

Article

Cutting Force Model for Thermal-Assisted Machining of Tool Steel Based on the Taguchi Method

Thi-Bich Mac ^{1,2}, Van-Chien Dinh ³, Tien-Long Banh ¹ and Duc-Toan Nguyen ^{1,*} 

¹ School of Mechanical Engineering, Hanoi University of Science and Technology, 1A-Dai Co Viet Street, Hai Ba Trung District, Hanoi 100000, Vietnam; bich.utehy@gmail.com (T.-B.M.); long.banhvien@hust.edu.vn (T.-L.B.)

² Faculty of Mechanical Engineering, Hung yen University of Technology and Education, Hung yen 160000, Vietnam

³ Faculty of Electro-mechanical Engineering, Hanoi University of Mining and Geology, Hanoi 100000, Vietnam; pgs.tsinhvanchien@gmail.com

* Correspondence: toan.nguyenduc@hust.edu.vn; Tel.: +84-43-869-2007; Fax: +84-43-869-2006

Received: 25 October 2018; Accepted: 23 November 2018; Published: 26 November 2018



Abstract: This paper investigates cutting force in thermal-assisted machining (TAM) by induction heating for SKD11 tool steel which is widely used in the mold industry. Experimental studies were first conducted at room and elevated temperatures to evaluate the effectiveness of the heating process on chip morphology and the cutting forces during the thermal-assisted machining and comparing with conventional machining method. The Taguchi method based on orthogonal array and analysis of variance ANOVA method was then used to design the number of experiments and evaluate the influence of cutting speed, feed rate, cutting depth, and elevated temperature on the cutting force. Study results showed a decrease in the cutting force in the TAM process. The optimal condition of parameters obtained for thermal-assisted machining were cutting speed 280 m/min, feed rate 230 mm/min, cutting depth 0.5 mm and temperature 400 °C. Finally, a proposed equation was established to determine the cutting force that was presented as a function of elevated temperatures when milling SKD11 material. A proposed cutting force model was compared, evaluated and confirmed to be in good agreement with experimental results.

Keywords: thermal-assisted machining (TAM); induction heating; Taguchi method; ANOVA; SKD11 material

1. Introduction

Thermal-assisted machining (TAM) is one of the new technology solutions for the continuous development of advanced materials that have high hardness, less resistance to wear and thermal conductivity. It supports the cutting process, improves the machinability of material, increases machining productivity, improves surface quality, and reduces product cost [1,2]. With TAM, metals are softened and hardness decreases [3]. Thereby, the machining process during elevated temperatures is easier than one during room temperature.

The manufacturing industry has developed various preheating technologies such as electrical resistance, oxyacetylene gas flame, laser-assisted machining (LAM), induction heating, plasma-enhanced machining (PEM), etc. In thermal-assisted machining, a blank is preheated with outside power to the material's softening temperature. Then, it is machined by immediately using a normal machining method. Researchers [4–7] have studied various preheating methods for the machining process, and their benefits. However, each thermal-assisted method has different advantages and disadvantages and suitability for some machining methods. The induction preheating

method is effective and inexpensive. It is a good choice for end milling with magnetic metals and alloys [8]. Sadeghipour K. et al. [9] used a finite element method to analyze the temperature distribution during induction heating by high frequency of steel (40–200 kHz). The simulation results showed good agreement when comparing with experimental data.

To test new technology solutions before their application to actual production, studying cutting forces is very important. In practice, the cutting forces are very important to the design of cutting tools, fixture, calculation, and design machine. Under effect of the cutting forces and cutting temperature, the tool will be worn or destroyed [10]. Ginta et al. [11] presented the effectiveness of thermal-assisted machining on machinability in end milling of Ti–6Al–V4 material. This study used an induction heating system. The research results concluded that direct heating of the blank before machining affected force cutting, chatter, tool life, and material removal rate. The cutting forces reduced in TAM. It made the decreasing stress on the tool, increasing tool life and reducing chatter in the cutting process. Baili et al. [2] studied thermal-assisted turning by induction heating to improve the machinability of Ti-5553. The research results also showed that the cutting forces reduced 34.4% when the blank's temperature was 750 °C. However, the material structure could not be changed.

The aims of thermal-assisted machining are to reduce the material's strength and the hardness of the blank. Therefore, the cutting force is reduced and chip morphology is changed. Sun et al. [12] researched chip formation during thermal-assisted machining by laser beam of Ti–6Al–V4 alloy. This study showed that chip formation was segmental with conventional machining, but beam power and cutting force were important in the process of transition from segmentation to continuous chip in LAM. Table 1 shows an analysis of previous studies during thermal-assisted machining. The effects of heating process on machinability have been analyzed in detail.

Table 1. Summary of previous studies during thermal-assisted machining.

No.	Authors	Material	Tool	Heating Method	Results
1	Wang Z. Y. et al. [13]	Inconel 718	Coated-carbide cutting inserts	Plasma Enhanced Machining (PEM)	The surface roughness decreased by 250%. The cutting forces reduced by approximately 30–50%. The tool life increased by 170% in comparing with conventional machining.
2	Novak J.W et al. [14]	Inconel 718	WG-300 inserts aluminum oxide reinforced with silicon-carbide whiskers		Experimental results during conventional and plasma enhanced machining were compared. Several advantages of PEM were analyzed, including improvement of surface roughness by as much as a factor of 4, lower cutting forces by approximately 20% and extended tool life.
3	Leshock C. E. et al. [15]	Inconel 718	Coated-carbide cutting inserts		A numerical and experimental analysis of PEM were presented. A three-dimensional finite difference model was established to determine the temperatures distribution in a cylindrical workpiece. The results showed in good agreement with experimental data. Benefits of PEM were demonstrated in comparing with conventional machining, including 30% decreasing of the cutting force and 40% increase in tool life and two-fold improvement in surface roughness.
4	Shi B. et al. [16]	Inconel 718	Coated-carbide cutting inserts	Laser assisted machining (LAM)	The cutting forces decreased from 24% to 46% and chip thickness increased 40% during thermal-assisted machining at 800 °C.
5	Dumitrescu P. et al. [17]	AISI D2 tool steel	TiN-coated carbide insert		LAM of AISI D2 tool steel was studied using a high-power diode laser. The results showed that tool life was improved by as much as 100%, the cutting force was reduced, and laser heating wasn't of significant thermal detriment to the machined surface.
6	Rajagopal S. et al. [18]	Inconel-718 and Ti-6Al-4V	Ceramic tools for Inconel 718 and carbides for Ti-6Al-4V		LAM using a 15-kW continuous-wave laser was researched. The metal removal rate was significantly increase for both materials without aggravating either cutting force or tool wear, the gain in removal rate being 33 % for Inconel 718 and 100 % for Ti-6Al-4V.
7	Ganta V. et al. [19]	15-5PH stainless	K313 carbide cutting inserts	Oxy-acetylene gas flame	Material removal rate was maximum in TAM at 400 °C. The optimum cutting speed was 31 m/min to achieve the smallest roughness.
8	Muhammad R. et al. [20]	Ti-15333	Cemented-carbide cutting inserts	Hot ultrasonically assisted turning (HUAT)	The cutting forces reduced 80–85% during HUAT at 300 °C.

Table 1. Cont.

