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Investigation of Effects of Tool Geometry Parameters on Cutting Forces, Temperature and Tool Wear in Turning Using Finite Element Method and Taguchi's Technique

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Abstract: Turning is one of the most widely metal cutting methods. Machines, tool geometry and machining parameters are the main factors influencing machining quality and efficiency. So there is a lot of research on it. This paper studies on the influence of the geometrical parameters of the tool including: back rake angle (BR), side rake angle (SR) and side cutting-edge angle (SCEA) on cutting forces, temperature and tool wear in turning using FEM (by Deform 3D finite element simulation software) and Taguchi's technique (by Minitab16 statistical software) is used to design the experiment and to analyze output quality characteristics from simulation results. And the optimum tool geometry parameters are given.

Keywords: FEM, FEA, BR, SR, SCEA, Deform 3D, Taguchi Method, S/N Ratio

1. Introduction

Turning is a method of machining by cutting in which the workpiece carries out the main rotary motion while the tool performs the linear motion. The process is used for the external and internal turning of surfaces [1].

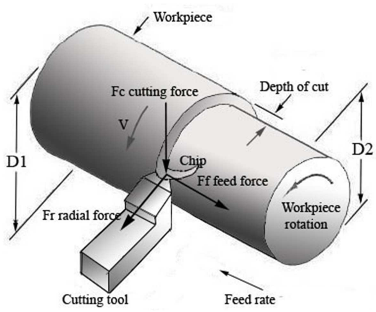


Fig. 1. *Schematic diagram of turning operation and cutting forces.*

The forces impacting on the cutting tool during machining process are named cutting forces. They influence the life of the tool, the machined work piece's dimensional accuracy and quality of the surface.

The heat generation is closely related to the plastic deformation and friction, we can specify three main sources of heat when cutting, plastic deformation by shearing in the primary shear zone (heat source Q1), plastic deformation by shearing and friction on the cutting face (heat source Q2), friction between chip and tool on the tool flank (heat source Q3) and heat is mostly dissipated by the discarded chip about 60~80% of the total heat (q1), the workpiece about 10~20% heat (q2) and the cutting tool about ~10% heat (q3) [2]. The cutting temperature affects the life of the cutting tool, on the tool and work piece material properties.

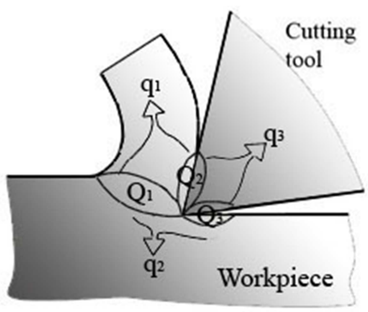


Fig. 2. *The balance of heat generation and heat dissipation in the metal cutting process.*

The wear of tool influences the machined work piece's dimensional accuracy and quality of the surface.

Therefore, the main objective of this research is the study of the influence of the geometric parameters of the tool on the cutting forces, temperature and tool wear in turning to improve the tool geometry parameters. The input quality characteristics of simulation analysis are shown in the tables below.

The workpiece material used for the metal cutting simulation is AISI 1045 steel, a medium carbon, medium tensile steel. It has very good machinability, reasonable weldability. Typical engineering applications of AISI 1045 steel are as gears, shafts, axles, bolts, studs and machine parts.

Table 1. *The tool geometry parameters and its levels.*

Tool geometry parameters	Level 1	Level 2	Level 3	Level 4
SCEA (°)	0	15	30	45
BR (°)	-5	-7	-9	-11
SR (°)	-5	-7	-9	-11

Table 2. *The machining parameters.*

Cutting speed(m/min)	Feed rate(mm/rev)	Depth of cut(mm)
103.2	0.16	2

Table 3. *Mechanical and thermal properties of AISI 1045 carbon steel.*

Density ($g.cm^{-3}$)	Poisson ratio	Elasticity (GPa)	Thermal conductivity ($W.m^{-1o}K^{-1}$)	Specific heat ($J.kg^{-1}.K^{-1}$)	Thermal expansion ($\mu m.m^{-1}\ K^{-1}$)	Hardness (HB)
7.87	0.29	212	41.7	450	11.9	170

The material for cutting tool insert is uncoated cemented carbide, which has a good hot hardness, wear resistance and strength for metal cutting operations.

