Investigating the Effect of Cutting Condition on the Plastic Energy in Turning Process of AISI 1050

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Abstract: Reducing energy consumption is a demanding issue considering the limited available energy resources and increasing environmental pollution. On the other hand, industry consumes a huge amount of energy, and manufacturing processes are the most energy consuming portions of the industry. Machining issues including cutting tool geometry and process parameters affect the cutting forces and also production consuming energy. By increasing cutting forces, the tool life would be reduced and therewith cost of machining process increases. In this work, the effect of machining condition on cutting force and energy consumption were studied in turning process during validated FE analysis using ALE method. So, the effect of rake angle, tool edge radius and cutting speed was investigated on the cutting force, plastic strain and plastic consuming energy. Results proved that these parameters are effective on plastic energy consumption in turning process among them cutting speed has more effect on the plastic energy. By increasing the cutting speed, the plastic energy decreases considerably. Rake angle is also effective on process energy consumption and the combination of increasing the rake angle and cutting speed, and choosing the optimal edge radius leads to the minimized plastic energy.

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1   INTRODUCTION

The main sources of energy consumption in the world are residential, commercial, industrial and transportation sections which among them, most of the energy consumption divisions are industries. So, industrial manufacturing processes such as machining operations attracted more attention in order to reduce the energy consumption and saving energy sources in the world [1]. In addition, for protecting the environment and reducing the pollution, efforts should be made reducing energy consumption in the industries [2]. Machining is the base final manufacturing process and shall be taken into consideration concerning energy consumption.

Researches in this topic can be divided into several categories. Some of the works have been done on energy modelling and efficiency in machining operations. Neugebauer et al [3] investigated energy efficiency in drilling and hard turning processes. They calculated the process energy originated from cutting forces and power. They showed that reducing the machining time by selecting capable tool would result in energy saving. Oda et al [4] studied the effective energy in five-axis ball nose milling process. Their main purpose was investigating the effect of inclination angle on the effective energy. They proposed an optimized inclined angle to reduce energy consumption and maximize the tool life. Rajemi et al [5] optimized tool life and energy consumption in turning process of parts. They introduced the parameters which have more effect on energy footprint.

Zhao et al [6] presented three computational, empirical and neural network model and for calculating energy efficiency and consumption in a turning process. They concluded that selecting a large amount of cutting depth and feed could reduce specific energy consumption in the turning process. Rief et al [7] introduced an energy model that could calculate energy consumption regarding milling process parameters. Balogun et al [8] worked on optimum value calculation for tool swept angle minimizing the plowing effects in the milling process of AISI 1045 that lead to reducing required electrical energy. Davim et al [9] compared high speed and conventional machining regarding plastic strain and plastic strain rate. According to their work, the friction coefficient is lower and the plastic strain rate is higher in high-speed machining processes relatively. Nowadays, FE methods are widely used for studying the manufacturing process including machining operations. Chip formation is a complicated phenomenon to study analytically and finite elements studies are applied to investigate the deformations of the chip, workpiece, machine tool, jig and fixtures and other aspects of the cutting process [10]. Ma et al [11] studied energy issues of machining process based on energy assessment regarding operation parameters and tool geometry using the FE method. They focused on turning operation of AISI 4140 steel and presented the effect of machining parameters on energy consumption. Ozel et al. [12] studied the orthogonal cutting process of AISI 4340 steel using Arbitrary Lagrangian-Eulerian (ALE) technique and simulate the plastic flow of work material around the cutter edge of the tool. They simulated the chip formation and temperature and stress distribution are studied as results for estimating the residual stress of the final part. Duan et al [13] implemented the finite element method to simulate the serrated chip geometry and cutting force during high-speed cutting of AISI 1045 steel which involves Johnson-Cook plastic deformation model and fracture criterion. In their work, the serrated chip geometry and cutting force were predicted and validated in the experiments. Their investigations demonstrated that the proposed finite element simulation method could accurately predict the chip geometry and cutting force during high-speed cutting of hardened steel. In the field of machining FE analysis, some of the works are performed studying the constitutive equations of the metals for simulating the machining processes. Seshadri et al. [14] studied the capability of Johnson-Cook constitutive equations for FE analysis of machining operation in Deform 2D. Umbrella [15] investigated the flow stress parameters in FE simulation of Ti6Al4V conventional and high-speed machining process and several Johnson-Cook constitutive model parameters have been examined in the work. Tool geometry and process parameters affect the cutting force and process consuming energy. Increasing cutting forces leads to decreasing tool life thereby process cost increases [16]. Due to shortage of energy sources, decreasing of energy consumption is a considerable issue in research works done in industries. In the previous works on metal cutting processes, the attempts have been made to investigate the effect of machining condition including tool geometry and process parameters on the consuming energy. The researchers use analytical, empirical and numerical method to reduce the inefficient energy consumption during the metal cutting processes for different materials.

