Application of FEM in Investigating Machining Performance

Hendri Yanda[1, a], Jaharah A. Ghani[2, b], Che Hassan Che Haron[3, c]

[1,2,3] Department of Mechanical and Materials Engineering,

Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia,

Bangi, Selangor Darul Ehsan, 43600 Malaysia

[a] Hyanda@eng.ukm.my, [b] jaharah@eng.ukm.my, [c] chase@eng.ukm.my

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Abstract. The two biggest problems that often experienced in machining cast iron are poor machinability and high hardness. Up to now, many researchers have investigated machining performance and how to find optimum condition in machining ductile cast iron. This study aims to investigate the machining performance of ductile cast iron and carbide cutting tool using FEM. Performances were evaluated by changing the cutting tool geometries on the machining responses of cutting force, stress, strain, and generated temperature on the workpiece. Deform-3D commercial finite element software was used in this study. Ductile cast iron FCD 500 grade was used as the work piece material and carbide insert DNMA432 type with WC (Tungsten) was used for the cutting tool. The effects of rake and clearance angles were investigated by designing various tool geometries. Various combination of carbide insert geometries were designed using Solid Work to produce +15, +20 and +30 deg for rake angle and 5, 7, 8 and 9 deg for clearance angle. Machining condition for the simulations were remained constant at cutting speed of 200 m/min, feed rate of 0.35 mm/rev, and depth of cut of 0.3 mm. The results of effective-stress, strain and generated temperature on both chip and material surface were analysed. The results show that by increasing the rake angle (α), it will improves the machining performance by reducing the cutting force, stress, strain and generated temperature on surface of workpiece. But, by increasing the clearance angle (γ), it will not affect much to the cutting force, stress, strain and generated temperature on chip.

Introduction

Finite Element Analysis (FEA) technique was the first introduced in 1960s and still widely used for analysis such as in tools design 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 [1], [2], [3], [4] and [5]. Cerenitti et al. [1] assumed a rigid sharp tool and elasto-plastic workpiece, and defined a node separation criterion based on the geometry of the element approaching the cutting edge. Cerenitti et al. [1] 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 [6].

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 in chip and the workpiece, as well as the cutting force, tool stress and temperature on the tool working under specific cutting parameter [7]. This paper presents the application of FEM in studying the effect of tool geometries in turning ductile cast iron FCD 500 on the machining performance of cutting force, stress, strain, and generated temperature.

Methodology

Orthogonal Cutting Condition Model. 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 magnitudes of tool cutting geometries have 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 effects in orthogonal metal cutting of ductile cast iron with continuous chip formation, while the other machining parameters of cutting speed, feed rate and depth of cut were kept constant. Finite element simulation results of the orthogonal metal cutting using three sets of perfectly sharp cutting tools with positive rake angles of 15, 20 and 30° and four clearance angles of 5, 7, 8 and 9 respectively. The commercial software Deform-3D for deformation analysis was used to simulate orthogonal metal cutting process. It is based on an updated Lagrangian formulation and employs an implicit integration scheme. Fig. 1 shows the schematic of orthogonal cutting condition model.

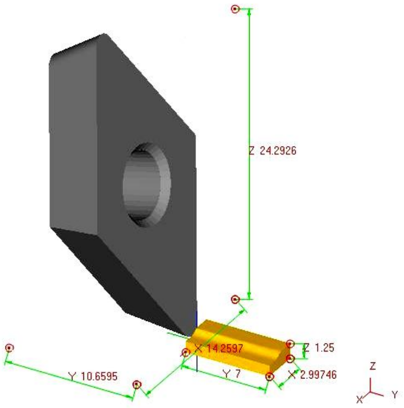

Fig. 1 Schematic of orthogonal cutting condition model

Parameter Inputs and Cutting Conditions. 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, $\sigma = \sigma_1 \varepsilon^n$ [8]. Cutting conditions are predefined are shown in Table 1.

Table. 1: Parameter inputs in the simulation process

Parameters												
Cutting speed	constant at 200 m/min											
Feed rate	constant at 0.35 mm/rev											
Depth of cut (DOC)	constant at 0.3 mm											
Rake angle (α), deg	15				20				30			
clearance angle (β), deg	5	7	8	9	5	7	8	9	5	7	8	9

The workpiece material was ductile cast iron FCD500 grade. This material was selected as the workpiece material in this study because it was widely used in automotive application. Deform-3D software was used to simulate the effect of tool cutting geometries in turning ductile cast iron using uncoated carbide cutting tool. The simulations were performed by changing the rake angle and clearance angle while the cutting speed, feed rate and depth of cut were kept constant at 200 m/min, 0.35 mm/rev and 0.3 mm respectively. The simulation results of cutting force, effective-stress, strain and generated temperature on the workpiece surface were studied and analyzed. The operation is simulated using insert carbide of DNMA432 type that has a nose angle of 55 deg and without the use of coolant. The tool was defined to be a rigid body which considers thermal transfer for modeling the cutting temperature field. Cutting condition, simulation models and material properties of carbide cutting tool and workpiece are shown in Table 2.