Table 4. *Mechanical and thermal properties of tungsten carbide insert.*

Density ($g.cm^{-3}$)	Poisson ratio	Elasticity (GPa)	Thermal conductivity ($W.m^{-1}K^{-1}$)	Specific heat ($J.kg^{-1}.K^{-1}$)	Thermal expansion ($\mu m.m^{-1o}C^{-1}$)	Hardness (HB)
15	0.25	650	59	15	5	1433

2. Finite Element Method (FEM)

In recent years, the finite element method (FEM) is the most popular method of simulation and finite element analysis (FEA) has become the main tool for simulating metal cutting processes. Because FEA requires less time and cost as well as it provides detailed results such as the cutting force, stress, strain, strain rate, tool wear and temperature of the metal cutting process. There are some popular finite element softwares for simulation of cutting process such as Ansys, Deform 3D, Abaqus, etc. In this paper, the FEM software Deform 3D with updated Lagrangian formulation combined with automatic remeshing techniques [3] is used to simulate turning process. In this approach, there is no need for a chip separation criterion, making it is highly effective in simulating metal cutting process [4]. The important factor in the metal cutting simulation is modelling the process properly in order to obtain true results. This software includes several key models as: the material constitutive model; tool wear model; friction model and thermal model.

And the most important one is the material constitutive model. The metal cutting process is the large strain, high strain rate and high temperature process. And Johnson-Cook material model (1) is favored as well in studies of problems like that.

$$\bar{\sigma} = [\mathrm{A} + \mathrm{B}(\bar{\varepsilon})^n][1 + \mathrm{C}\ln\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_o}\right)][1 - \left(\frac{T - T_o}{T_m - T_o}\right)^m] \quad (1)$$

Where $\bar{\sigma}$ = equivalent stress, $\bar{\varepsilon}$ = equivalent plastic strain, $\dot{\bar{\varepsilon}}$ = equivalent plastic strain rate, $\dot{\bar{\varepsilon}}\ o$ = initial reference plastic strain rate, T = operating temperature, T_o = room temperature, T_m = the melting temperature, A = initial yield stress, B = strain hardening coefficient, n = strain hardening index, C = strain rate dependency coefficient, and m = thermal softening index.

Tool wear calculation with Usui model as shown in eq (2):

$$w = \int ap\,V^{(-\frac{b}{T})}dt \quad (2)$$

Where p = interface pressure, V = sliding velocity, T = interface temperature (in degrees absolute), dt = time increment, a, b = experimentally calibrated coefficients.

Table 5. *Boundary conditions.*

Shear friction coeff.	Interface heat transfer coeff.	Convection coeff.	Environment temperature
0.5	100 (N/smm°C)	0.02	20°C

The tool is meshed with 45.000 tetrahedron elements, while the number of elements in the workpiece is kept at 20 % of feed rate. Simulation steps are 16000 and data are saved every 25 steps.

3. Taguchi Method

The Taguchi method is a powerful tool to design optimization for quality. This method uses a special design of orthogonal array (OA) to study the quality characteristics with a minimal number of experiments [5], and signal-to-noise ratios (S/N) are used to evaluate the performance characteristics.

$$\text{Minimum experiments} = 1+ (\#\text{factors x } (\#\text{levels}-1)) \quad (3)$$

For Taguchi method, there are 3 types of the signal-to-noise ratio.

$$\text{Smaller-is-the-better: } S/N = -10log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (4)$$

$$\text{Larger-is-the-better: } S/N = -10log\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}\right) \quad (5)$$

$$\text{Nominal-is-the-best: } S/N = 10log\left(\frac{\bar{y}}{s_y^2}\right) \quad (6)$$

The Taguchi method applied in this study, the input parameters includes 3 factors: back rake angle (BR), side rake angle (SR) and side cutting-edge angle (SCEA) with 4 levels.

$$\text{Minimum experiments} = 1 + [(L-1)\,P] = 1 + [(4-1)3] = 10 \approx L16.$$

And the output parameters of the simulation analysis are cutting forces, temperature and tool wear, so we will select the first criterion (smaller is the better).

