Retraction:

Hoang LV, Nguyen HN, Truong TH, Al-Tawaha ARMS, Le HC. (2020).
Experimental Study on Impact of Thermal-Assisted Machining on SKD11 Steel Machinability.
International Journal on Advanced Science, Engineering and Information Technology, 10, no. 5, 1954.
doi:10.18517/ijaseit.10.5.13336.

Experimental Study on Impact of Thermal-Assisted Machining on SKD11 Steel Machinability

Long Vuong Hoang[a], Hoai Nhan Nguyen[b], Thanh Hai Truong[c,1], A. Rahman M. S Al-Tawaha[d], Huu Cuong Le[c]

[a] *Industrial University of Ho Chi Minh City, Ho Chi Minh City, Vietnam*

[b] *Ho Chi Minh city University of Technology (HUTECH), Ho Chi Minh City, Vietnam*
E-mail: nh.nhan@hutech.edu.vn

[c] *Ho Chi Minh City University of Transport, Ho Chi Minh City, Vietnam*
E-mail: [1]haimt08b@gmail.com

[d] *Al-Hussein bin Talal University, Jordan*

Available online: 31 October 2020

This article has been retracted by International Journal on Advanced Science, Engineering and Information Technology

Editorial team, following clear correspondence and confirmation with authors.

The paper is retracted from 4 July 2022.

International Journal on Advanced Science Engineering Information Technology

Vol.10 (2020) No. 5
ISSN: 2088-5334

Experimental Study on Impact of Thermal-Assisted Machining on SKD11 Steel Machinability

Long Vuong Hoang[a], Hoai Nhan Nguyen[b], Thanh Hai Truong[c,1], A. Rahman M. S Al-Tawaha[d], Huu Cuong Le[c]

[a] *Industrial University of Ho Chi Minh City, Ho Chi Minh City, Vietnam*

[b] *Ho Chi Minh city University of Technology (HUTECH), Ho Chi Minh City, Vietnam*
E-mail: nh.nhan@hutech.edu.vn

[c] *Ho Chi Minh City University of Transport, Ho Chi Minh City, Vietnam*
E-mail: [1]haimt08b@gmail.com

[d] *Al-Hussein bin Talal University, Jordan*

***Abstract*— Machining in a heated environment has been used in pressure machining and metal cutting. Thermal-assisted machining is a new machining method performed on conventional machine tools, CNC machines, in which the workpiece is heated before machining. Different heat sources do the thermal-assisted: electrical energy, laser beam, magnetic induction. However, there is very little research on thermal-assisted machining when milling SKD11 steel, a difficult-in-processing material but widely used in the industry. Material machinability refers to the ability of material machining that is difficult or easy. Material machinability is measured by tool life, material removal ability, shear force, cutting vibration, surface roughness. The material's machinability is directly influenced by its microscopic structure and is related to the cutting mode. This paper has highlighted the study of material machinability when thermal-assisted machining and compared to the conventional one. This study also highlights the crucial role in assessing the effect of heating on the SKD11 steel machinability. This study analyzed the technological parameters' role on the shear force, chip shrinkage, surface roughness, and shear vibrations during normal machining and SKD11 steel heating. The study results showed that the material's microstructure and the amplitude of vibration did not change under the heating process's effect with a temperature range of 200°C - 400°C. However, the shearing force during heat processing is drastically reduced compared to conventional machining. Chip shrinkage decreased by 31.7% when heated to 400°C, while roughness decreased by 47.1%.**

***Keywords*— thermal-assisted machining; SKD11 steel; material machinability; microstructure; milling machine.**

I. INTRODUCTION

In the mechanical engineering industry, when machining various materials, especially with high hardness materials, machining difficulty, the geometry of cutting tools and the parameters of cutting mode (cutting speed, feed rate, cutting depth) are the main factors, it affects to the phenomena occur during machining (cutting force, cutting heat, cutting tool wear, cutting vibration, roughness surface, and chip geometry) [1]. Surface quality and reduce the cost of production is used to increase machining productivity; researchers are required to find new technology solutions to support the machining process such as: using cool lubricate solutions, using new materials as cutting tools, cutting with vibration support, thermal–assisted machining [2].