No.	Authors	Material	Tool	Heating Method	Results
9	Amin A. K. M. N. et al. [21]	AISI 1040	Coated-carbide cutting inserts	Induction heating	Preheating of the workpiece increased the tool life by 39% to 52%. The chatter and surface roughness reduced during TAM.
10	Lasis et al. [22]	AISI D2 hardened steel	Coated-carbide cutting inserts		The studied results presented the benefit of TAM of hardened steel components in reduced machining costs and lead times in comparing with conventional machining. 335 °C preheating temperature coupled with 40 m/min cutting speed, 1.0 mm depth of cutting and 0.02 mm/tooth resulted reduction in tool wear rate, maximum tool life of 188.55 min. The surface roughness was decreased.
11	Amin A. K. M. N. et al. [23]	Resistant steel 3N-481 and titanium alloys BT3-1	Cemented carbide tools		The influence of instability of chip formation and preheating of workpiece on tool life in TAM resistant steel and titanium alloys were researched. Results investigations showed the chip formation process was unstable in machining these alloys. Preheating of both the work materials leads to the decrease of tool wear and amplitude of vibration of the cutting forces.
12	Amin A. K. M. N. et al. [24]	SKD11	Coated-carbide cutting inserts		An investigation on TAM of SKD11 on VMC using ball nose was studied. The Design of Experiments was done in order to develop empirical mathematical models of vibration and surface roughness. The results showed that the surface roughness and vibration amplitude were reduced. Optimum temperatures support for machining process were between 400 °C and 500 °C.

SKD11 tool steel is widely used in the automotive industry and mold manufacturing industry because of its great properties, such as its strength, ductility, and hardness being maintained at high temperatures [25]. Normally, SKD11 is machined using advanced methods such as grinding with abrasive diamond wheels or electro-discharge machining. However, these methods are limited because the tools are expensive and wear quickly; there is a low material removal rate, and so on. The cutting force, roughness, and wear were studied [25] to analyze the effect of high temperatures created by laser beam and compared with conventional machining methods. The research concluded that wear on tools was reduced, the cutting force decreased 40%, and roughness was reduced by up to 50% compared with machining at room temperature.

To investigate the effect of input parameters on the output experimental results, DoE (Design of Experiment) method has been well-known as a powerful tool which can upgrade/improve the performance of the product, process, design, and system with a significant slash in experimental time and cost [26,27]. The method is based on the mathematical statistics combined with the scientifically arrangement and evaluation of experiential data [27]. It has been used to apply to various research fields [28–32]. Where, the mean (ANOM) and variance (ANOVA) analysis is used to verify the effect of input parameters on the observation of interesting output. In order to minimize the tests and indicate the optimum levels of input parameters, the orthogonal array of DoE could be chosen from Taguchi's standard orthogonal array table [33].

Recent research has concentrated on the effect of the thermal-assisted process on the output parameters of the cutting process: cutting force, surface roughness, tool wear, and chatter. The number of studies on the hot machining method with elevated temperatures heated by induction is still limited. So, this study looked at the effect of cutting parameters on cutting force in thermal-assisted milling of SKD11 steel by induction heating. The chip morphologies in conventional machining and TAM were compared and analyzed to predict the improvement of the cutting force and effectiveness of the thermal-assisted process. An experimental machining process was performed at room and elevated temperatures to find the optimum cutting and temperature parameters in order to minimize cutting force based on the Taguchi method. The relationship between cutting force and cutting parameters such as cutting speed, feed rate, and cutting depth were also simply constructed using the Gauss–Newton method in the nonlinear regression tool of Minitab17 software. However, the current study proposed a new method for predicting cutting force at different elevated temperatures. The prediction results were analyzed and compared, and were in good agreement with the experimental data.

2. Experimental Procedure

2.1. Material

Experimental studies were performed by machining SKD11 tool steel material. Tables 2 and 3 show the chemical composition and material properties of the workpiece, which is widely used in the mold manufacturing industry [34]. To present the flow stress curves as the function of temperature, previous study [34] applied Johnson Cook' flow stress model (J-C) and determined the (J-C) coefficients as shown in Table 3. Where A, B, C, n, and m are the material parameters to be identified, T (K) is the current temperature, T_m (K) is the melting temperature, and T_r is a reference temperature i.e., 298 (K), $\dot{\epsilon}$ and $\dot{\epsilon}_0$ are the equivalent plastic strain rate and the reference strain rate used for normalization, respectively.

Table 2. Chemical compositions of SKD11 tool steel (%) [34].

C	Cr	Mo	Si	Mn	Ni	V
1.4–1.6	11–13	0.7–1.2	≤0.6	≤0.6	-	0.15–0.3

Table 3. Material properties and Johnson–Cook flow stress coefficient of SKD11 tool steel [35].

Johnson–Cook Flow Stress $\sigma = (A + B\bar{\epsilon}^n)(1 + C \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_0})(1 - (\frac{T - T_r}{T_m - T_r})^m)$				
Physical property	Value	J-C flow stress coefficient	Value	
Density (kg/m ³)	8400	A (Mpa)	1766	
Poisson's ratio	0.3	B (MPa)	904	
Thermal expansion coefficient (10 ^{−6} /K)	11	n	0.39	
Melt temperature T_m (K)	1733	C	0.012	
Specific heat (J/kg °C)	461	T_r (K)	298	
Thermal conductivity coefficient (w/m·K)	20.5	m	3.38	

2.2. Experimental Setup

The experiments were conducted using an MC500 milling machine (Fuhong, Taichung City, Taiwan). A spindle speed of 100–30,000 r/min; spindle motor power of 15 kW; feed rate of 30,000 mm/min; maximum idle speed of 48,000 mm/min; and travel distances of the operating platform in X, Y, and Z axes of 500 mm, 400 mm, and 300 mm, respectively, were used. Cooling solution was not used during the machining process.

Figure 1 shows a photograph of the experimental setup for induction-assisted milling of SKD11 steel. The MC500 milling machine is illustrated by the spindle. The heat-assisted parts consist of magnetic induction power, frequency generator and induction coil. An experimental specimen of 70 mm × 31 mm × 80 mm was placed on the dynamometer with a clamp. Force measuring equipment was connected to a computer to display the measurement results. The researchers used an induction heating system to heat the workpiece to reach machining temperatures. The experiments used a three-component cutting force measurement device from Kistler in Switzerland that uses a piezoelectric force dynamometer (9257B, Kistler) with multi-component dynamometer up to 10 kN. The sensor sensitivity in the X, Y direction is 7.39 pC/N, and Z direction is 3.72 pC/N. DASYLab 10.0 software (DASYTec, Amherst, NH, USA) was used to convert A/D signals and save the data on a computer. A40 mm carbide insert milling tool diameter was used in the experiments. The APKT 1604PDR–GM cutting tool from Pramet in the Czech Republic was used with geometric parameters, as described in Figure 2 and Table 4.

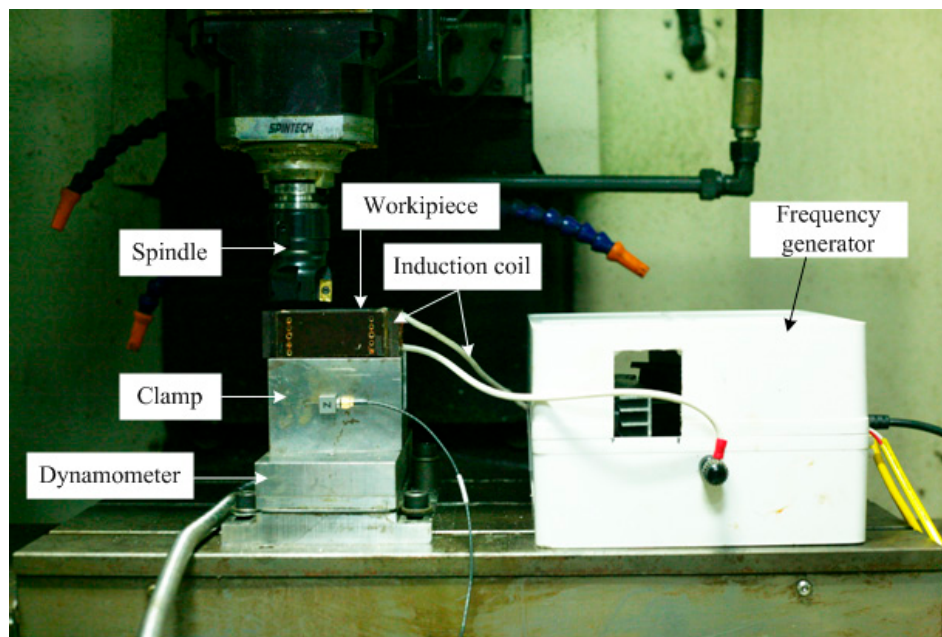


Figure 1. Photograph of experimental setup for induction-assisted milling of SKD11 steel.