Table 6. *The L16 inner orthogonal array.*

Trial no	Side cutting- edge angle (SCEA) (°)	Back rake angle (BR) (°)	Side rake angle (SR) (°)
1	0	-5	-5
2	0	-7	-7
3	0	-9	-9
4	0	-11	-11
5	15	-5	-7
6	15	-7	-5
7	15	-9	-11
8	15	-11	-9
9	30	-5	-9
10	30	-7	-11
11	30	-9	-5
12	30	-11	-7
13	45	-5	-11
14	45	-7	-9
15	45	-9	-7
16	45	-11	-5

This setup allows the testing of all 3 factors with 4 levels without having to run 64 (=4^3)

4. Simulation Results and Discussion

4.1. Numerical Results

Based on the L16 inner orthogonal array, finite element analysis (FEA) is conducted to investigate effects of tool geometry parameters: SCEA, BR and SR on cutting forces, temperature and tool wear in turning. The results are shown in Table 7.

Table 7. *The output quality characteristics of simulation analysis.*

Trial no	Tool-chip interface temp (°C)	Wear depth (mm)	Cutting forces (N)			
			Fx	Fy	Fz	F resultant
1	682	1.15E-7	173	960	168	989
2	690	1.19E-7	209	971	206	1014
3	737	1.46E-7	314	1304	314	1377
4	772	1.23E-7	364	1302	389	1406
5	686	1.18E-7	209	1049	233	1094
6	695	1.34E-7	184	1104	271	1151
7	729	1.35E-7	329	1217	390	1319
8	720	1.35E-7	288	1192	409	1292
9	679	1.11E-7	171	802	218	848
10	700	1.24E-7	224	954	339	1036
11	674	1.13E-7	127	792	236	836
12	696	1.13E-7	159	826	295	891
13	679	0.93E-7	150	751	254	806
14	694	1.07E-7	139	832	297	894
15	685	0.96E-7	120	796	273	824
16	683	0.95E-7	101	745	268	798

Based on the results in Table 7, when the side rake angle and the back rake angle decrease from -5° to -11°, the temperature on the tool-chip interface and the cutting force increase from 682°C to 772°C and from 989 N to 1406 N, respectively. This is fully agreeable with theory and the previous studies by Stephenson et al. [6], Gunay et al. [7], Haci Saglam et al. [8], Cerenitti [9] and Sabri [10]. Because the rake angles decrease, it causes more the contact area and friction between the rake face and the chip as well as the chips flow more difficult across the rake face (chip jamming) as the rake angles decrease, then it causes more the temperature at the tool-chip interface during cutting process and the cutting force is bigger.

Using Minitab software to analysis the results from the simulation, showed in Table 8 and Fig. 3.

Table 8. *The combined S/N ratio of the output quality characteristics.*

Trial no	Tool-chip interface temp (°C)	Wear depth (mm)	Cutting forces (N)				Combined S/N ratio
			Fx	Fy	Fz	F resultant	
1	682	1.15E-7	173	960	168	989	-56.7731
2	690	1.19E-7	209	971	206	1014	-56.9624
3	737	1.46E-7	314	1304	314	1377	-59.1014
4	772	1.23E-7	364	1302	389	1406	-59.3329
5	686	1.18E-7	209	1049	233	1094	-57.4493
6	695	1.34E-7	184	1104	271	1151	-57.8004
7	729	1.35E-7	329	1217	390	1319	-58.7913
8	720	1.35E-7	288	1192	409	1292	-58.6286
9	679	1.11E-7	171	802	218	848	-55.9481
10	700	1.24E-7	224	954	339	1036	-57.1692
11	674	1.13E-7	127	792	236	836	-55.8477
12	696	1.13E-7	159	826	295	891	-56.2951
13	679	0.93E-7	150	751	254	806	-55.6847
14	694	1.07E-7	139	832	297	894	-56.3038
15	685	0.96E-7	120	796	273	824	-55.8186
16	683	0.95E-7	101	745	268	798	-55.6557