Thermal-assisted machining (TAM) is a new machining method performed on conventional machine tools, CNC machines, in which the workpiece is heated before machining. The heating method was first researched in 1945 and quickly applied to the production practice until today [3]. Compared with conventional machining methods, thermal-assisted machining has some outstanding effects: increasing the durability of cutting tools, reducing cutting force, reducing power consumption, reducing cutting tool wear, increasing peeling speed leads to an increase the machining productivity, increasing machining surface quality [4]. Thermal-assisted machining is used for both chip-based machining (turning, milling, drilling, etc.) and chip-free machining (forging, pressing, drawing, etc.). Different heating methods perform the thermal–assisted machining: electric-assisted machining, laser-assisted machining (LAM), plasma-assisted machining (PEM), furnace assisted machining (FAM), electromagnetic assisted machining (IAM) [5]. Each heating method has its advantages and disadvantages and is suitable for each specific machining method. In which, heating by electromagnetic-assisted machining is an effective heating method because of its high heating capacity, ease of use, low cost, and suitable for vertical milling [6].

The characteristics of machining difficulty materials are high hardness, good abrasion resistance, and less mechanical properties when working at high temperatures [7]. Thanks to these advantages, hard materials such as alloy steel have been used in most industries such as aerospace, aviation, mechanical, automotive, defense, medical, electrical - electronics. - automation etc. The total number of tasks such as milling, turning, and drilling through the survey showed more than 30% of the total number of tasks [8-11].

Tool steel - SKD11, a machining difficulty materials, popular application in mold making and automotive manufactures with strength, ductility, and hardness maintained at high temperature working conditions [12]. Typically, SKD11 is machined by advanced methods such as diamond grinding or electrostatic discharge. However, these methods are limited due to low material removal rates, expensive tools, and fast wear. Therefore, heat processing is a technological solution when processing SKD11 steel. When machining in the heated environment, the cutting tool wear and the cutting force are 40% reduced, and the roughness improves by 50% compared to conventional machining [13].

Increasing productivity and product quality is always the top goal of the manufacturer. Therefore, the optimal cutting design is widely used to determine the optimal cutting conditions [14]. The cutting process parameters have an important role such as cutting mode parameters, cutting tool geometry, cutting tool material, workpiece material, machining environment, etc [15]. Usually, the technical parameters are built based on the craftsman's experience or the technical manual. However, such data is not always optimal and satisfy the required in all cases, especially in the cases such as processing new workpiece materials, new tooling materials, and new machining methods or the machining of the parts with special structures [16].