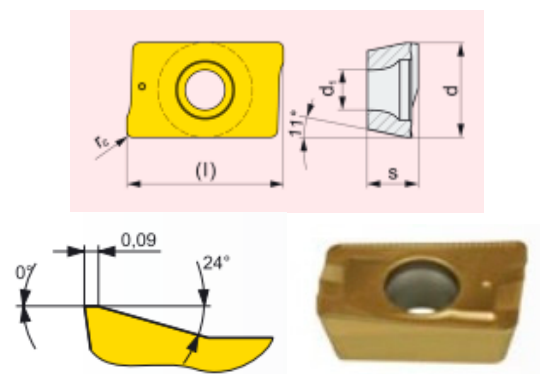


Figure 2. APKT 1604PDR-GM cutting tool.

Table 4. Geometric parameters of APKT 1604PDR-GM cutting tool.

Symbol	l (mm)	d (mm)	s (mm)	d_1 (mm)	r_e (mm)
Value	17	9.44	5.67	4.6	0.8

To control the temperature which supports the machining process accurately and safely, the relationship between generated temperatures and heating times has been studied before cutting. A hand-held digital thermometer, model 3527A from TSURUGA corporation-Japan, had been used. During heating process, the thermometer was placed on the workpiece surface to measure the temperature based on heating time. A time-dependent temperature graph was constructed as shown in Figure 3. Three studied temperature levels of 200 °C, 300 °C, and 400 °C were achieved at 2, 3.8, and 6.3 min, respectively. Therefore, in order to verify the effect of temperature parameter on cutting force during the machining trials, the heating times have been utilized instead of measuring the elevated temperatures on the machining workpiece. Besides that, to evaluate the effect of heating process on material hardness, the initial workpiece and workpieces after preheating then air quenching at 200 °C, 300 °C, and 400 °C (Figure 4) were measured. Experimental results showed that the material hardness before and after preheating and air quenching were remained 250 HB.

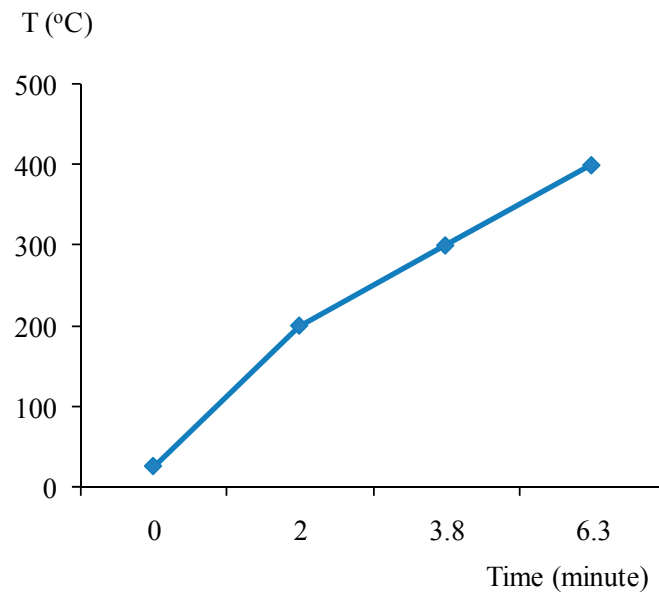


Figure 3. The relationship between generated temperatures and heating times by using induction coil of SKD11 tool steel.

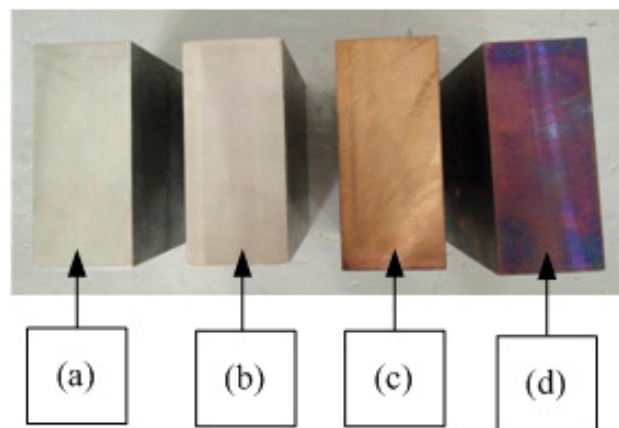


Figure 4. The initial workpiece (a) and preheating workpieces of 200 °C (b), 300 °C (c), and 400 °C (d).

3. Design of Experiment

In this research, the Taguchi design of experiment (DoE) method [33] was chosen because of the objective optimization of control parameters and simple, effective, and economical number of experiments. In this method, each parameter can be evaluated individually and for random experiments with an orthogonal array (OA). The Taguchi method has the potential to narrow the scope of specific research or identify problems in production with existing data. In this method, the typical value for average performance that is close to the target value is appreciated more than a value with limited technical specifications [28–32].

The study identified four control parameters that had the biggest effect on cutting force, namely cutting speed (V_c), feed rate (f), cutting depth (t), and workpiece temperature at processing time (T). Measurement of the interactions between parameters was made with an S/N ratio. The S/N ratio was constructed with the following three objectives: larger is better, smaller is better, nominal is best.

This paper researched the influence of these control parameters on cutting force. Therefore, the smaller is better objective was chosen. The S/N ratio with the smaller is better objective is expressed as a mathematical function as follows [33]:

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

where $\sum_{i=1}^n y_i^2$ is the sum of the square of all results for each experiment, and n is the number of repeated experiments.

To investigate the benefits of the thermal-assisted machining method compared to conventional machining, the experimental effects of V_c , f , and t parameters on cutting force was studied when milling was performed at room temperature. After that, temperature parameter T was included in the experiments with the same technological parameters. The control parameters and their levels shown in Table 5 with cutting speed, feed rate, cutting depth, and temperature studied were 190 m/min–280 m/min, 230 mm/min–380 mm/min, 0.5 mm–1.5 mm, and 200 °C–400 °C, respectively. The experiments were designed using the orthogonal method of Taguchi L9, as shown in Tables 6 and 7.

Table 5. Control parameters and their levels.

No.	Control Parameter	Symbol	Unit	Level 1	Level 2	Level 3
1	Cutting speed (A)	V_c	m/min	190	235	280
2	Feed rate (B)	f	mm/min	230	305	380
3	Cutting depth (C)	t	mm	0.5	1.0	1.5
4	Temperature (D)	T	°C	200	300	400

Table 6. Results of cutting force (FR) and S/N ratios at room temperature.

Exp. No	Experiment at Room Temperature			FR (N)				S/N
	A	B	C	1st	2nd	3rd	Average	
1	1	1	1	138.12	134.87	134.95	135.98	−42.6695
2	1	2	2	292.56	299.67	303.83	298.69	−49.5043
3	1	3	3	432.86	425.13	444.20	434.06	−52.7510
4	2	1	2	218.3	211.45	211.20	213.65	−46.5941
5	2	2	3	349.96	362.79	367.75	360.17	−51.1301
6	2	3	1	163.78	157.92	159.69	160.46	−44.1074
7	3	1	3	262.76	268.19	257.05	262.67	−48.3881
8	3	2	1	119.78	120.43	116.09	118.77	−41.4940
9	3	3	2	238.18	241.89	237.96	239.34	−47.5804

Table 7. Results of the cutting force (F_T) and S/N ratios at elevated temperatures.