In the present work, the turning operation concerning plastic energy is studied through FE analysis using the Arbitrary Lagrangian-Eulerian (ALE) method. So, the effect of a cutting tool and process parameters including rake angle, cutter edge radius and cutting speed on the plastic strain and the consumed energy was investigated in the turning process of AISI 1050. This steel is commonly used for forged gears and shafts because of its achievable mechanical properties. The results can be used for better understanding of the process form an energy perspective and appropriate selection of process inputs. So far, similar work has not been addressed in the literature.

2   FINITE ELEMENT MODEL

In this work, finite element analysis in ABAQUS/CAE software with explicit approach is conducted on AISI 1050 steel using a carbide tool. Mechanical and physical properties of workpiece and cutting tool material are listed in "Table 1". Cutting conditions in studies are summarized in "Table 2". This range of parameters is selected based on cutting tools manufacturers' suggestions.

Table 1 The mechanical and physical properties of the workpiece and tool material

Properties	1050 Steel	Carbide Tool
Young's modulus (GPa)	210	800
Density (g/cm3)	8.03	15.0
Poisson's ratio	0.3	0.3
Expansion (μm/m°C)	13.7	4.7
Specific heat (J/kg/°C)	486	203
Thermal Conductivity (W/m°C)	51.9	46
Melting Temperature (°C)	1460	2870

Table 2 The cutting conditions

Parameter	Values
Cutting Speed (m/min)	120, 180, 240
Rake angle (degree)	0, 5, 10, 20
Edge radius (mm)	0, 0.1, 0.2

In the present work, the Johnson-Cook constitutive and failure models were used for finite element simulations as equations (1) and (2). In order to mind the effect of heat in the simulation, the approach was employed considering thermal couple analysis and dynamic displacement.

$$\sigma_{JC} = [A + B\varepsilon^n]\left[1 + C \ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right]\left[1 - \left(\frac{T-T_r}{T_m-T_r}\right)^m\right] \quad (1)$$

$$\varepsilon_f = \left[D_1 + D_2 exp\left(D_3 \frac{\sigma_m}{\sigma}\right)\right]\left[1 + D_4 \ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right]\left[1 + D_5 \frac{T-T_r}{T_m-T_r}\right] \quad (2)$$

Where A, B, C, n, m and D1 to D5 are material constants and determined from empirical tests. The material and damage model constants of steel AISI 1050 are presented in "Table 3" [17]. The initial temperature of the workpiece was set as 25°C. A straight path with 40 mm length is selected for cutting simulation and the analysis is considered based on moving of the cutting tool relative to the workpiece. The imposed forces on the tool edge are considered as cutting forces.

Eulerian and Lagrangian methods are two types of analysis which can be used for describing a medium for finite element modelling of forming processes. The computational grid of nodes and elements will deform with the containing material during the analysis in the Lagrangian method, while they are fixed in Eulerian analysis. In other words, by using the Lagrangian calculation, the software embeds the mesh in the material domain and solves for the position of the mesh at discrete points in time, while the material is allowed to move inside mesh grid. Langrangian analysis can be performed for both implicit and explicit time integration techniques.

Table 3 Constants of AISI 1050 steel used in the Johnson cook material and Damage mode

Material Constants				
A	B	n	C	m
880	500	0.234	0.013	1.00
Damage Constants				
D1	D2	D3	D4	D5
0.06	3.31	-1.96	0.018	0.5

As known, the implicit technique is appropriate for solving linear static problems while the explicit is used for non-linear dynamic ones. The dynamic temperature-displacement explicit is applied to analysis. The ALE method has the aspects of both Eulerian and Lagrangian methods and is useful for simulating machining process to avoid many remeshing of material.

Both 2D and 3D FE based models have been addressed in the literature for analysis of turning process. The 2D model has limitation of defining chip morphology and surface topology particularly in oblique machining analysis and is restricted to 2D studies. But 2D approaches can sufficiently help for providing some analysis purposes and their result for cutting forces and orthogonal burr formation are in good agreement with empirical results [18]. In this work, the tool geometry was modelled as discrete rigid and the 2D shell workpiece is also modelled using four-node bilinear displacement and temperature quadrilateral CPE4RT elements. The numbers of tool and workpiece elements were 615 and 1510 respectively. A plane strain assumption for the deformations was applied. Also, the reduced integration in the selected mesh helps to overcome the shear-lock error in bending deflections which is more probable in cutting process and the hourglass is enhanced to evolve artificial stiffness to some extent and control hourglass effects.