The thermal-assisted machining method has been studied by many authors and applied in production practice. Ozler et al. [17] studies cutting tool long-life use when heated with the cutting tools made of austenitic– manganese steel. In this work, the author concludes that tool long-life use depends on workpiece temperatures. However, it is independent of cutting velocities [18]. The study results indicate that thermal-assisted machining allows the use of a higher cutting speed compared to conventional machining for a particular tool life[19-22]. Ginta et al. [23] investigated the advantages of thermal-assisted of machinability improvement analysis when milling the Ti-6Al-4V titanium alloy under magnetic induction heating [24]. The study results show that thermal-assisted machining significantly increases cutting tool durability and decreases the material removal rate. Tool life increases up to 169.4% when heated at 650°C [25]. The results indicate that the magnetic induction heating system is successful in improving tool life and material removal rates. Additionally, thermal-assisted machining contributes significantly to increased contact-length between the cutting tool and the chip. The contact-length between the cutting tool and chip is one of the main factors influencing shear force, vibration, and cutting stress [26]. SEM images show that heating at 650°C increases contact-length between cutting tool and chip by 2.05 times. Cutting force decreases 21.6%, vibration decreases 53%÷86% when heated at 650°C. Baili et al. [27] studied the effect of heating on titanium Ti-5553 alloy. Ti-5553 alloy is a high hardness material used for the manufacture of marine engine parts [28]. The study uses a magnetic induction heating system with a semi-circular induction coil and a support system that maintains a constant temperature throughout the turning process. Wang et al. [12] have proposed a new method of Inconel 718 material machining. The study combines traditional turning, freezing reinforcement and plasma heating. Cold machining is used to reduce the cutting tool temperature, thereby reducing wear, and increasing tool life. The plasma is used to increase the workpiece temperature. The results show that the surface roughness reduced 250%, the cutting force reduced 30%÷50% and the tool life increased 170% compared to conventional machining. Rudresh and Hiren et al. [29] studied the effect of technological parameters (V, f, t) on the surface roughness of the average steel turning in the heating environment. The Taguchi method's optimal parameters were determined from experimental data [22], [30]. The result shows that the minimum surface roughness is achieved when heated at 50°C, cutting speed at 915 rpm, feed rate 0.5583 mm/sec and cutting depth is 1 mm. Thermal-assisted machining is performed with machining parameters control to increase the quality of the product surface. Chang et al. [1] analyzed the surface-roughness in machining Al_2O_3 workpieces under laser heating. Experimental data is shown that the Taguchi measurement as well as the optimal technological input set is recorded. Cutting velocity plays a vital surface-roughness of 42.58%. There were some input parameters such as cutting depth, feed rate and pulse frequency with fewer influences, respectively 20.73%, 22.58%, 14.01%. The input data of optimal control process is defined as A1B2C3D2 corresponding to t = 0.2mm, V = 1500rpm, f = 0.03mm/rev, pulse-frequency of 40 kHz [31].

Thus, there are many studies on thermal-assisted machining methods for different heating methods and materials. This machining method is effectively applied in modern production due to the development of new materials. The studies focused on the impact of heating mechanism on chip geometry and materials machinability. However, the study of the effect of the technological parameters on output parameters such as shearing force, chip shrinkage coefficient, surface roughness, cutting vibration, cutting tool wear, longevity tools when heated with magnetic induction is still very limited. In particular, the optimization of technological parameters for different evaluation criteria when thermal-assisted machining needs to be studied to develop the optimal parameters for using SKD11 mold material into practical production. Thermal-assisted machining research is considered an important and urgent task at present [32]. The problem is to study the material's machinability when milling SKD11 steel in the heating environment to evaluate this method's effectiveness compared to the conventional machining methods. Besides, it is necessary to study the effect of cutting mode and cutting temperature to the output parameters (such as chip formation, chip shrinkage coefficient, shear force, cutting vibration and surface roughness). Simultaneously, the construction of the optimal technological parameters when thermal-assisted machining is a high practical significance task. A major concern when machining in an electromagnetic induction heating environment is the heating of big parts in different sizes or complex shapes part.

This paper presents the research of the heating machining method advantages and compares to the conventional machining methods by evaluating the effect of heating on SKD11 steel materials' machinability. This work highlights the relationship between input parameters (depth, feed rate and speed of cutting) and output parameters (shear force, chip shrinkage coefficient, surface-roughness, cutting vibration) in normal machining and electromagnetic induction heating of SKD11 steel.

II. Material And Method

A. Materials

1) Experimental workpiece sample: SKD11 steel is an alloy steel that is commonly applied in mold manufacturing [33]. This steel has some advantages, including high hardness, high compressive strength, impact toughness, and effective deformation resistance. Besides, it is noticed that they remain longly the hardness in high-temperature conditions. Therefore, this alloy steel has become a good candidate for mold manufacturing in the pressure machining industry. Table I show about the chemical composition of SKD11 steel.