Exp. No	Experiment at Elevated Temperature				FR (N)				S/N
	A	B	C	D	1st	2nd	3rd	Average	
1	1	1	1	1	60.286	61.965	64.364	62.205	−35.8765
2	1	2	2	2	129.768	132.879	127.104	129.917	−42.2733
3	1	3	3	3	157.198	149.546	158.676	155.140	−43.8145
4	2	1	2	3	93.124	89.865	87.754	90.248	−39.1087
5	2	2	3	1	228.178	219.897	226.810	224.962	−47.0422
6	2	3	1	2	71.899	76.124	74.018	74.014	−37.3862
7	3	1	3	2	109.765	110.9	115.540	112.068	−40.9897
8	3	2	1	3	39.123	38.935	39.710	39.256	−31.8781
9	3	3	2	1	130.895	135.267	136.612	134.258	−42.5588

4. Results and Discussion

4.1. Chip Morphology

Figure 5 shows chips that were produced by end milling of SKD11 steel at $V_c = 235$ m/min, $f = 305$ mm/min, and $t = 1.5$ mm with different machining conditions. Figure 5a,b is chip morphology during conventional machining and thermal-assisted machining, respectively. Continuous chips are generally formed due to the ductility characteristics of the workpiece material. However, in conventional machining, the chips are burnt to a violet-black color (Figure 5a). That means the heat generation and transfers from the heating sources to the chips are very elevated. In contrast, in TAM with the workpiece's temperature at 200 °C, the chips' color is much brighter (Figure 5b). This phenomenon could be explained that the cutting temperature transferred to the chips is lower because the heat transfer condition between cutting tool, work-piece and chip is more uniform at elevated temperatures. It leads to local heat generation by friction and heat transfer to the chip decreases.

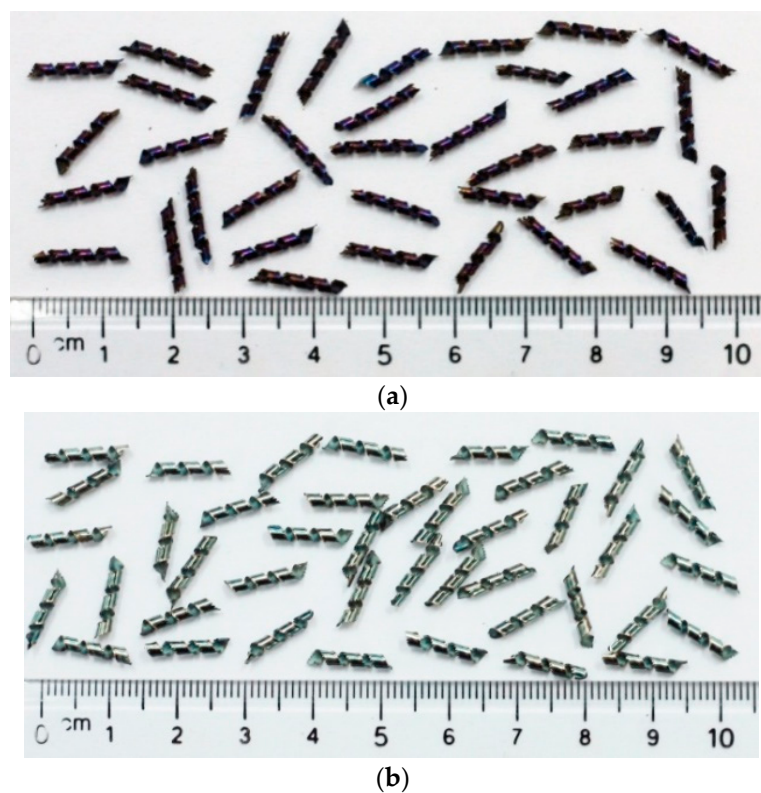


Figure 5. Chip morphology in conventional machining (a) and thermal-assisted machining (b) which were conducted using an MC500 milling machine.

4.2. Experimental Machining at Room Temperature

In this study, each experiment was performed three times. Cutting force values, the average cutting force and the S/N ratios are shown in Table 6. The S/N ratios were calculated based on Equation (1). Synthetic analysis of the influence of the technological parameters on the cutting force in conventional machining is shown in Table 8. The S/N ratio of each factor with three levels is shown in Figure 5.

Table 8. Multiple S/N response.

Parameter	Mean of Multiple S/N Ratio			Sum of Squares	Contribution (%)
	1	2	3		
A	−48.308	−47.277	−45.821 *	9.371	8.087
B	−45.884 *	−47.376	−48.146	7.938	6.850
C	−42.757 *	−47.893	−50.756	98.56	85.062

* Optimum level.

Analysis of the mean of multiple S/N ratios of control parameters for each level is shown in Table 7. From this, the optimum values in conventional machining of SKD11 were obtained as A3B1C1 with a cutting speed of 280 m/min, feed rate of 230 mm/min, and cutting depth of 0.5 mm, as shown in Figure 6.

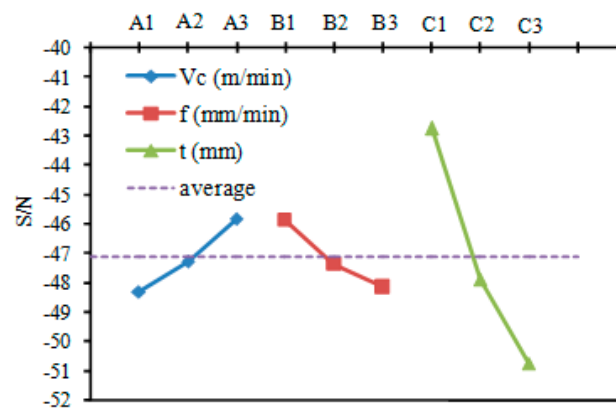


Figure 6. S/N ratios of control parameters at room temperature.

The mathematical model of cutting force depends on technological parameters (V_c , f , t) in the milling of SKD11 steel at room temperature, and is described by Equation (2).

$$F_R = a_1 \cdot V_c^{b_1} \cdot f^{c_1} \cdot t^{d_1} \quad (2)$$

where F_R is the synthetic cutting force, which is broken down into three component cutting forces, F_{XR} , F_{YR} , and F_{ZR} , with Equation (3):

$$F_R = \sqrt{F_{XR}^2 + F_{YR}^2 + F_{ZR}^2} \quad (3)$$

a_1 , b_1 , c_1 , and d_1 are the coefficients determined from the experiment. Using the nonlinear regression tool of Minitab 17 software, the nonlinear regression function in the milling of SKD11 steel at room temperature was found as Equation (4).

$$F_R = 842.365 \cdot V_c^{-0.70513} \cdot f^{0.458888} \cdot t^{0.824242} \quad (4)$$

4.3. Experimental Machining at Elevated Temperatures

To study the influence of the thermal-assisted process on cutting force in the milling of SKD11 steel, experimental studies were conducted with L9 orthogonal array. Each experiment was performed three times for the average cutting force and the S/N ratio of each experiment, as shown in Table 7. The S/N ratio was calculated according to the Equation (1).

From the analysis of the S/N ratio for each control parameter at three levels, optimum controls were chosen for the minimum cutting force gain, which were A3B1C1D3 (Table 9 and Figure 7).

The optimum cutting parameters and temperatures were obtained as a cutting speed of 280 m/min, feed rate of 230 mm/min, cutting depth of 0.5 mm and temperature of 400 °C.