Friction is a very important factor in analysis of machining processes and several researches were performed for studying this phenomenon. The common approach in modelling the friction at the chip–tool interface is using an average friction coefficient. In some models, the friction region was considered to be a sticking region for constant friction force plus a sliding region for which the friction force varies linearly based

on Coulomb's law. The researchers worked on various workpiece and parts material considering process parameters and developed specific model for each condition. In the present work, based on the data and models reported in the literature [19-21], Coulomb model with a constant friction coefficient of 0.3 was assigned between tool and workpiece surfaces. This average value can be a proper assumption for the selected cutting velocity range.

In order to increase the accuracy of the analysis, the area where the chip will be formed was meshed more precisely and with a significantly smaller size. Mesh size is selected based on the convergence of simulation results with minimum 0.5 mm size in an upper partition of the workpiece. Due to the sever condition of elements during the Temperature-Displacement analysis, the Arbitrary Lagrangian-Eulerian (ALE) method was applied to help both the convergence of the FE analysis and the mesh deletion procedure resulted from extreme distortion of elements. Rather than manual mesh refinement in the upper partition, the adaptive meshing was activated during the FE analysis. Adaptive meshing and a remeshing technique were performed to the upper partition of the workpiece in the frequency of 10 times and in each increment. A simulation model is illustrated in "Fig. 1".
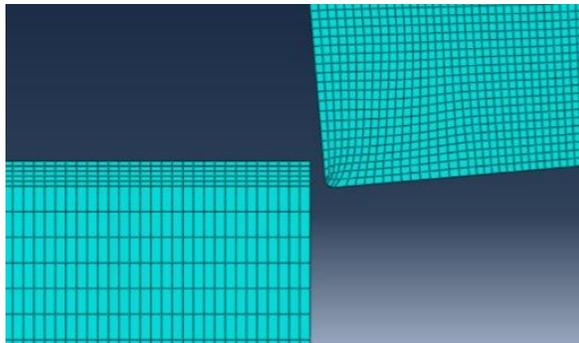

Fig. 1   Finite element model of the process.

3   ENERGY CONSUMPTION DURING TURNING PROCESS

In the metal cutting process, energy is generally consumed in primary and secondary shear zones during chip removal procedure ("Fig. 2"). By entering the material into cutting zone, shear stresses cause material deformation in the primary zone. In this zone, large strains, shear flow, and increasing temperature occur and a layer of metal is removed from the part. Some part of energy imposed by cutting forces generates a large amount of strain and cut a chip from the part. This part of the energy is beneficial for performing the cutting process and mostly is consumed in the primary shear zone.

By facing the formed chip on the cutter rake face, a secondary shear zone will be created in which the temperature increased due to friction between chip and cutter rake face. Part of process energy wasted in this area for deformation of a chip and overcoming the friction forces by way of heat generation [11]. The cutting tool geometry and the cutting speed are the important parameters affecting the energy consumed during turning operation and in this paper; the effects of them on consumed energy are investigated.
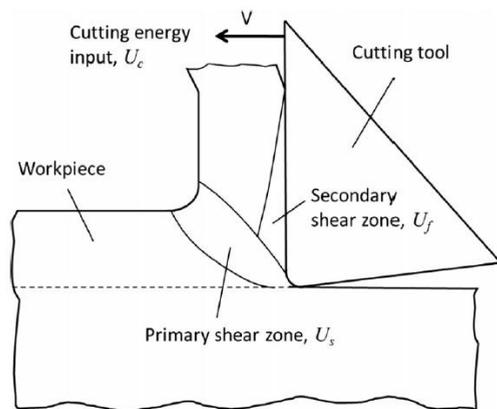

Fig. 2   Deformation zones in metal cutting.