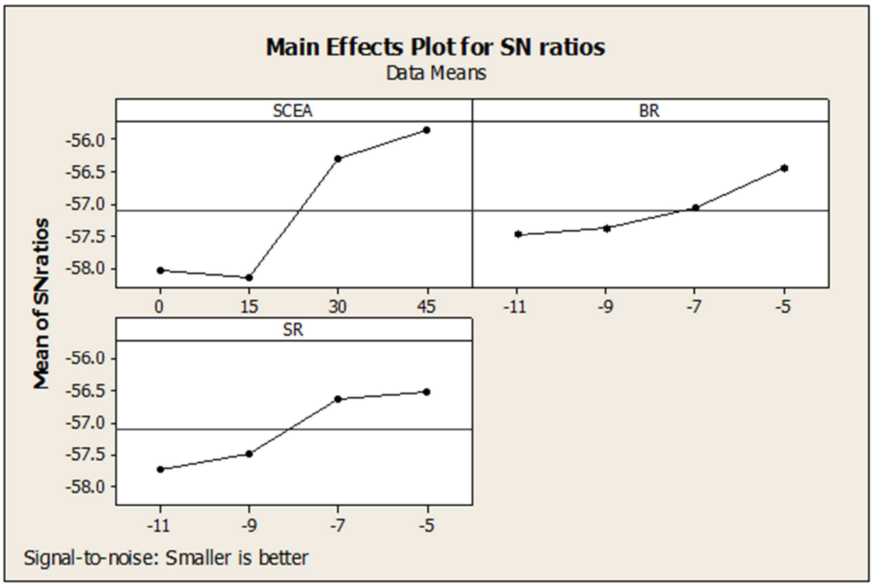


Fig. 3. *Main effects plot for S/N ratios.*

From Table 8 and Fig. 3, the optimum tool geometry parameters are SCEA=45°, BR= -5° and SR= -5°.

Furthermore, an analysis of variance (ANOVA) is performed to see which process parameters are significant [11]. The ANOVA is given in Table 9.

Table 9. *ANOVA for S/N ratio.*

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
SCEA	3	16.6686	16.6686	5.5562	29.70	0.001	67.11
BR	3	2.5333	2.5333	0.8444	4.51	0.056	10.20
SR	3	4.5150	4.5150	1.5050	8.04	0.016	18.18
Residual error	6	1.1226	1.1226	0.1871			
Total	15	24.8396					

From the ANOVA: SCEA has the largest effect on the output quality characteristics with 67.11%, SR with 18.18% and BR has the smallest effect on the output quality characteristics with 10.20%.

With the identified optimum tool geometry parameters, a validation simulation analysis is performed.

Table 10. *The output quality characteristics of simulation analysis with the identified optimum tool geometry parameter.*

Trial no	Tool-chip interface temp (°C)	Wear depth (mm)	Cutting forces (N)			
			Fx	Fy	Fz	F resultant
1	655	0.86E-7	86	696	176	723

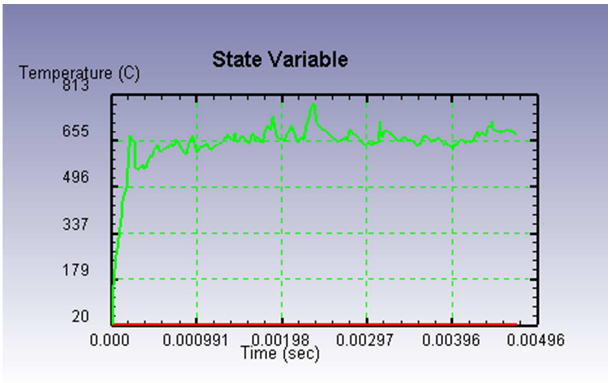


Fig. 4. *The generated temperature in machining process.*

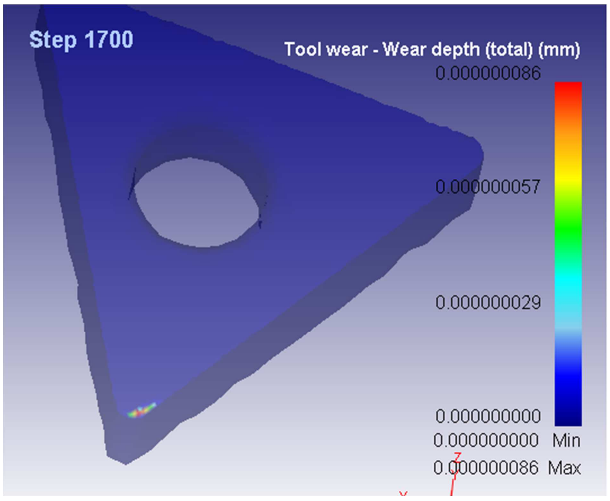
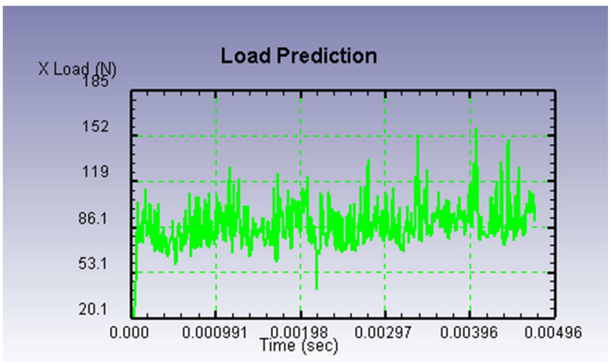
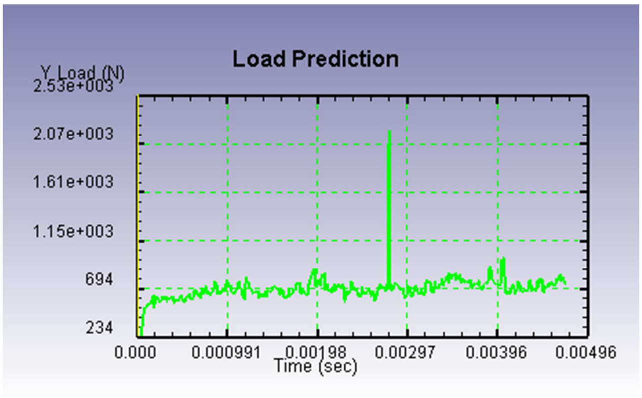