Table 9. Multiple S/N response.

Parameter	Mean of Multiple S/N Ratio			Sum of Squares	Contribution (%)
	1	2	3		
A	−40.65	−41.18	−38.48 *	12.332	7.370
B	−38.66 *	−40.40	−41.25	10.491	6.269
C	−35.05 *	−41.31	−43.95	125.459	74.973
D	−41.83	−40.22	−38.27 *	19.055	11.386

* Optimum level.

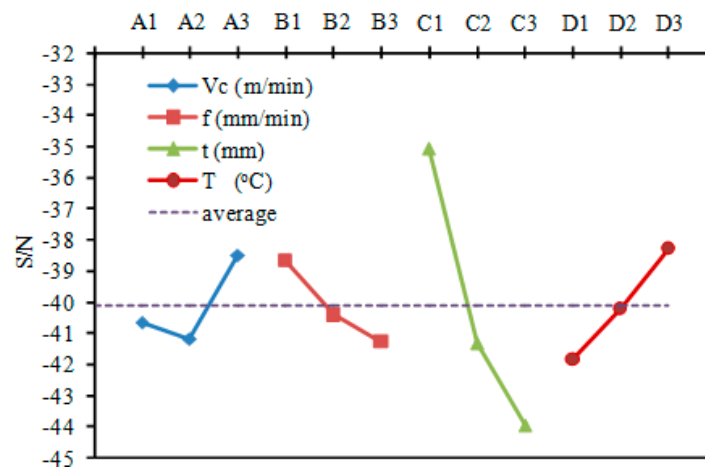


Figure 7. S/N ratios of control parameters at elevated temperatures.

The cutting force doesn't only affect the technological system such as machine, tool, and fixture, but also causes vibration in the cutting process, affecting the precision of the machining process. The goal of thermal-assisted machining is to reduce the cutting force to improve product quality. As the conclusions from previous studies, the elevated temperatures of the workpiece lead to reduce the hardness and strength of the machining material during heating time [1,2]. The material is softer, making the cutting process easier [3]. Therefore, the cutting force is reduced and the separating of the chips from the workpiece is easier. Figure 8 is a graph of conventional and elevated machining at 200 °C with cutting parameters at $V_c = 190$ m/min, $f = 230$ mm/min, $t = 0.5$ mm. Table 10 gives a comparison of the cutting force in conventional and elevated machining. Cutting force reduction ΔF (%) is according to Equation (5):

$$\Delta F(\%) = \frac{F_R - F_T}{F_R} \cdot 100\% \quad (5)$$

The results show that the cutting force is strongly supported in thermal-assisted machining. The highest cutting force reduction was 66.9% in the eighth experiment with a temperature of 400 °C. The lowest cutting force reduction was 37.5% in the fifth experiment with a temperature of 200 °C. With the effect of high temperatures, the softening of the workpiece material reduces the friction between chips and the front of the tool, and between the back of the tool and the workpiece surface that is being machined. So, the cutting process is made easier.

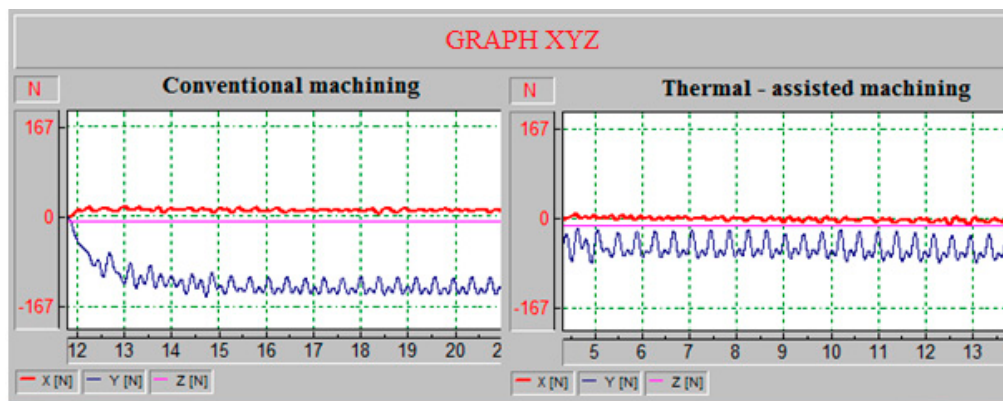


Figure 8. Cutting force with cutting parameters at $V_c = 190$ m/min, $f = 230$ mm/min, $t = 0.5$ mm in conventional and thermal-assisted machining.

Table 10. Comparison of cutting force in conventional and thermal-assisted machining.

Trial	F_R (N)	T ($^{\circ}\text{C}$)	F_T (N)	ΔF (%)
1	135.98	200	62.205	54.3
2	298.69	300	129.917	56.5
3	434.06	400	155.140	64.3
4	213.65	400	90.248	57.8
5	360.17	200	224.962	37.5
6	160.46	300	74.014	53.9
7	262.67	300	112.068	57.3
8	118.77	400	39.256	66.9
9	239.34	200	134.258	43.9

4.4. Establishing Cutting Force Model with Thermal-Assisted Machining

a. Average Ratio Method

This method is based on the average ratio of the experimental results of the cutting force in conventional and thermal-assisted machining, as shown in Table 10.

The rate of cutting force during machining at elevated temperatures compared to conventional machining is a function of workpiece temperature at cutting time. The mathematical equation of the cutting force as Equation (6).

$$F_T = \frac{F_R}{f(T)} \quad (6)$$

where $f(T)$ is a function of the workpiece temperature at cutting time.

Based on results of the cutting force of these two machining methods with the same cutting parameters as in Table 10, the average ratio of the cutting forces reduction at different temperatures of 200 $^{\circ}\text{C}$, 300 $^{\circ}\text{C}$, and 400 $^{\circ}\text{C}$ was determined as shown in Table 11. Using Excel software, the equation $f(T)$ was defined as in Equation (7). The results show that the equation $f(T)$ is a linear equation. The graph of $f(T)$ is shown in Figure 9, with the R-square variance analysis of 0.998 showing high reliability.

$$f(T) = 0.004T + 1 \quad (7)$$

Table 11. Average ratio of cutting force reduction.

No.	T ($^{\circ}\text{C}$)	Average Ratio
1	200	1.85
2	300	2.27
3	400	2.73

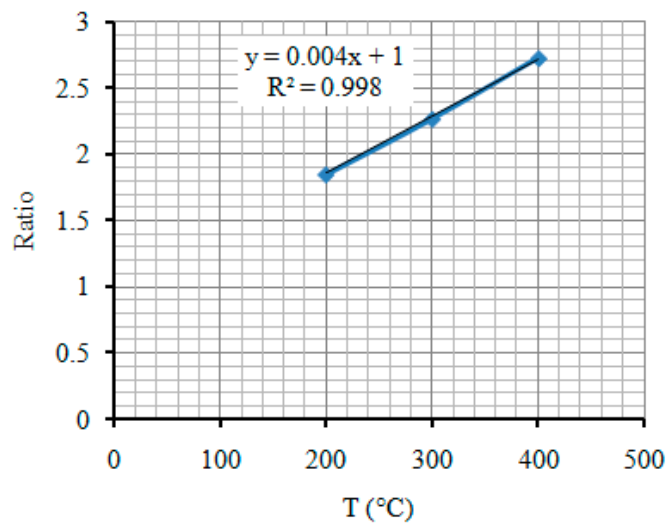


Figure 9. Equation and graph of $f(T)$.