TABLE I
CHEMICAL COMPOSITION OF SKD11 ALLOY STEEL BY %MASS

C	Cr	Mo	Si	Mn	Ni	V
1.3-1.7	12-13	0.72-1.25	≤0.65	≤0.6[illegible]	-	0.16-0.35

The SKD11 steel experimental workpiece's dimensions are 70 mm x 31 mm x 80 mm as shown in Fig.1. The workpiece is roughly machined to ensure clamping accuracy. The workpiece is chamfered with 7 mm x 7 mm to ensure uniform contact of the induction coil. Technical requirements include surface roughness Ra = 3.2 μm; The non-parallel tolerance between opposing surfaces is less than 0.05 mm; The non-perpendicularity tolerance between adjacent surfaces is less than 0,05 mm; Blunt sharp edges.

2) Measuring and processing equipment:

Vertical milling machine: Spindle rotation speed 100 ÷ 10000rpm; Spindle power 15 kW; The movement speed of the machine table is 1 ÷ 30000 mm/min; Max idling speed: 48000 mm/min; Movement of the machine X x Y x Z = 500 mm x 400 mm x 300 mm.

Cutting tool: This study using a face milling cutter with a diameter ϕ = 40 mm with a hardened titanium-coated piece of PRAMET, the company of Czech, with cutting edge parameters, is shown in Table II. Hardened alloy piece designation is APKT 1604PDR - GM. In this study, cutting tools and workpieces do not use coolant liquid when machining.

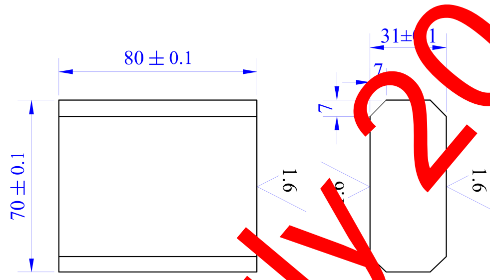

Fig.1 Dimension of workpiece sample

TABLE II
HARDENED ALLOY FRAGMENT APKT 1604PDR - GM PARAMETERS

Define	l (mm)	d (mm)	s (mm)	d_1 (mm)	re (°)
Parameter	1[illegible]±0.1	9.45	5.68	4.5	0.9

Electromagnetic induction heating equipment: In this study, a high-frequency electromagnetic induction heating device is used for heating the workpieces to support the machining process. The device consists of two parts: the power supply and the frequency generator. Input: Voltage U = 220 V, Current I = 12 A, Frequency f = 50 Hz, Power P = 2.5 kW. Output parameters: Voltage U = 26 V, Current I = 20 A, Frequency f = 84 kHz, Power P = 7.5 kW.

Thermometer: To determine the temperature on the surface of the workpiece, the experiment uses a digital contact thermometer, the model is 3527A of TSURUGA, Japan. The thermometer uses K-type thermocouples. The temperature range is -99.9°C to 1299°C. In order to control the high-temperature support to the cutting process with safely and accurately, the relationship between the support temperature and the heating time is investigated before the cutting experiment is conducted. During heating, the thermometer is placed on the surface of the workpiece to measure. The three study temperatures are 200°C, 300°C and 400°C were achieved after 2 seconds, 3.8 seconds, and 6.3 seconds, respectively. Therefore, to determine the experimental temperature levels, this heating time can be used instead of measuring the workpiece's temperature.

B. Method

The study used a microscopic imaging method by Axiovert 25 CA optical microscope to test the material's microscopic structure after heating at different temperatures and compare to the original sample. These samples are heated to the temperature requirement, then naturally cooled with air. Besides, to test the hardness of initial and after heating samples, the study used a Brinell hardness tester.