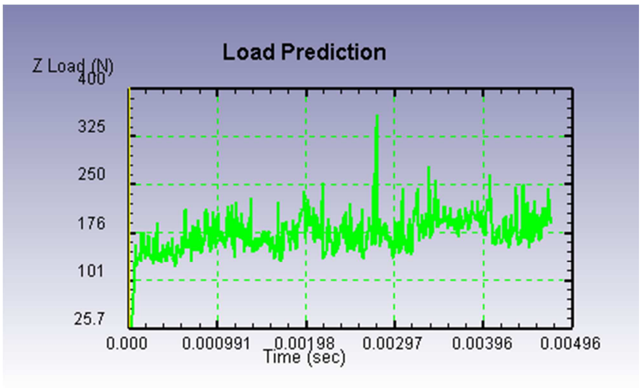
Fig. 5. *The wear of tool in machining process.*



a. Feed force



b. Main cutting force



c. Radial force

Fig. 6. *The generated cutting forces during the cutting simulation analysis.*

4.2. Comparison Between Experimental and Numerical Results

The simulation result obtained were validated by comparison with appropriate tool-work thermocouple measurements provided in Ref [12]. The cutting process simulation parameters were taken same conditions used in the reference experiment, i.e. cutting speeds of 103.2, 206.4 and 330 m/min, feed rate of 0.16 mm/rev, depth of cut of 2 mm, AISI 1045 steel workpiece and tungsten carbide tool material as well as the tool's geometrical features. The comparison between measured and computed values of the average tool–chip interface temperature is presented in Fig. 7 [13].

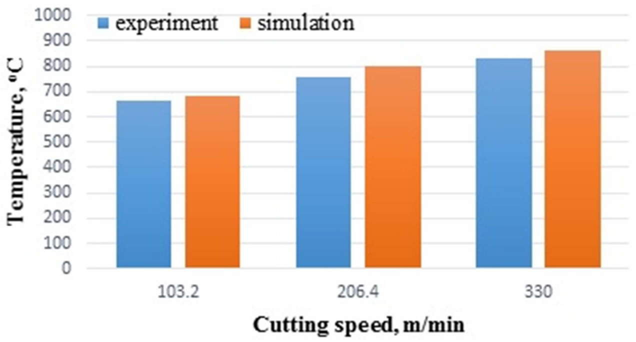


Fig. 7. *Comparison between measured and computed tool-chip interface temperatures.*

It shows good agreement between experimental and simulation values for the three selected cutting speeds with the percentage error of 2.3, 5.3, and 3.6 % for speeds 103.2, 206.4, and 330 m/min respectively.

5. Conclusion

From the simulation results, it is concluded that:

When the side rake and back rake angles decrease from -5° to -11°, the temperature in the machining process and the cutting force increase from 682°C to 772°C and from 989 N to 1406 N, respectively.

The identified optimum tool geometry parameters are SCEA=45°, BR= -5° and SR= -5°. The SCEA has the largest effect on the output quality characteristics with 67.11%, SR with 18.18% and BR has the smallest effect on the output quality characteristics with 10.20%.

All of the results are agreeable with theory and some simulations and experiments in references.

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