So, the cutting force model in thermal-assisted machining is as seen in Equation (8).

$$F_T = \frac{F_R}{0.004T + 1} \quad (8)$$

Substituting Equation (4) into Equation (8), the cutting force model for thermal-assisted machining depends on the cutting parameters V_c , f , t and T and is written as Equation (9)

$$F_T = \frac{842.365 \cdot V_c^{-0.70513} \cdot f^{0.458888} \cdot t^{0.824242}}{0.004T + 1} \quad (9)$$

The cutting force in Equation (9) ($F_{T(Eq.)}$) is compared with the experimental data ($F_{T(Ex.)}$), as shown in Table 12. The error percentage (ΔF_T (%)) is determined with Equation (10).

$$\Delta F_T(\%) = \frac{|F_{T(Eq.)} - F_{T(Ex.)}|}{F_{T(Ex.)}} \cdot 100\% \quad (10)$$

Table 12. Estimation of error of cutting force determined with average ratio method.

Exp. No.	1	2	3	4	5	6	7	8	9
ΔF_T (%)	27.4	0.6	10.1	7.3	14.6	5	8.9	21	0.1

The results show that the percentage of errors in some experiments is relatively large. The maximum error percentage is 27.4% in experiment 1. The next is 21% in experiment 8. So, it is necessary to propose another method to establish a cutting force model for machining at elevated temperature. The second method is presented in the next section.

b. Gauss-Newton Method

This study is based on the data set of L9 experimental parameters and the results of cutting force are defined as Table 8. The Gauss-Newton method was used to find nonlinear regression function (F_T). This method was applied with the nonlinear regression tool of Minitab 17 software.

The cutting force model for thermal-assisted machining depends on the control parameters V_c , f , t , and T , as Equation (11).

$$F_T = a_2 \cdot V_c^{b_2} \cdot f^{c_2} \cdot t^{d_2} \cdot T^{e_2} \quad (11)$$

where a_2, b_2, c_2, d_2, e_2 are the coefficients determined from the experiment.

With nine-point experimental data in machining at elevated temperatures, the nonlinear regression function in thermal-assisted milling of SKD11 steel was defined as in Equation (12). The error percentage of the comparison with the experimental data was evaluated according to Equation (10). The results are shown in Table 13.

$$F_T = 36235.7 \cdot V_c^{-0.737867} \cdot f^{0.453832} \cdot t^{0.964106} \cdot T^{-0.770712} \quad (12)$$

Table 13. Estimation of error of cutting force determined with Gauss-Newton method.

Exp. No.	1	2	3	4	5	6	7	8	9
ΔF_T (%)	23.6	4	5.2	16.7	4.2	18.4	8.7	2	5.4

The results in Table 14 show that the percentage of errors is relatively large. The highest error percentage is 23.6% in experiment 1. The error percentage is 18.7% in experiment 6. However, the error percentage of the Gauss-Newton method is lower than in the average ratio method.

Table 14. S/N ratio of each experiment with various methods.

Exp. No	S/N Ratio		
	Method 1	Method 2	Method 3
1	−24.6373	−20.9968	−23.3397
2	2.125087	−4.05212	−14.2712
3	−23.9383	−27.0762	−18.175
4	−16.4083	−20.9676	−23.5718
5	−30.3401	−27.8572	−19.5419
6	−11.4257	−20.4168	−22.6809
7	−19.9561	−16.4373	−19.8295
8	−18.3414	−7.60736	2.217361
9	15.30213	4.028598	−17.2207
m value	−14.18	−15.7092	−17.3793

Therefore, this study proposes a new method to determine the cutting force equation in thermal-assisted machining of SKD11 steel, which is presented in the next section.

c. New determine the Cutting Force Equation in Thermal-Assisted Machining

Experiments at elevated temperatures used the orthogonal array Taguchi L9, as shown in Table 8, with four control parameters, which were V_c, f, t , and T , and three levels. The goal of minimizing the number of experiments was met; evaluation of the order of influence of control parameters, and optimization of output parameters was also a great success. However, finding the regression function with nine points was difficult due to the low number of regression points, while the number of control parameters was higher. The two methods of finding the cutting force regression described above gave very little accuracy. For these reasons, the study proposes a new equation (Equation (13)). This equation uses input data, which are the cutting force model for conventional machining at room temperature as in Equation (4), and elevated temperatures that support the machining process (Table 8). Then, the cutting force model for machining at elevated temperatures could be presented as a function of corresponding one at room temperature with the same cutting parameters and workpiece temperatures, as Equation (13):

$$F_T = a_3 \cdot F_R^{b_3} \cdot T^{c_3} \quad (13)$$

where a_3, b_3 , and c_3 are the coefficients determined from experiments.

To find the regression function Equation (13), the results of the cutting force in conventional machining (F_R), which are determined from Equation (4) for nine corresponding cases from Table 6,

and workpiece temperatures (T) (Table 8) were used as input data of Equation (13). While, the cutting force results in machining at elevated temperatures (F_T) (Table 10) for nine corresponding cases were set as output data of Equation (13). By programming with MATLAB software (R2015a, The MathWorks Inc., Natick, MA, USA) using least squares, the coefficients a_3 , b_3 , and c_3 were found, corresponding to 5.8027, 1.1336, and -0.5823 , respectively. Equation (13) is rewritten as follows:

$$F_T = 5.8027 \cdot F_R^{1.1336} \cdot T^{-0.5823}. \quad (14)$$

Substitute Equation (4) into Equation (14). Then, the cutting force model for thermal-assisted machining depends on the cutting parameters and the elevated temperatures that support machining, as shown in Equation (15).

$$F_T = 12017.97 \cdot V_c^{-0.67299} \cdot f^{0.41355} \cdot t^{0.803237} \cdot T^{-0.58229} \quad (15)$$

To evaluate the accuracy of the new method and compare it with the two old methods, the study used the method of evaluating the S/N ratio variance of each method. First, the S/N ratios of the cutting force value in each experiment were determined according to Equation (16) with the standard value (experimental value) as the best value [33]. The results are presented in Table 14. Then, the variances of the test set at different temperature levels (200 °C, 300 °C, and 400 °C) were calculated according by Equation (17). The average S/N ratio for heating temperatures is shown in Table 15. The total variance of each method is found in Equation (18). From that, the accuracy of the three methods was evaluated. Table of variance results are shown in Table 16.

$$\frac{S}{N} = -10 \log(\text{MSD}) \quad (16)$$

Table 15. Average S/N ratio for heating temperatures.

m_{jn}	Method 1	Method 2	Method 3
m_{j1}	−13.2251	−14.9418	−20.0341
m_{j2}	−9.75223	−13.6354	−18.9272
m_{j3}	−19.5627	−18.5504	−13.1765

Table 16. Analysis of the variance of the cutting force determined by method.

Method	T (°C)			SS
	200 °C	300 °C	400 °C	
1	2.7356	58.8154	86.9196	148.4706
2	21.1444	7.1885	52.9903	81.3232
3	1.7667	12.9019	24.2171	38.8857

MSD is the average square deviation defined as follows:

$$\text{MSD} = \frac{1}{r} \sum_{i=1}^r (y_i - y_o)^2 \quad (17)$$

where y_o is standard value; y_i is the cutting force value determined from the model; and r is the number of tests in each experiment.

$$\text{SS} = 3(m_{j1} - m)^2 + 3(m_{j2} - m)^2 + 3(m_{j3} - m)^2 \quad (18)$$

where m_{j1} , m_{j2} , and m_{j3} are average values of S/N ratios of the experiments at 200 °C, 300 °C, and 400 °C of the methods.

$$m_{jn} = \frac{1}{3} \sum_{n=1}^3 \left(\frac{S}{N} \right)_n \quad (19)$$

m is the average value of S/N ratios of nine experiments with each method and is defined as follows:

$$m = 9 \sum_{n=1}^9 \left(\frac{S}{N} \right)_n \quad (20)$$

Table 16 shows that the new proposed method, which finds the cutting force regression through the cutting force model for conventional machining, has the least variance. This means that the results of the cutting force determined by the third method are the most accurate. Figure 10 is a graph of predicted cutting forces with the new method, and is compared with the experiment value.