For accurate microscopic examination of material, the preparation of the sample is very important. The sample preparation process goes through these main stages: sample cutting, sample grinding, sample polishing and reagent etching. Sample cutting is performed with wire cutters to avoid the effect of cutting heat. The grinding process is intended to minimize ripple phenomena due to the large difference in height between different hardness structural components. Sample polishing to remove coarse abrasions, scratches occur on the grinding process. Finally, the deformations occur during cutting, grinding, and polishing should be removed or leveled to a sufficient size to be eliminated with etching reagent.

Chip form is an important aspect to evaluate a material's machinability. Chip form can also provide useful information for the cutting tool design [34]. Thus, the research on-chip geometry has important implications in evaluating the heating process's efficiency on the material machinability of SKD11 steel.

Cutting force is influenced by technological parameters, processing materials, cutting tool materials, cutting tool geometry, machining environment ... The current research focuses on the impact analysis of the thermal-assisted machining on the shear force when machining SKD11 steel. The thermal-assisted machining at room temperature and high temperature is performed in the same cutting mode. The study using the 3-component shear force measuring device (F_X, F_Y, F_Z) of Kisler – Switzerland [35]. This device uses dynamometer 9257B - Kisler with the force measuring range: F_X = 1500N, F_Y = 1500N, F_Z = 5000N. The sensor sensitivity in X, Y directions: 7.39 pC/N, in the Z direction: 3.72 pC/N. Measuring method: The sample is placed on the clamping device. The clamping is mounted on a dynamometer. The dynamometer is mounted on the machine table. DASYlab 10.0 software installed on a computer is used to convert A/D signals and collect measurement results to a computer.

The chip shrinkage coefficient K is a very important parameter to evaluate the material plastic deformation, and it affects the size variation of the cut metal layer. The chip shrinkage coefficient value depends on the factors that influence chip deformation: mechanical properties of the workpiece material, the geometry of the cutting tool, cutting mode and other cutting conditions. This work researched the chip shrinkage coefficient in the thermal-assisted machining and compared to the popular machining methods at specific cutting mode, in order to evaluate the contribution of the thermal-assisted on-chip shrinkage coefficient, thereby assessing the deformation ability of the chip and the softening of materials under the effect of high temperature. The study measured chip length by 3D scanning method combined with GOM Inspect Professional, the 3D data analysis software to determine the chip shrinkage coefficient with high accuracy.

Surface roughness is a parameter to evaluate the surface quality of a workpiece. In this study, the workpiece is heated before machining to evaluate the effect of the thermal-assisted machining on the workpiece's surface roughness and compare to the conventional machining method at room temperature. The study uses the Mitutoyo SV-C3200 roughness tester combined with Formtracepak software. The X-axis and Z-axis unit controller is equipped with high-precision linear encoder (ABS type on Z-axis). Measuring speed: 0.02-5mm/s. Measuring method: measuring head displaced perpendicular to the machining trace.

III. Results And Discussion

A. Impact of The Heating Process on The Microstructure and The Material Hardness After Heating

1) Impact of the heating process on the material microstructure: Fig.2 shows the microscopic structure of the test sample's material. In which, Fig.2a is the microorganism of the original sample. Fig.2a, Fig.2b, Fig.2c, respectively are the material's microscopic structure after being heated at temperatures of 200°C, 300°C, 400°C. Observing the results showed that, analyzing the structure of SKD11 micro-material include 4 samples: Chromium Cr_7C_3 Carbide structure with white plates, bright round particles scattered on the surface; Cementide structures are spherical dark dots; Peclite structures are light background. Thus, the microscopic structure of the samples after heating does not change compared to the original sample. The reason is that the heating temperature is lower than the phase transition temperature of the material. For alloy steel, the material phase transition temperature is more than 700°C. Therefore, heating SKD11 workpiece at the temperatures up to 400°C before machining does not change the material's microscopic structure.

