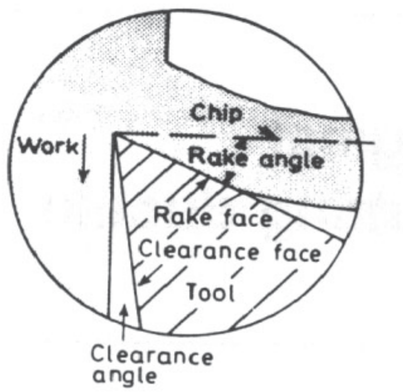

Fig.1. Terminology of Cutting tool and Workpiece material

separation criterion based on the geometry of the element approaching the cutting edge. Cerenitti et al. [3] 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. Today, DEFORM-3D™ code is commonly used by researchers and industry in machining simulation [8].

Currently Deform-3D system has Archard's model and Usui's model apart from the user routine support. Especially, Usui's model is used for machining applications to compute insert wear. Archard's model can used with either isothermal or non-isothermal runs, On the other hand Usui's model can be run only be used with non-isothermal run as it required interface temperature calculations as well [9], [10].

Applications of FEM models for machining can be divided into six groups: 1) tool edge design, 2) tool wear, 3) tool coating, 4) chip flow, 5) burr formation and 6) 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. 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, stresses, strain and temperature chip and the work piece, as well as the cutting force, tool wear, tool stress and temperature on the tool working under specific cutting parameter [10].

2. Methodology

One of the important parameters in the orthogonal metal cutting process is the rake angle between the face of the cutting tool and the plane perpendicular to the cutting direction. The magnitude of tool cutting geometries has significant effects on the performance of the cutting tool and the integrity of the cut surface. The main objective of this research is to apply the finite element method to study the rake angle and clearance angle effects in orthogonal metal cutting of ductile cast iron with continuous chip formation, while the other machining parameters of feed rate and depth of cut were kept constant. Finite element simulation results of the orthogonal metal cutting using seven sets of perfectly sharp cutting tools for DNMA 432 Insert Carbide with rake angles -15, -10, -5, 0 and +5, +10, +15 deg. The commercial software Deform-3D for doing tool wear analysis was used to simulate orthogonal metal cutting process. It is based on an updated Lagrangian formulation and employs an implicit integration scheme.

Figure 2 shows geometry and schematic of orthogonal cutting condition model using DNMA 435 insert carbide and work piece.

The three-dimensional finite element model was generated under a plane strain assumption because the width of cut was larger than the undeformed chip thickness in this orthogonal cutting arrangement. The flow stress behavior of the work material and the contact conditions were used as equation for flow stress σ models, $\sigma = \sigma_1 \varepsilon^n$ [11]. Physical and thermo-mechanical properties of the work piece and tool materials, and cutting conditions are predefined are shown in Table 1.

The work piece material was FCD 500 (ductile cast iron). This material had been selected as the work piece material in this study because currently, this material was much used in automotive application and had been interesting become the focus of many recent modeling studies. The tool is modeled as a rigid body, so there are no mechanical properties need to be assigned and only thermal properties are needed. The cutting condition to the simulation models and the mechanical properties of carbide cutting tool and work piece are shown in Table 2. The tool was defined to be a rigid body which considers thermal transfer for modeling the cutting temperature field. The model of insert should be meshed, with appropriate boundary conditions and inter-object relations defined.

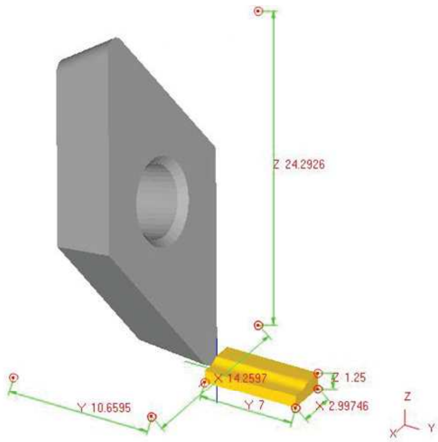

Fig.2. Geometry and schematic of orthogonal cutting condition model

Table 1 Input Parameters in the simulation process

Cutting Speed (m/min)	200 m/min (constant)
Feed Rate	0.35 mm/rev (constant)
Depth of cut	0.3 mm (constant)
Nose Angle (^{o}C)	Kept constant at 55 ^{o}C
Rake Angle (α), deg	-15 -10 -5 0 +15 +10 +5