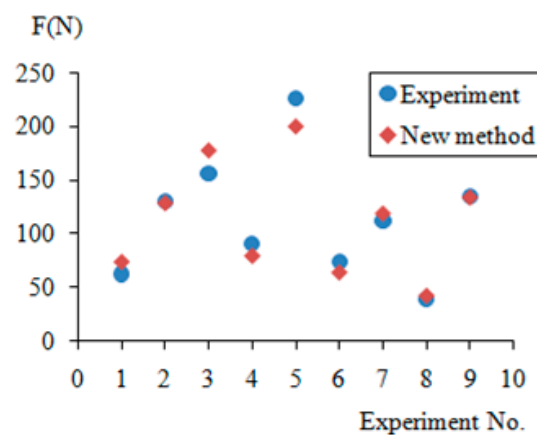


Figure 10. Results of predicted cutting force with new proposal method and in comparison with the experiment.

Based on Equation (15), graphs showing the relationship between the cutting force and cutting parameters at different temperatures were made using the Maple software tool (Maplesoft, a division of Waterloo Maple Inc., Waterloo, ON, Canada) and are shown in Figure 11.

Figure 11 shows that, as temperature increases, the cutting force decreases. However, the cutting force decreases gradually as the billet temperature increases in order from room temperature to 200 °C, 300 °C, and 400 °C. Figure 11a,b are the cutting force graph when fixing V_c and f shows the maximum slope of the cutting force graph when changing the cutting depth. Thus, t has the greatest influence on the cutting force. Figure 11c is the cutting force graph when fixing t . The slope in changing V_c is greater than the one in changing f . That means the effect of V_c is greater than the one of the feed rate (f).

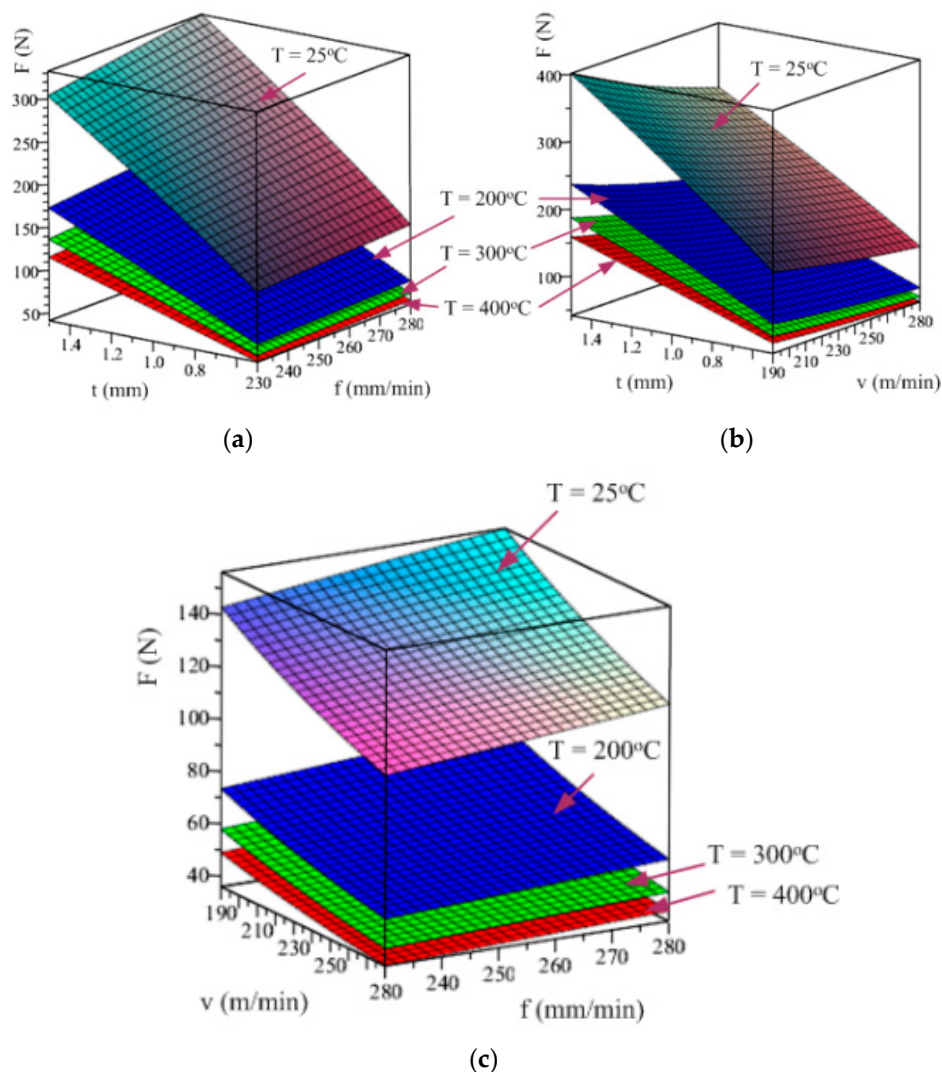


Figure 11. The relationship between F with V_c , f and t at different temperatures (a) with fixed cutting speed, (b) with fixed feed rate, (c) with fixed cutting depth.

5. Conclusions

This paper studied the chip formation and the cutting forces during thermal-assisted machining for SKD11. The following specific conclusions were drawn on the work:

1. Thermal-assisted process effect on chip morphology. The chip's colour change in TAM with brighter colour while chip's colour is violet-black in conventional machining.
2. It is observed that the maximum cutting forces reduction of 66.9% in TAM when compared to conventional machining.
3. The optimal condition of parameters obtained for thermal-assisted machining are cutting speed of 280 m/min, feed rate of 230 mm/min, cutting depth of 0.5 mm, and temperature of 400°C .
4. A new method for predicting the cutting forces in thermal-assisted milling by induction heating of SKD11 is presented show good result when comparing with experimental data.

Author Contributions: M.T.-B. and N.D.-T. designed most of the experiments, performed most experiments, analyzed the results and wrote this manuscript. B.T.-L. and D.V.-C. helped gave some constructive suggestions about how to write this manuscript.

Funding: This research is funded by the Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number "107.02-2016.01".

Conflicts of Interest: The authors declare no conflict of interest.