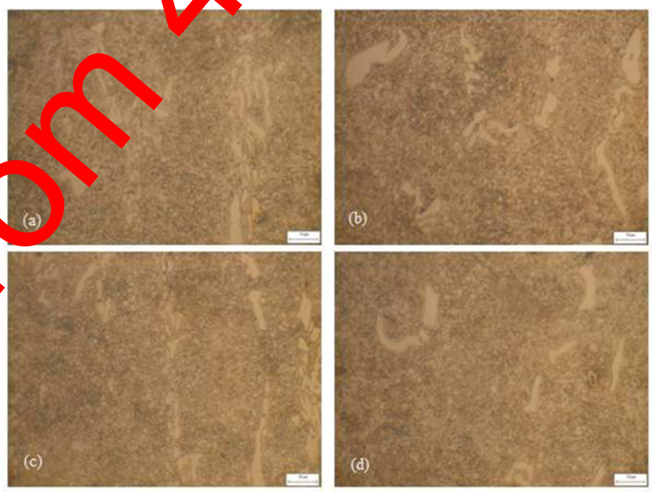

Fig.2. SKD11 steel microstructure with the magnification of 1000 times (a)- increment samples, (b), (c), (d) is the samples after heating at 200°C, 300°C, 400°C, respectively.

2) Impact of high temperature on material hardness after heating: Hardness measurement was performed at 3 positions per sample and the average value was obtained, the results obtained are shown in Table III. The results showed that, with the sample heated to 200°C, the material's hardness decreased by 2 HB compared with the original sample due to the heating process has eliminated the post-machining residual stress. With 300°C heated sample, the hardness is reduced by 3 HB compared to the original sample, then the residual stress is completely reduced. With the sample heated at 400°C, the hardness increases by 3 HB compared to the original sample due to fine fine bits' secretion. However, the increase or decrease in hardness is negligible and the material structure does not change. Thus, heating the SKD11 workpieces with temperatures up to 400°C just before machining does not change the microscopic structure as well as the hardness of the material. This is a prerequisite to continue doing the next research.

TABLE III

RESULTS OF HARDNESS MEASUREMENT ON EXPERIMENTAL SAMPLES

Temperature, °C	25	200	300	400
Hardness, HB	250	248	247	253

B. Impact of The Thermal-Assisted Machining On-Chip Geometry When Heating Skd11 Steel

Fig.3 shows the chip image when milling SKD11 steel with cutting mode V = 235m/min, f = 305mm/min, t = 1.5mm in different heating conditions. Fig.3a, b, c, d is the chip geometry at the room temperature 25°C and high-temperature 200°C, 300°C, 400°C, respectively. Ductility is an outstanding property that determines the chip formation of a workpiece during machining. However, observing the results shows that the chip color is completely different. In the normal machining, the chips are black purple. That means the heat generation and transfer from the source to the chips are very high. On the contrary, when heated to 200°C, 300°C chips are bright white. Chips are yellow when heated to 400°C. This phenomenon can be explained by the lower heat transfer transferred to the chips because the heating mechanism in the cutting tool, workpiece and chips is more uniform when heated. Besides, under the effect of high temperature, the tensile strength, mechanical strength, and yield stress of the material decrease while deformation of the material increases. The friction between the chips and the cutting-tool front-surface, between the cutting-tool back-surface and the machined-surface, is reduced. Besides, the reduced binding force between metal molecules under the effect of high temperature causes holes to grow and merge more easily. Easier chip evacuation and drastic heat reduction cause bright chip color when heated.

Fig. 3. Chip image when machined at (a) room temperature, (b)200°C, (c)300°C, (d)400°C

C. Effect of the Thermal-Assisted Machining on The Shear Force When Heating Skd11 Steel

Fig.4 shows the results of temperature dependent on shear test for the machining process with: Experiment 1: V = 235 m/min, f = 305mm/min, t =1.5 mm, at room temperature T = 25°C; Experiment 2: V = 235m/min, f = 305mm/min, t = 1.5mm, T = 200°C; Experiment 3: V = 235 m/min, f = 305mm/min, t = 1.5mm, T = 300°C; Experiment 4: V = 235m/min, f = 305mm/min, t = 1.5mm, T = 400°C.

