

Finite element modeling of power consumption in turning of AISI 1040 steel

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Abstract

AISI 1040 stainless steel is well known for its immense strength and favorable resistance to corrosion. On the other hand, a difficult workability process during machining operations causes a high-power consumption. Energy consumption is an important expense in the machining process. Therefore, this study is aimed to model the power consumption of AISI 1040 stainless steel by using the finite element method. The Third Wave Systems AdvantEdge program was applied for finite element analysis. This program which provides numerous design and analysis tools is specially designed to simulate cutting processes. Optimum cutting parameters to minimize the power usage were developed in three levels based on the Taguchi L9 experimental design. The Taguchi L9 orthogonal array was used as an experimental design. Finite element simulations were performed with three different cutting parameters feed rate (f), cutting speed (V), and cutting depth (a). As a result of Taguchi analysis based on S / N ratios, S / N graphs, S / N response table, ANOVA results, it was determined that progression speed is the most critical parameter in energy consumption.

Keywords: AISI 1040, Finite element method, Power usage, Turning

1. Introduction

The machining industry includes metal cutting operations such as milling, drilling, turning, and grinding. Turning is one of the most common methods to produce components with the desired shapes and dimensions [1]. Various types of materials are used in the machining process. Among these materials' stainless steels, which are the leading ones, create high cutting forces in the cutting process due to their high strength values [2]. In addition to optimum material selection according to the needs, optimization of cutting parameters is also critical in machining production methods. Reducing CO₂ emissions and ensuring energy sustainability can be achieved by optimizing cutting parameters [3]. Reduction in energy consumption has a vital role in the machining process not only to reduce the machining costs but also to enhance environmentally friendly production [4].

With the use of simulation programs both in academia and industry in recent years, users can obtain more reliable and much faster results without doing physical experiments. Also, it allows the users to take early precautions for possible errors that may be encountered during the production process. Thus, significant gains can be obtained in expenses such as time, production cost, and energy consumption. Among these methods, the finite element method

(FEM) is mostly used tool, especially for the simulation of metal cutting processes [5, 6]. FEM is one of the simulation methods that are frequently used in this field. FEM helps users to obtain results such as cutting forces, temperature, and power consumption that occurs during the cutting process [6-9]. Korkmaz et al. investigated cutting forces and power consumption in turning of AISI 420 Martensitic Stainless Steel. In that study, the FEM with the Third Wave AdvantEdge software is used. In their study, it was concluded that the reduction in cutting forces could lead to low power consumption and this could be possible by optimizing the cutting speed, and feed rate parameters, depth of cut [9]. In another study, FE analysis was performed to compare the impacts of conventional and newly developed turning methods, on titanium and Hastelloy-X alloys with regards to the different process variables. A new hybrid machining method (Hot ultrasonic assisted turning) changes the cutting system between tool and workpiece. Therefore, it leads to lower cutting forces and enhances the surface finish. [10]. Şahinoğlu and Rafighi conducted turning tests with different cutting parameters on AISI 1040 steel of different hardness. This study aimed to increase surface quality and reduce energy consumption by optimizing working parameters. The impacts of cutting variables and workpiece hardness on surface roughness, noise

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level, and power consumption were analyzed. The results demonstrated that the feed rate has the highest impact on power consumption and surface roughness [11].

When the literature was examined, it was seen that the Taguchi test method was quite effective in evaluating the optimum process parameters [9, 12]. It also reveals that power consumption is one of the

2. Materials and methods

In this work, the effects of cutting parameters on the power consumption of AISI 1040 stainless steel material were investigated in the turning operations

most significant aspects while limited literature discusses the power consumption in the manufacturing industry. Therefore, the power consumption in the turning of AISI 1040 stainless steel was examined by a finite element analysis method. Taguchi L9 orthogonal array was used as an experimental design. The changes in the cutting parameters selected for the turning operation on the power consumption were recorded.

by using the FEM. Some mechanical properties of AISI 1040 stainless steel material are given in Table 1 [13,15].