According to literature, several energy consumption models have been presented for turning operation. Each function of the machine is part of energy consumption source in machining process which could be ignorable in energy consumption modelling. Processing the material often accounts 20%-30% of the total energy consumption of machine [22] and is related to material properties, processing parameters and tool condition. Figure 3 classifies the factors have an effect on the process energy consumption.
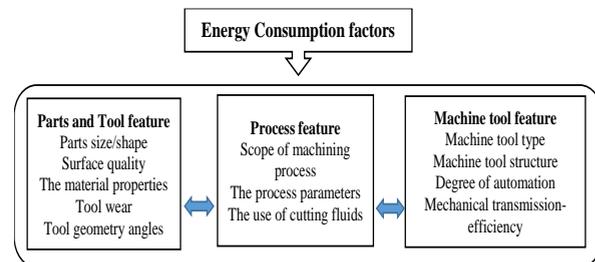

Fig. 3   Factors in energy consumption of machine tools [18].

The turning process energy is the sum of the energy consumed on metal cutting and energy consumed on plastic deformation without cutting known as ploughing or plowing energy. Tool nose radius, cutting edge radius, wear of cutting tool and uncut chip thickness are effective parameters on ploughing energy. With the

increase of the first three parameters, the ploughing energy increases while the fourth one has a reverse effect on it. One of the energy consumption models is based on a linear relationship between the Specific Energy Consumption (SEC) and Material Removal Rate (MRR). The most famous model was presented by Gutowski et al. [23] for sharp cutting edges as follow:

$$P = P_0 + k.MRR \quad (3)$$

$$SEC = \frac{P_0}{MRR} + k \quad (4)$$

Where P is the machine tool total power for metal cutting, P_0 is the machine tool idle power without metal cutting and $k.MRR$ is a specific power for processing the material. k is a constant related to work material and processing conditions. Some of the energy consumption models have been focused on the cutting parameters.
Ma et al in [11] expressed a simple model for calculating total consuming energy, U_c as follows:

$$U_c = F_c V = U_s + U_f \quad (5)$$

Where F_c is the main cutting force, V denotes the cutting speed, U_s stands for shear energy, and U_f is friction energy and have the following equations:

$$U_s = F_s V_s \quad (6)$$

$$U_f = F_f V_c \quad (7)$$

F_s proposes shear force, V_s is shear velocity, F_f is related to friction force and V_c represents the chip velocity.

4   SIMULATION VERIFICATION

For verifying the FEM simulation results, literature data supported by Davim [9] and Gunay [20] were used. In the first work, the plastic strain has been determined in machining of 1045 steel and its result was compared with the present model result for material 1045. The machining condition of reference [9] can be found in "Table 4".

Table 4 Machining condition and plastic strain results [9]

Cutting Speed	300 m/min
Feed	0.3 mm/rev
Depth of cut	3 mm
Rake angle	-6°
Relief angle	6°
Cutter edge radius	0.02 mm

Figure 4 shows a simulation model according to the experiment conditions. Figure 5 compares the finite element analysis and experiment results. As shown, the finite element results are in a good agreement with the experimental values. It should be noted that the finite element conditions are considered similar to the experimental conditions.
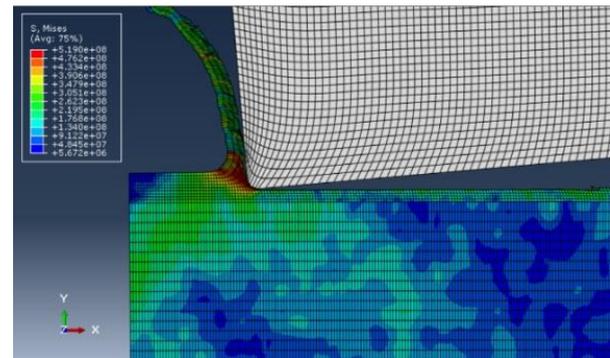

Fig. 4   The simulation model**.**
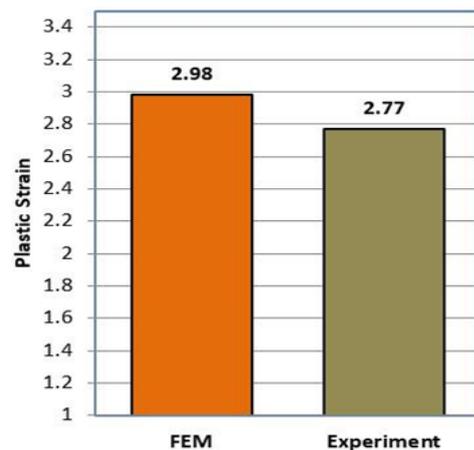
Fig. 5   Comparing plastic strain of experiment and present simulation**.**