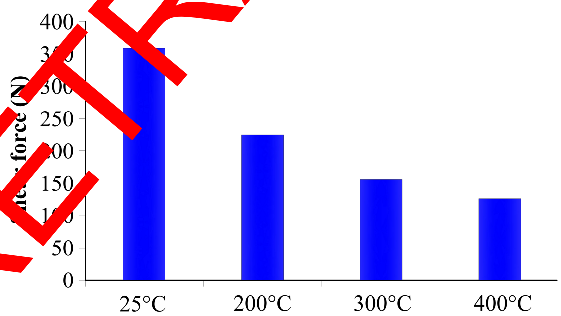

Fig.4 Shear force at different temperatures

Table IV shows the shear force's values at different cutting conditions and the reduction in shear force at high temperature compared to the popular machining method. The results show that the cutting force is significantly reduced when heated at 200°C compared to the popular method. The shear force is slower when heating temperature increases to 300°C and 400°C. The largest reduction in shear force ΔF is 65.1% when heated at 400°C.

TABLE IV

VALUE AND THE REDUCTION OF SHEAR FORCE AT DIFFERENT MACHINING CONDITIONS

T (°C)	25	200	300	400
F (N)	36017	224962	1596134	1257869
ΔF (%)	-	37.5	55.7	65.1

The higher temperature that supports the cutting process, the less force will be reduced. This is because the temperature that supports the cutting process reduces the strength and reduces the bonds between metal molecules. The weak binding force of the metal molecules makes the cutting process easier. In addition, the compressive stress in the secondary strain zone decreases with thermal-assisted machining [44]. Therefore, with the same cutting mode, the cutting force is significantly reduced when heated.

D. Effects of the thermal-assisted machining on-chip shrinkage coefficient when heat processing SKD11 steel

The results of measuring the chip length are shown in Fig.5. Here is the image of chips with the technology mode: V = 235m/min, f = 305mm/min, t = 1.5mm and heated at T = 400°C.

Fig.5 Measuring the length of the chip

Fig.6 shows the test results of temperature dependent on chip shrinkage coefficient for machining with technological parameters and heating conditions as follows: Experiment 1: V = 235m/min, f = 305mm/min, t = 1.5, T = 25°C. Experiment 2: V = 235m/min, f = 305mm/min, t = 1.5mm, T = 200°C. Experiment 3: V = 235m/min, f = 305mm/min, t = 1.5, T = 300°C. Experiment 4: V = 235m/min, f = 305mm/min, t = 1.5mm, T = 400°C.

Table V shows the chips shrinkage coefficient values and the changing of chip shrinkage coefficients under different heating conditions. The results show that, compared to conventional machining methods, the chip shrinkage coefficient increases with heating. The chip shrinkage coefficient is increased by 27.6% when heated by 200°C. The largest increase in chip shrinkage coefficient is 46.5% when heated at 400°C. Thus, when the thermal-assisted temperature increases, the chip shrinkage coefficient also increases. The reason is that, under the impact of high temperature, the material softens, the bonds between the atoms are weak, arranging the metal lattice more easily destroyed.