Table 2 Cutting condition to the simulation models and material properties

Tool Geometry of DNMA 432 (WC as base material, uncoated carbide tool)	
Side Cutting Edge Angle (SCEA)	-3
Back Rake Angle (BR) (deg)	-5
Side Rake Angle (SR) (deg)	-5
Nose Angle (^{o})	55
Tool properties (uncoated carbide)	
Modulus Young (GPa)	650000
Thermal Expansion	5e-06
Poison Ratio	0.25
Boundary Condition	
Initial Temperature (^{o}C)	20
Shear friction factor	0,6
Heat transfer coefficient at the interface (N/s mm°C)	45
Work piece geometry	
Depth of cut	0,3
Width of cut (mm)	3,4
Length of workpeace	7
Work piece properties (FCD 500; Poisson's ratio, 0.25)	
Modulus of elasticity (kN/mm^2)	169
Thermal Conductivity (W/m. °C)	35.2
Thermal expansion Coeff. (10^{-6} °C^{-1})	12.5
Heat capacity (N/mm2 ° C)	3.7
Emissivity	0.95

Deform software had been used to simulate the effect of change in tool cutting geometries (rake angle) when turning ductile cast iron using DNMA 432 uncoated carbide cutting tool (Figure 3). The simulations were performed by changing the rake angle only while the feet rate and depth of cut were kept constant at 0.35 mm/rev and 0.3 mm respectively as shown in Table 1.

The simulation results are in form of cutting force (N), and wear depth (mm), stress in around work piece contact, temperature on tool edge, chip and work piece.

Fig.3. Some variation of DNMA Cutting Insert Carbide

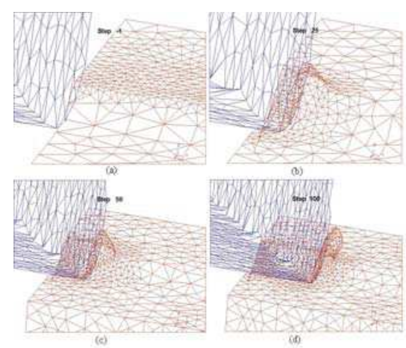

Fig.4. (a) Initial mesh and tool indentation, (b) Chip formation at step 25, (c) Chip formation at step 50, (d) Developed continues chip at step 100.

Displacement, shape and surface mesh of tool and work piece at initial mesh in the beginning of the cutting operation until the developed chip formation at step 100 as illustrated in Figure 4.

The work piece and the tool are characteristized by non uniform mesh distribution in the simulation. Very small element is required in the contact area between tool and work piece because of very large temperature gradient and stress that will develop in this region during the simulation.

Figure 5 shows an example of simulation result for cutting speed 200 m/min that was found from 200 steps of simulation running.

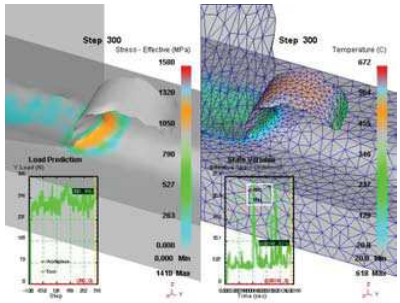

Fig.5. Example of the simulation result for cutting speed at 200 m/min (300 steps)

Wear is a constant problem in any process that includes dynamic or static components. Continuous demands for increased productivity and reduced wear cost require constant improvements in design and material properties. Typically, tools with a high hardness are used to prevent wear. But, high hardness (wear resistance) requires a compromise to toughness (impact resistance). For a long time, therefore, steels and cast irons with alloy additives were applied as standard materials. Tungsten carbide (WC), a material known for more than 70 years, opens up new possibilities concerning wear minimization in stone applications through both developments of new materials and targeted analysis of application technology. Tool life varies from customer to customer and from application to application. However, carbide provides tool life that is 10 times longer than steels (Noname, 2001).

3. Simulation Results and Discussion

After the simulations were run in seven types of rake angle combinations, the result of wear depth and cutting force read from simulation results were put in Table 3.

Table 3 Cutting condition to the simulation models and material properties

No	Rake Angle (deg)	Cuttin g Force	Wear Depth (mm)	Cutting Force
1	15	203	0.00766	203
2	10	412	0.00633	412
3	5	435	0.00603	435
4	0	451	0.00466	451
5	-5	454	0.00457	454
6	-10	494	0.00449	494
7	-15	522	0.00361	522

3.1. The Effect of Rake Angle Change on Cutting Force.

As can be seen fron Figure 6 that the cutting force decreased while the rake angles were increased. Transition from rake angle of -15 to +15 with cutting speed remained constant at 200 m/s, caused decrease of cutting force from 522N to 203N (decreased 61%).