Table 2: Cutting condition to the simulation models and material properties

Tool geometry of DNMA 432	
Side Cutting Edge Angle (SCEA), deg	-3
Back Rack angle (BR), deg	-5
Side Rack angle (SR), deg	-5
Nose angle, deg	55
Tool properties (WC as base material, uncoated carbide tool)	
Modulus young (GPa)	650
Thermal expansion	5e-06
Poison ratio	0.25
Boundary condition	
Initial temperature, deg. C	20
Shear friction factor	0.6
Heat transfer coefficient at the interface, N/s mm^{o}C	45
Workpiece geometry	
Depth of cut, mm	0.3
Width of cut, mm	3.4
Length of workpiece, mm	7
Workpiece properties (Ductile cast iron FCD500)	
Modulus elasticity (GPa)	169
Thermal conductivity (W/m. °C)	35.2
Thermal expansion coefficient ($\cdot 10^{-6}$ °C^{-1})	12.5
Heat capacity (N/mm^2 ° C)	3.7
Emissivity	0.95

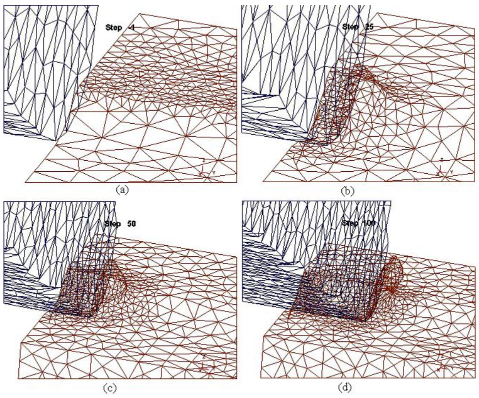

Fig. 2 (a) Initial mesh and tool indentation, (b) Chip formation at step 25, (c) Chip formation at step 50, (d) Developed continues chip at step 100.

Displacement, shape and surface mesh of the tool and workpiece at the initial mesh of beginning the cutting operation was developed until chip formation reach step 100 as illustrated in Fig. 2a , 2b, 2c and 2d respectively. The workpiece 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 workpiece because of very large temperature gradient and stress that will develop in this region during the simulation.

Design of Cutting Tool Geometries. Cutting tools were designed for various rake angles of +15, +20 and +30 deg and the clearance angles of 5, 7, 8 and 9 deg. There are twelve combinations of geometry designs for carbide tool using Solid Work software as shown in Fig 3.

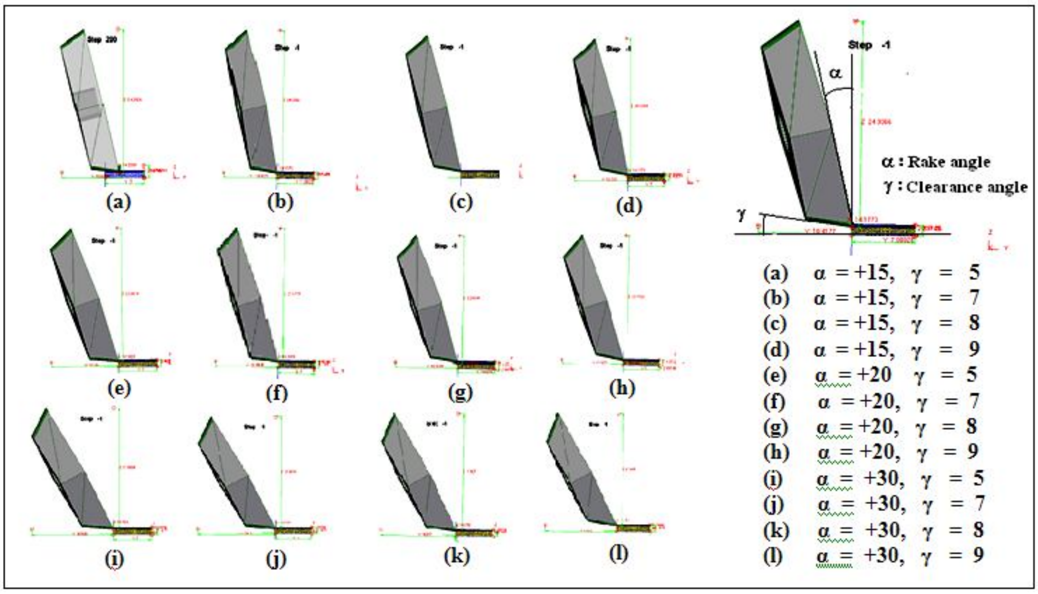

Fig. 3 Modeling for 12 combinations of geometry designs of rake and Clearance angle for DNMA carbide tool cutting