Table 1. Material Properties

	Hardness (Rockwell C)	Density (g/cm ³)	Poisson ratio	Young modulus (GPa)	Thermal conductivity coefficient (W/m K 100°C)
AISI 1040	30	7.845	0.29	205	24.7

Plastic deformation properties of AISI 1040 stainless steel are defined according to the Johnson-Cook (JC) model. Johnson-Cook material model was taken as shown in equation 1. This model used is especially used in modeling the high strain deformation rate of metals. It is usually applied in adiabatic transient dynamic analysis. Hardening is a specific type of isotropic hardening where the yield stress is accepted

as σ^0 [16-18].

$$\sigma^0 = (A + B(\varepsilon^p)^n) \left(1 + C \log\left(\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_0}\right)\right) \left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right) \quad (1)$$

Johnson-Cook parameters for AISI 1040 stainless steel used in this study are given in Table 2 [19].

Table 2. AISI 1040 Johnson-Cook (J-C) Model Parameters [19]

Material	A (MPa)	B (MPa)	C	N	m
AISI 1040 Steel	553.1	600.8	0.013	0.234	1

Numerical analysis of the turning operation (turning simulations) was studied using Third Wave AdvantEdge® software. Analyzes 2D orthogonal cutting and Lagrange methods were used. Variable

cutting is shown in Table 3. In this study, the workpiece size $\varnothing 50 \times 150 \text{ mm}^3$ is used. The tool rake angle (γ) is -6° , Clearance angle (α) 6° , Edge radius (r) 0.02 applied for all the experiments.

Table 3. Cutting Parameter Variables

Cutting parameters	
Cutting speed (V) (m/min)	200–225 – 250
Feed rate (f) (mm/rev)	0.15–0.25–0.35
Depth of cut (a) (mm)	1.5–2.5–3.5

3. Results

The Taguchi method was used as an experimental design and analysis method. The test list was created according to the Taguchi L9 experiment design. Optimum cutting parameters for power consumption, minimum best signal to noise ratio equation is used with the Taguchi method. As shown in Equation 2,

S/N ratios were calculated in MINITAB 17 using the smallest best equation. N is the number of repetitions in the equation, y_i is the measured value of the change. The values obtained are given in Table 4.

$$\frac{S}{N} = -10 \log \left[\frac{1}{n} \sum_{i=1}^n y_i^2 \right] \quad (2)$$

Table 4. Design of Experiments and Power Consumptions for S/N Ratios

Exp.#	V (m/min)	f (mm/rev)	a (mm)	Power (W)	S/N (dB)
1	200	0.15	1.5	1371.18	-62.74
2	200	0.25	2.5	3570.37	-71.05
3	200	0.35	3.5	6797.97	-76.64
4	225	0.15	2.5	1545.28	-63.78
5	225	0.25	3.5	5664.44	-75.06
6	225	0.35	1.5	3797.37	-71.58
7	250	0.15	3.5	4023.12	-72.09
8	250	0.25	1.5	2691.41	-68.59
9	250	0.35	2.5	6099.40	-75.70

As can be seen in Table 4, the lowest power consumption was obtained with 1371.18 W in experiment no. 1, and the highest power consumption

was obtained with 6797.97 W in experiment no. 3. The results of experiment 1 and experiment 3 analysis are shown in figure 1.