In other meaning, increasing on rake angle on positif section from 0 deg to +15 deg, caused reduce of cutting force from 451N to 203N, and the other hand, increasing of the rake angle on negatif section caused increase the ctutting force from 451 N to 522 N.

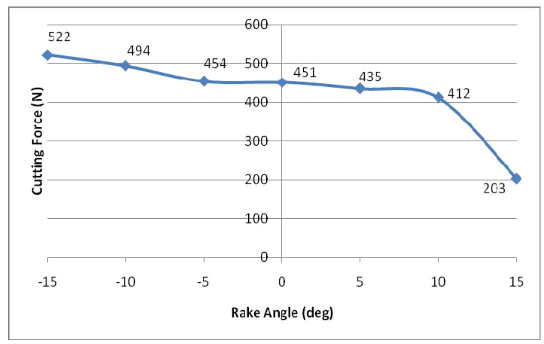

Fig.6. Effect of increase of rake angle of DNMA to cutting force

This phenomenon is agreeable with experiment by [2] that the main cutting force was reduced by increasing rake angle in positive and was increased by increasing rake angle in negative value.

3.2. The Effect of Rake Angle Change on Wear Depth.

The good result were also get for all of the graph of wear depth where the incerasing of rake angle in negative section will bring the change in cutting force, stress and strain on tool and workpiece, generated temperature on tool and workpiece.

Figure 7 , Figure 8 and Figure 9 show the depth of wear happened after simulation running in 200 steps. Upper step 42 cutting force begin look stabil or just get a bit fluactuation on 283 N. From Figure 7 can be seen that sliding and cutting process during machining process resulted wear depth on nose or cutting edge of carbide insert around 0.00766 mm on depth (+15 of rake angle), then followed by deeper wear were about 0.00307 mm, 0.00230 mm, 0.00153 mm and 0.000766 mm respectively. The same phenomenon accured for the rake angle 0 and -15, but the maximum wear depth reached for these case were 0.0046 mm and 0.00361 mm respectively (Figure 8 and Figure 9).

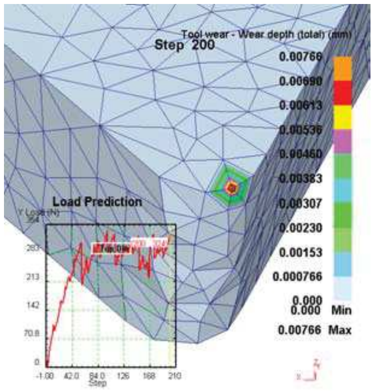

Fig.7. Wear depth for rake angle +15 maximum wear depth reached 0.00766 mm

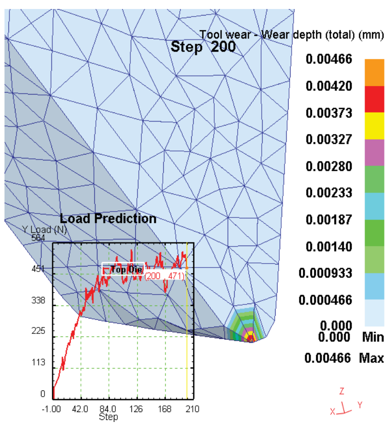

Fig.8. Wear depth for rake angle 0 maximum wear depth reached 0.00466 mm

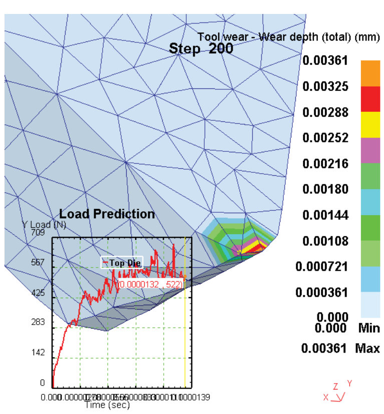

Fig.9. Wear depth for rake angle -15, the maximum wear depth reached 0.00361 mm

All of simulation result for every rake angle combination were plotted on graph as can be seen on Figure 8. In this simulation, As the rake angle that was changed, the clearance angle was also changed as the change of rake angle.

As can be seen from Figure 10, the wear depth increased, while the rake angle were increased in positif section and the wear depth decreased while the rake angle were increased in negatif section.