Simulation Results and Discussion

Primary and Secondary Deformation Zone. Fig. 4 shows the simulation results for displacement, cutting force, effective stress, strain and generated temperature for rake angle of +20 deg and clearance angle of 5 deg (cutting speed of 200 m/min, feed rate of 0.35 mm/rev and DOC of 3 mm)

The biggest displacement was reached around 2.84 mm in total displacement at the end of chip formation (Fig. 4a). The biggest deformation was occurred on the primary deformation zone, followed by the secondary deformation zone. This also causes higher stress occurred on this area, about 3565 MPa in primary shear zone (Fig.4b). These results are agreeable with Kalhori [9], 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.

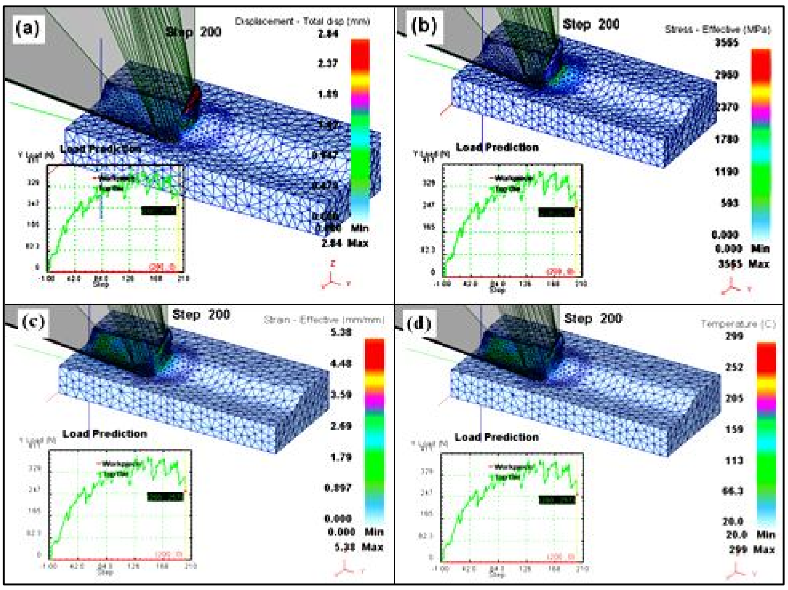

Fig. 4 Simulation results for cutting speed of 200 m/min, rake angle of +20 deg and clearance angle of 5 deg), a) Displacement, b) Effective stress, c) Effective Strain and c) Generated temperature.

Fig. 4c shows the highest effective strain occurred on primary shear zone about 5.03 mm/mm, and then followed by secondary shear zone about less than 2.69 mm/mm. And, the highest temperature was occurred at sliding region on primary shear zone around 299 ^{o}C as shown in Fig 4d. Table 3 shows the simulation results for all various rake and clearance angle where cutting speed, feed rate and depth of cut (DOC) that were kept constant at 200 m/min, 0.35 mm/rev and 3 mm respectively.

Table 3: The result of simulation for cutting force, stress, strain, and temperature

No	Rake angle[α]	Clearance Angle [β]	Cutting Speed [m/min]	Feed [mm/rev]	DOC [mm]	Cutting Force [N]	Stress [MPa]	Strain [mm/mm]	Temp [^{o}C]
1	+15	5	200	0.35	3	346	4320	6.11	321
2	+15	7	200	0.35	3	347	4230	6.56	318
3	+15	8	200	0.35	3	400	4195	6.24	334
4	+15	9	200	0.35	3	402	4340	7.13	304
5	+20	5	200	0.35	3	239	3565	5.03	299
6	+20	7	200	0.35	3	295	3690	4.96	304
7	+20	8	200	0.35	3	271	3690	5.56	272
8	+20	9	200	0.35	3	297	3720	5.65	263
9	+30	5	200	0.35	3	165	3360	4.31	198
10	+30	7	200	0.35	3	178	3540	4.45	206
11	+30	8	200	0.35	3	196	3537	5.07	218
12	+30	9	200	0.35	3	262	3400	4.68	225