In Gunay work [20], the cutting force measured for different rake angles and its results is also compared with the present model output. Therefore, in a simulation study, the workpiece, cutting tool, and other machining parameters are selected according to their work. Workpiece material was AISI 1040, and standard carbide inserts were used as the cutting tool. Simulation results were obtained with five different rake angles in constant cutting speed of 100 m/min, feed rate of 0.25 rev/min and cutter relief angle of 7°. Fiure 6 compares cutting force values resulted from the simulation and experiment. It can be seen that the trend and value of simulation results are similar to experiment with the maximum error of 7% in higher rake angles which is acceptable.
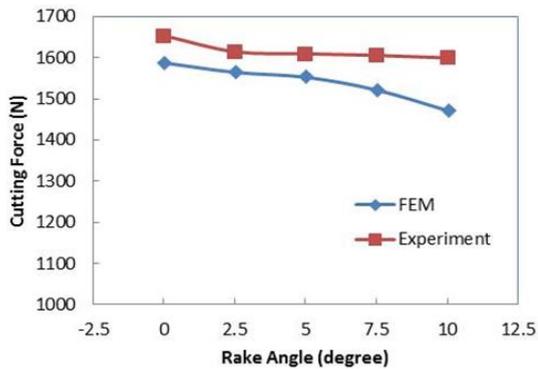
Fig. 6   Comparison of cutting force in the experimental work and the present finite element model**.**

The verifications have shown that the present work result is in good agreement with the experimental data and can be well used for studying the process in these issues.

5   RESULTS AND DISCUSSION

Using the FE simulation method, the effect of process parameters on AISI 1050 cutting was investigated. Figure 7 shows the effect of rake angle on the cutting force in which, by increasing the rake angle, the cutting force and also consumed energy reduced according to equation (5).
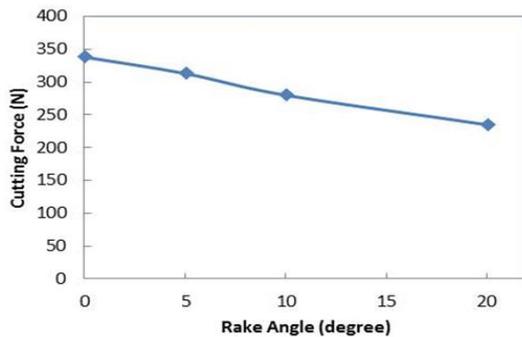

Fig. 7   Effect of rake angle on cutting force at cutting speed of 120m/min**.**

Fiure 8 shows the cutting force against the cutter edge radius in different rake angles. According to figure, in a specific edge radius which here is 0.1 mm, the cutting force and energy would be minimal. In addition to cutting force, it is also possible studying plastic energy during the turning operation. In the simulation of turning process, part of external work was used for the separation of chip from the part which is called damaged absorbed energy. Another part of external work was used for overcoming the friction and plastic deformation.
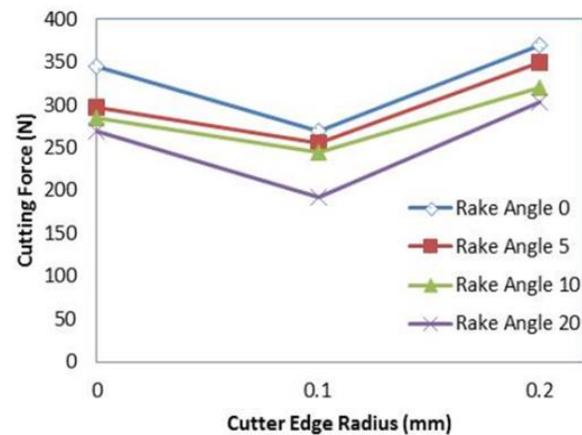
Fig. 8   Effect of cutter edge radius on cutting force at cutting speed of 180m/min**.**

In the appropriate condition, most of the external work must be used for the cutting process. So, decreasing a part of the energy which was used for plastic deformation and chip formation is the aim of simulation studies. In addition, if a large amount of energy is consumed for plastic deformation, more forces will exert to the tool and reduces tool life correspondingly. Figure 9 shows plastic energy against the cutting speed in different rake angle of the tool. According to result, increasing cutting speed decreases plastic energy due to increasing of strain rate and more brittle behaviour of the material in high cutting speeds.
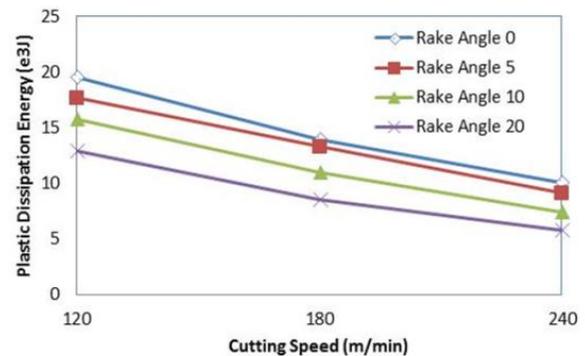
Fig. 9   Effect of cutting speed on plastic energy in different rake angle.