These were agreeable with theory that the when the clearance angle will affect to wear occurred. And, in this study, the simulations were held and just focused for DNMA 430 carbide insert type.

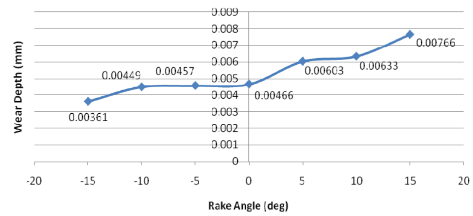

Fig..10 Effect of increase of rake angle of DNMA to wear depth (decreasing of clearance angle).

As the rake angle changed, the clearance also changed conversely following as big as rake angle change. When the rake angle was increased in 5 deg, the clearance angke will decreased in 5 deg. For example, the rake angle was increased from +5 to +10 deg, the clearance angle was decreased from from 15 to 10 deg (Figure 11).

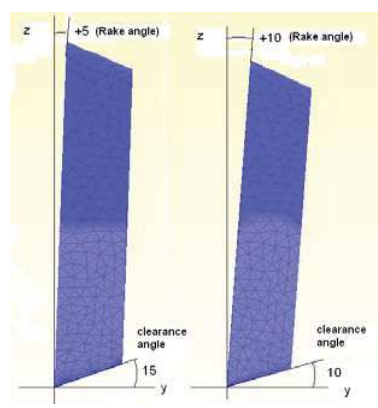

Fig.11. Change of the rake angle in 5 deg, cause the clearance changed conversely in 5 deg

Increase of rake angle on potitif section means that the clearance angle will be reduced (Figure 11). The reduce of clearance angle means that the area of contact between the clearance face with material surface increased, so this will bring to increase of wear depth. The wear depth increased by increasing rake angle (reducing clearance angle). This was agreeable with theory that the bigger contact area between clearance face and work piece, so the bigger the wear occurred as denoted by [13].

3.3. Analysis of Generated Temperature on Work Piece and Tool.

The generated temperature on chip, material surface and tool edge can be seen on Figure 12.

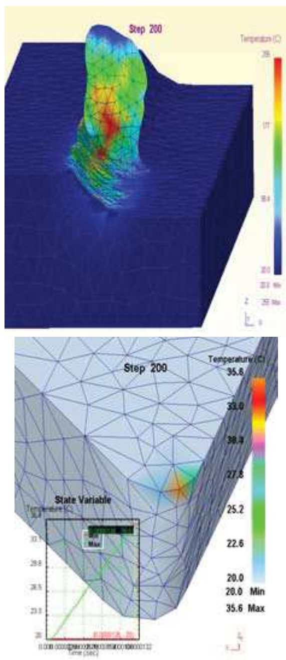

Fig.12. Generated temperature on chip, work piece and tool edge when set up of rake angle +15

As can be seen from Figure 13 that the most of heat or generated temperature is carried away by the chip (about 70%), there was maximum of generated temperature on shear zone about 255 ^{O}C and only around 35 ^{O}C generated on tool (around 10%) and its remain absorbed by work piece.

These are agreeable with the theory denoted by [14] that the maximum heat produced is at shear zone because there is the highest plastic deformation of the metal in this primary shear zone. If it is assumed that all the cutting energy is converted to heat and, so a considerable amount of heat generated at the following three distinch zones are as given Figure 11, those are 1). Shear zone (75%); 2). Chip sliding on the tool face (20%); c). Tool sliding on the

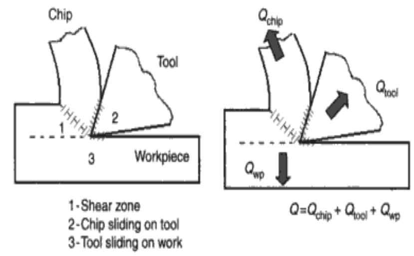

Fig.13. Heat generated and heat dissipation in metal cutting [14]

workpiece machined surface (5%) which neglected for perfectly sharp cutting tools.

3.4. Analysis of Stress and Shear on chip and Work piece

From Figure 14 can be seen that the highest stress and strain were found on the primary deformation zone, which resulted the stress about 2200 MPa and strain about 4,8 mm/mm.