The Effect of Rake Angle (α). By increasing the rake angle, effect on the cutting force, stress, strain and generated temperature are decreasing as shown in Fig. 5a, 5b, 5c and 5d respectively. For example, increasing the rake angle from +15 deg to +20 deg, will reduce the cutting force from 346 N to 239 N, stress from 4320 MPa to 3565 MPa, strain from 6.11 to 5.03 mm/mm and temperature from 321 ^{o}C to 299 ^{o}C. This can be accepted that the reducing in cutting force, stress, strain and temperature were resulted from reduction of tool/chip contact area, so the cutting force and friction are expected to be decreased. This is agreeable with theory and experiment done by Gunay et al [10].

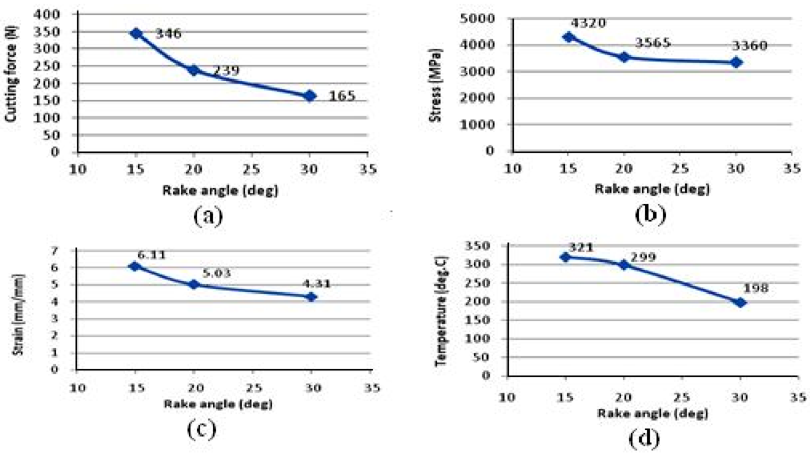

Fig. 5 Effect of rake angle, (a). rake angle vs cutting force, (b). rake angle vs stress, (c). rake angle vs strain, and (d). rake angle vs

The Effect of Clearance Angle (γ). The increase of clearance angle does not much influence the cutting force, stress, strain and generated temperature as shown in Fig. 6a, 6b, 6c, and 6d. All of these results were also agreeable with the theory, because the change of clearance angle will not affect the cutting force and stress, but the increase of clearance angle only affects slightly on the wear rate. Clearance angle will affect wear and tool life of the cutting tool because the clearance face will rub against the freshly cut metal surface. In industry, the clearance angle is varied, but often in the order of 6 – 10 deg [11].

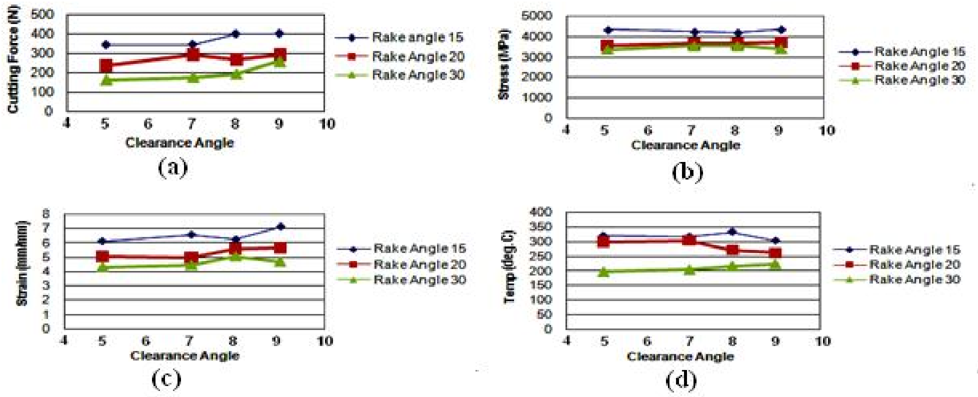

Fig. 6 Effect of clearance angle, (a) clearance angle vs cutting Speed, (b) clearance angle vs stress, (c) clearance angle vs strain, (d) clearance angle vs temperature.

Conclusion

The distribution of cutting force, effective stress and generated temperature obtained from simulations are agreeable with the results given in literature. From the simulation, it can be concluded that increasing the rake angle (α) in the turning of ductile cast iron using tungsten carbide (CW), it will improves the machining performance by reducing the cutting force, stress, strain and generated temperature. But, by increasing the clearance angle (γ), it will not influence much to the cutting force, stress, strain and generated temperature on chip.

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