References

- Shatarupa, G.; Gurav, P.; Rajiv, B.; Suvrna, P. A Review on Effect of Cutting Parameters in Hot Turning Operation on Surface Finish. *Int. J. Eng. Dev. Res.* **2016**, *4*, 55–61.
- Baili, M.; Wagner, V.; Dessein, G.; Sallaberry, J.; Lallement, D. An experimental investigation of hot machining with induction to improve Ti-5553 machinability. *Appl. Mech. Mater.* **2011**, *62*, 67–76. [[CrossRef](#)]
- Brecher, C.; Emonts, M.; Rosen, C.; Hermani, J. Laser-assisted Milling of Advanced Materials. *Phys. Procedia* **2011**, *12*, 599–606. [[CrossRef](#)]
- Germain, G.; Santo, P.D.; Lebrun, J.L. Comprehension of chip formation in laser assisted machining. *Int. J. Mach. Tools Manuf.* **2011**, *51*, 230–238. [[CrossRef](#)]
- Amin, K.M.N.; Binti, S.; Binti, M.; Lajis, M.A. Effects of workpiece preheating on surface roughness, chatter and tool performance during end milling of hardened steel D2. *J. Mater. Process. Technol.* **2007**, *1*, 466–470. [[CrossRef](#)]
- Thi-Hoa, P.; Thi-Bich, M.; Van-Canh, T.; Tien-Long, B.; Duc-Toan, N. A study on the cutting force and chip shrinkage coefficient in high-speed milling of A6061 aluminum alloy. *Int. J. Adv. Manuf. Technol.* **2018**, *98*, 177–188. [[CrossRef](#)]
- Ozler, L.; Inan, A.; Ozel, C. Theoretical and experimental determination of tool life in hot machining of austenitic manganese steel. *Int. J. Mach. Tools Manuf.* **2001**, *41*, 163–172. [[CrossRef](#)]
- Amin, K.M.N.; Ginta, T.L. *Heat-Assisted Machining*; Elsevier: Amsterdam, The Netherlands, 2014; Volume 11.
- Sadeghipour, K.; Dopkin, J.A.; Li, K. A computer aided finite element/experimental analysis of induction heating process of steel. *Comput. Ind.* **1996**, *28*, 195–205. [[CrossRef](#)]
- Pham, T.-H.; Mac, T.-B.; Tong, V.-C.; Banh, T.-L.; Nguyen, D.-T. Simulation and experimental studies to verify the effect of cutting parameters on chip shrinkage coefficient and cutting forces in machining of A6061 aluminum alloy. *Adv. Mech. Eng.* **2016**, *8*. [[CrossRef](#)]
- Ginta, T.L.; Amin, A.K.M.N. Thermally-assisted end milling of titanium alloy Ti-6Al-4V using induction heating. *Int. J. Mach. Mach. Mater.* **2013**, *14*, 194–212. [[CrossRef](#)]
- Sun, S.; Brandt, M.; Dargusch, M.S. The Effect of a Laser Beam on Chip Formation during Machining of Ti6Al4V Alloy. *Phys. Metall. Mater. Sci.* **2010**, *41*, 1573–1581. [[CrossRef](#)]
- Wang, Z.Y.; Rajurkar, K.P.; Fan, J.; Lei, S.; Shin, Y.C.; Petrescu, G. Hybrid machining of Inconel 718. *Int. J. Mach. Tools Manuf.* **2003**, *43*, 1391–1396. [[CrossRef](#)]
- Novak, J.W.; Shin, Y.C.; Incropera, F.P. Assessment of plasma enhanced machining for improved machinability of Inconel 718. *J. Manuf. Sci. Eng.* **1997**, *119*, 125–129. [[CrossRef](#)]
- Leshock, C.E.; Kim, J.-N.; Shin, Y.C. Plasma enhanced machining of Inconel 718: Modeling of workpiece temperature with plasma heating and experimental results. *Int. J. Mach. Tools Manuf.* **2001**, *41*, 877–897. [[CrossRef](#)]
- Shi, B.; Attia, H.; Vargas, R.; Tavakoli, S. Numerical and experimental investigation of laser-assisted machining of Inconel 718. *Mach. Sci. Technol.* **2008**, *12*, 498–513. [[CrossRef](#)]
- Dumitrescu, P.; Koshy, P.; Stenekes, J.; Elbestawi, M.A. High-power diode laser assisted hard turning AISI D2 tool steel. *Int. J. Mach. Tools Manuf.* **2006**, *46*, 2009–2016. [[CrossRef](#)]
- Rajagopal, S.; Plankenhorn, D.J.; Hill, V.L. Machining aerospace alloys with the aid of a 15 kW laser. *J. Appl. Metalwork.* **1982**, *2*, 170–184. [[CrossRef](#)]
- Ganta, V.; Chakradhar, D. Multi objective optimization of hot machining of 15-5PH stainless steel using grey relation analysis. *Procedia Mater. Sci.* **2014**, *5*, 1810–1818. [[CrossRef](#)]
- Muhammad, R.; Maurotto, A.; Demiral, M.; Roy, A.; Silberschmidt, V.V. Themelly enhanced ultrasonically assisted machining of Ti alloy. *CIRP J. Manuf. Sci. Technol.* **2014**, *7*, 159–167. [[CrossRef](#)]
- Amin, A.K.M.N. The effect of preheating of work material on chatter during end milling of medium carbon steel performed on a vertical machining center (VMC). *J. Manuf. Sci. Eng.* **2003**, *125*, 674–680. [[CrossRef](#)]
- Lajis, M.A.; Amin, A.K.M.N.; Karim, A.N.M.; Radzi, H.C.D.M.; Ginta, T.L. Hot machining of hardened steels with coated carbide inserts. *Am. J. Eng. Appl. Sci.* **2009**, *2*, 421–427. [[CrossRef](#)]

23. Amin, A.K.M.N.; Talantov, N.V. Influence of the Instability of Chip Formation and Preheating of Work on Tool Life in Machining High Temperature Resistant Steel and Titanium Alloys. *Mech. Eng. Res. Bull.* **1986**, *9*, 52–62.
24. Amin, A.K.M.N.; Saad, M.H.B.; Arif, M.D. Modeling & Optimization of Surface Roughness & Vibration Amplitude in Heat Assisted End Milling of SKD 11 Tool Steel using Ball Nose Tool. *Adv. Mater. Res.* **2012**, *541*, 799–803.
25. Xavierarockiaraj, S.; Kuppan, P. Investigation of cutting forces, surface roughness and tool wear during Laser assisted machining of SKD11 Tool steel. *Procedia Eng.* **2014**, *97*, 1657–1666. [[CrossRef](#)]
26. Edwin, K.P.C.; Stanislaw, H.Z. *An Introduction to Optimization*, 2nd ed.; John Wiley & Sons: Hoboken, NJ, USA, 2001.
27. Montgomery, D.C. *Design, Analyses of Experiments*, 3rd ed.; John Wiley & Sons: Hoboken, NJ, USA, 1997.
28. Giasin, K.; Ayvar-Soberanis, S.; Hodzic, A. Evaluation of cryogenic cooling and minimum quantity lubrication effects on machining GLARE laminates using design of experiments. *J. Clean. Prod.* **2016**, *135*, 533–548. [[CrossRef](#)]
29. Giasin, K.; Ayvar-Soberanis, S. An investigation of burrs, chip formation, hole size, circularity and delamination during drilling operation of GLARE using ANOVA. *J. Compos. Struct.* **2017**, *159*, 745–760. [[CrossRef](#)]
30. Nguyen, D.-T.; Kim, Y.-S. Combination of isotropic and kinematic hardening to predict fracture and improve press formability of a door hinge. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **2009**, *224*, 435–445. [[CrossRef](#)]
31. Duc-Toan, N.; Young-Suk, K.; Dong-Won, J. Coupled thermomechanical finite element analysis to improve press formability for camera shape using AZ31B magnesium alloy sheet. *Met. Mater. Int.* **2012**, *18*, 583–595. [[CrossRef](#)]
32. Du, S.; Chen, M.; Xie, L.; Zhu, Z.; Wang, X. Optimization of process parameters in the high-speed milling of titanium alloy TB17 for surface integrity by the Taguchi-Grey relational analysis method. *Adv. Mech. Eng.* **2016**, *8*, 1–12. [[CrossRef](#)]
33. Taguchi, G. *On-Line Quality Control during Production*; Japan Standard Association: Tokyo, Japan, 1981.
34. Wang, C.; Xie, Y.; Zheng, L.; Qin, Z.; Tang, D.; Song, Y. Research on the Chip Formation Mechanism during the high-speed milling of hardened steel. *Int. J. Mach. Tools Manuf.* **2014**, *79*, 31–48. [[CrossRef](#)]
35. Wang, C.; Ding, F.; Tang, D.; Zheng, L.; Li, S.; Xie, Y. Modeling and simulation of the high-speed milling of hardened steel SKD11 (62 HRC) based on SHPB technology. *Int. J. Mach. Tools Manuf.* **2016**, *108*, 13–26. [[CrossRef](#)]



© 2018 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).