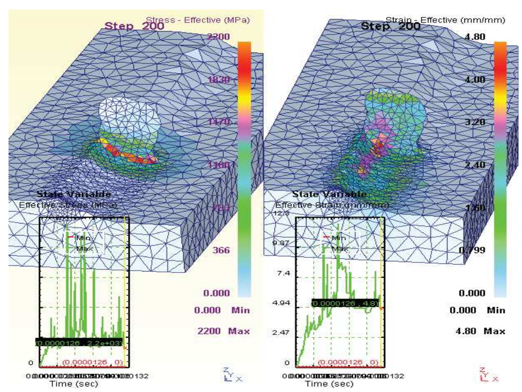

Fig.14. Stress and strain on chip and material surface when set up of rake angle +15

This result is agreeable with [15] and [16] where the major deformation during cutting process were concentrated in two region close to the cutting tool edge, and the bigger deformation were occurred in the primary deformation zone, followed by secondary deformation zone, sliding region and sticking region

4. Conclusions

The good result were get for all of the graph of wear depth where the incerasing of rake angle in positip section will cause decrease of cutting force, and increase the rake angle in negatif section cause inrease of cutting force. Stress and strain on tool and workpiece occurred in primary shear zone because highest defoemation found, the maximum generated temperature was found shear zone then get away by chip, and its remain was in tool and worpiece. The increase of rake angle (the reduce of clearance angle) means that the area of contact between the clearance face with material surface increase, so this will bring to increase of wear depth.

Acknowledgements

The authors would like to Government of Malaysia and Universiti Kebangsaan Malaysia for their financial support under 03-01-01-SF1214 and UKM-GUP-BTT-07-25-025 Grants.

References

[1] Habig, K. H., Kocker, G.M, *Simulation of the the tribological behavior of tools for cutting ductile materials,* Converence paper, presented at International Converence of Frontier of Tribology, 15-17 April 1991, IOP Publishing, Ltd, Sttratford-upon-Avon, 1992.

[2] Gunay. M, korkut. I, Seker, U, *Exsperimental inverstigation of the effect of cutting tool rake angle on main cutting force,* Journal of Material Processing Technology, 2005, vol 166: 44 – 49.

[3] Cerenitti A.E, Fallbohmer B.P, W. Wu C.W.T & Altan B.T,. *Application of 2D FEM to Chip Formation in Orthogonal Cutting,* Journal of materials Processing Technology, 1996, Volume 59: 169-180.

[4] Cerenitti.A.E., Lazzaroni.C, Menegardo. L. & Altan. T., T*urning Simulation Using a Three- Dimensional FEM Code,* Journal of materials Processing Technology, 2000, volume 98: 99-103.

[5] Marusich, T.D. & Ortiz, *Modeling and Simulation of High-Speed Machining,* To appear: International Journal Num. Metallurgy Engineering, 1995.

[6] Xie. J. Q, Bayoumi. A.E., & Zbib. H. M., *FEA Modelling and Simulation of Shear Localized Chip Formation in Metal Cutting*, Journal of Materials Processing Technology. 1998, Volume 38: 1067-1087.

[7] Shet, C., *Finite Element Analysis of the Orthogonal Metal Cutting Process*, Journal of Materials Processing Technology, 2000, Volume *105*: 95-109

[8] Columbus, O.H. , *Deform^{TM} - 3D Machining (Turning) Lab*, Scientific Forming Technologies Corporation, 2007.

[9] Deform^{TM}-3D, *Deform-3D Tool Wear lab*, Scientific Forming Technologies Corporation, 2007.

[10] Mackerle. J., *Finite Element Analysis and Simulation of Machining: a Bibliography (1976 – 1996)*, Journal of Materials Processing Technology, 1999, Volume 86: 17-44.

[11] Oxley, P. L. B., *Mechanics of Machining: An Analytical Approach to Assessing Machinability*, 223–227 (Ellis Horwood, Chichester, West Sussex). 1989.

[12] Stephenson. A.A, Agapiou, J.S, *Metal Cutting Theory and Practice*, Marcel Dekker. Inc, New York, 1996

[13] El-Hofy, H. *Fundamentals of Machining Processes: Conventional and Nonconventional Processes,* Published by CRC Press, http://books.google.com.my/books?id=ZdQEZ5pyCv4C&vq=cutting+speed&dq=affecting,+temperature,+cutting+speed&source=gbs_summary_s&cad=0. Date of download : November, 10th 2008

[14] Kalhori. V., *Modelling and Simulation of Mechanical Cutting*, Doctoral Thesis, *Institutionen for Maskinteknik*, Sweden. 2001

[15] Hendri. Y., Jaharah A.G., Che Hassan C.H. *Machining Simulation of AISI 1045 and Carbide Tool Using FEM*, Procedding Seminar Regional II, AMReG 08, 15 December 2008.