Figure 10 illustrates that increasing rake angle leads to reducing the plastic energy of the process in different cutting speeds. This result could be due to less deformation of the chip with increasing of rake angle.
The relation between cutter edge radius and plastic energy is shown in "Fig. 11". As shown, in a specific radius consuming plastic energy would be in its minimum amount.
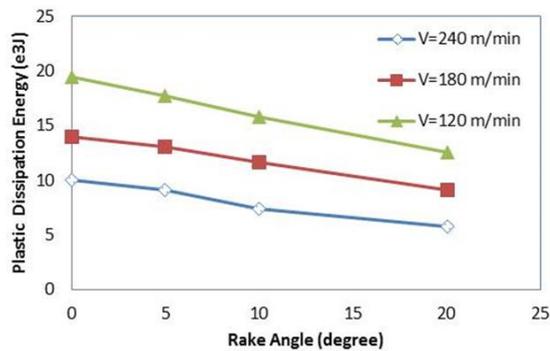
Fig. 10　Plastic energy in different cutting speed and rake angle (edge radius=0).
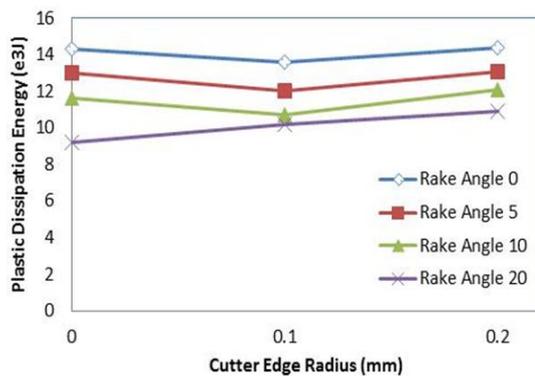

Fig. 11　Plastic energy in different edge radius and rake angle (cutting speed = 180 m/min).

According to "Fig. 11", by increasing the tool edge radius, absorbed plastic energy firstly decreased and then increased. In other words, in order to improve machining conditions, it is necessary to analyze the process via different cutter edge radius and select an optimum value for the cutting tool. When the cutting tool is sharp and the edge radius is zero, stress concentration occurs by contacting the cutting tool with the part, and so the cutting force and consumed energy would be relatively high. It is obvious that when the edge radius and the tool-chip-workpiece interface are large, most of the energy is wasted due to the plastic deformation.

6　CONCLUSION

Manufacturing is one of the main energy consumption sections in industry and metal cutting is the most common method of manufacturing processes. In this article, the effects of cutting tool geometry and cutting speed on energy consumption have been investigated for AISI 1050. At first, the turning process was simulated using the finite element method and verified by experimental data. Then, the effects of parameters on cutting forces and plastic energy were studied and the main findings are summarized as:

1- The parameters rake angle, cutter edge radius and cutting speed can affect plastic energy consumed in the turning process.
2- Among the parameters, cutting speed has more effect on the plastic energy relative to rake angle.
3- The cutter edge radius has less effect on the plastic energy and it should be studied for selecting an appropriate value.
4- Totally for minimizing plastic energy, the high value of cutting speed and rake angle should be selected.

NOMENCLATURE

σ	Equivalent stress
ε	Plastic strain
$\dot{\varepsilon}$	Strain rate
$\dot{\varepsilon}_0$	Reference strain rate
T	Operating temperature
T_r	Room temperature
T_m	Melting temperature
σ_m	Mean stress
A, B, C, n, m	Material constants of Johnson-Cook constitutive model
D_1 to D_5	Material constants of Johnson-Cook failure model
P	Machine tool total power for metal cutting (kW)
P_0	Machine tool idle power without metal cutting (kW)
MRR	Material Removal Rate (cm^3/sec)
k	Constant (kJ/cm^3)
SEC	Specific Energy Consumption (kJ/cm^3)
U_c	Shear energy
F_c	Main cutting force
V	Cutting speed
U_s	Shear energy
F_s	Shear force
V_s	Shear velocity
F_f	Friction force
V_c	Chip velocity

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