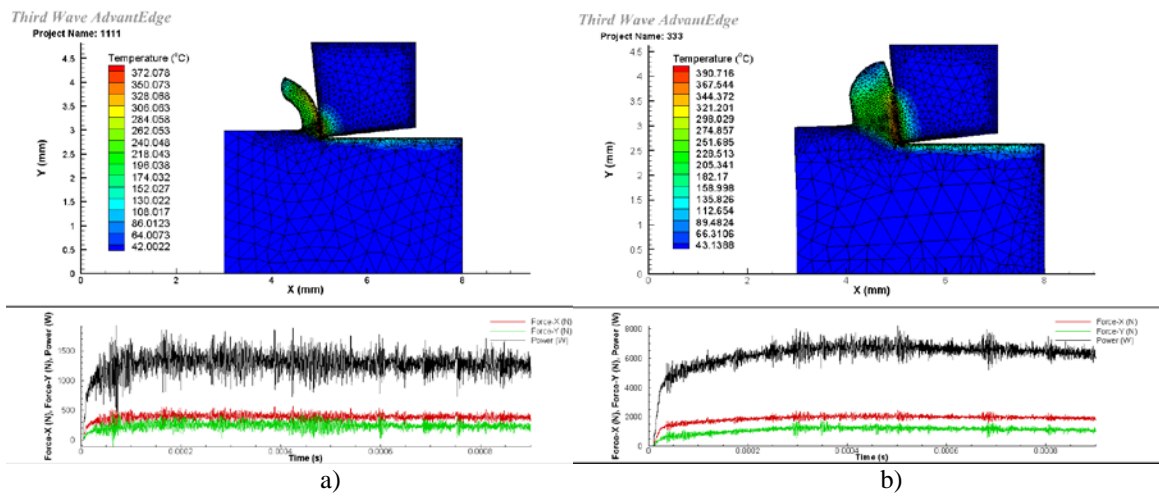


Fig. 1.FEM Results for Experiments a) Experiment 1 b) Experiment 3

Level values of factors obtained from the MINITAB 17 program for power consumption according to Taguchi design are given in Table 5. In Figure 2, the graph of the power consumption S/N answer table is given. As Figure 2 demonstrates power consumption reduces with the decrease of studied parameters. Besides, Figure 2 shows that the feed rate is the most significant process parameter to decrease power

consumption. In future studies, the level values of A, B, and C factors are shown in Table 5 and Figure 2 can be taken into consideration.

In addition, Table 5 shows the effect order of the cutting parameters on the power consumption. It is seen that the first line is the feed rate, the second is the depth of cut and the last is the cutting speed.

Table 5. S/N Results Table for The Power Consumption Factor

Level	V (m/min)	f (mm/rev)	a (mm)
1	-70.15	-66.20	-67.64
2	-70.14	-71.57	-70.18
3	-72.13	-74.65	-74.60
Delta	1.99	8.44	6,96
Rank	3	1	2

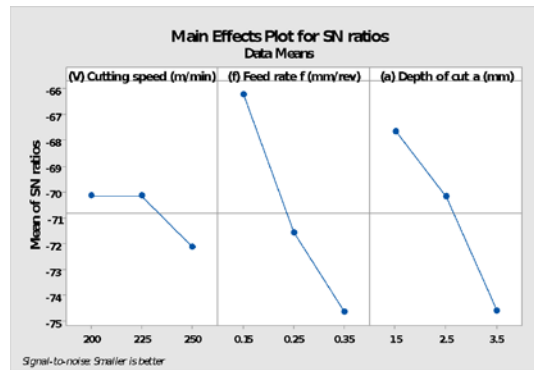


Fig. 2. The Smallest Best S / N Ratio for Power Consumption

While the optimum shear conditions were determined from the S / N ratio obtained by the Taguchi method, the relationship between the shear parameters was determined by analysis of variance. Relationships

between S / N's cutting speed, feed rate, and depth of cut were evaluated. S / N ANOVA analysis results are given in Table 6.

Table 6. S / N-Relationship Among Cutting Parameters

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value
(V) (m/min)	2	7.889	7.889	3.944	1.31	0.433
(f) (mm/rev)	2	109.559	109.559	54.780	18.20	0.005
(a) (mm)	2	74.374	74.374	37.187	12.35	0.075
Error	2	6.020	6.020			
Total	8	197.842	197.842			

4. Conclusions

In this work, the effects of cutting parameters on power consumption in turning AISI 1040 steel were investigated. For this, the analysis list was created according to the Taguchi L9 experiment design and the experimental method was used. Based on the findings obtained from the study, the following conclusions were reached:

- The lowest power consumption was obtained as 1371.18 W at 200 m / min cutting speed, 0.15 mm / rev feed rate, and 1.5 mm depth of cut conditions.
- The highest power consumption was obtained as 6797.97 W under 200 m / min

cutting speed, 0.35 mm / rev feed rate, and 3.5 mm depth of cut conditions.

- It has been finalized that the most effective process parameters in power consumption is feed rate, whereas the cutting speed, is the least effective on this process.
- It is determined that optimal process parameters may result in lower power consumption.

The power consumption values can be estimated without experiments in the turning operation by FEM.

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