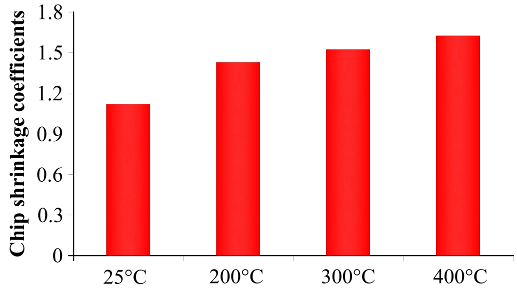

Fig.6. Chip shrinkage coefficients at different heating experiments

TABLE V
THE VALUE AND INCREASING OF CHIP SHRINKAGE COEFFICIENTS AT DIFFERENT HEATING CONDITIONS

T (°C)	25	200	300	400
K (N)	1.1325	1.4451	1.5456	1.6587
ΔK (%)	-	27.6	36.5	46.5

E. Effect of The Thermal-Assisted Machining on Surface Roughness When Heating the Skd11 Steel

This section assesses the effect of the thermal-assisted machining on surface roughness when heating SKD11 steel and compares it with conventional machining methods. The tests at room temperature and at high temperature were carried out with the same cutting mode respectively as follows: Test 1: V = 190m/min, f = 230mm/min, t = 0.5mm, at room temperature T = 25°C; Experiment 2: V = 190m/min, f = 230mm/min, t = 0.5mm, T = 200°C; Experiment 3: V = 190m/min, f = 230mm/min, t = 0.5mm, T = 300°C; Experiment 4: V = 190m/min, f = 230mm/min, t = 0.5mm, T = 400°C.

The results show that the roughness when heated machining is significantly reduced when compared with conventional machining. The reason is that the material's heat softening makes the cutting process easier, and the cutting process's stability increases. Fig.7 shows the graph of surface roughness when machining at different temperature conditions corresponding to experiments 1, 2, 3, 4. Table VI shows the average surface roughness value when machining at different temperature conditions and percentage reduction in roughness. Thus, the surface roughness decreases as the machining support temperature increases from 200°C to 400°C. Surface roughness is reduced by the largest 47.1% when heated at 400°C.

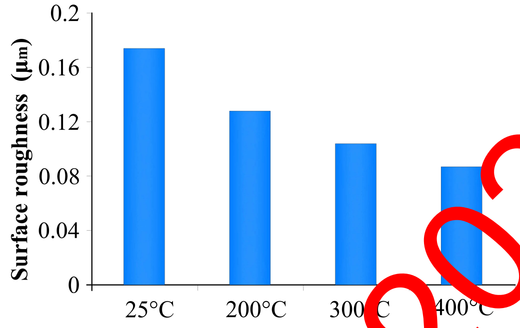

Fig.7 Surface roughness when milling at different temperature conditions

TABLE VI
THE VALUE AND REDUCTION OF SURFACE ROUGHNESS WHEN MILLING AT DIFFERENT TEMPERATURE CONDITIONS

T (°C)	25	200	300	400
Ra (μm)	0.174	0.128	0.108	0.092
ΔRa (%)	-	26.4	37.9	47.1

F. Effects of the thermal-assisted machining on vibrations when heating the SKD11 steel

To evaluate the effect of the thermal-assisted machining on vibrations, two tests at ambient temperature and heating temperature were performed respectively with the same cutting mode: Test 1: V = 235m/min, f = 305mm/min, t = 1.5mm, T = 25°C; Experiment 2: V = 235m/min, f = 305mm/min, t = 1.5mm, T = 200°C; Experiment 3: V = 235m/min, f = 305mm/min, t = 1.5mm, T = 300°C; Experiment 4: V = 235m/min, f = 305mm/min, t = 1.5mm, T = 400°C.

Fig.8 and Fig.9 are the results of vibration experiment 1 (machined at room temperature) and experiment 2 (processed at 200°C), respectively, in two directions X and Y. Based on the analysis of machining vibration data, combining separate vibration data and load-free vibrations show that the resonant does not occur. It is observed that the amplitude of vibration when heating is reduced compared to conventional machining.

TABLE VII
THE VIBRATION VALUE AND AMPLITUDE REDUCTION WHEN MILLING AT DIFFERENT TEMPERATURE CONDITIONS.

T (°C)	25	200	300	400
A_{XY}	174.08	151.139	148.071	146.526
ΔA_{XY} (%)	-	13.2	14.9	15.8

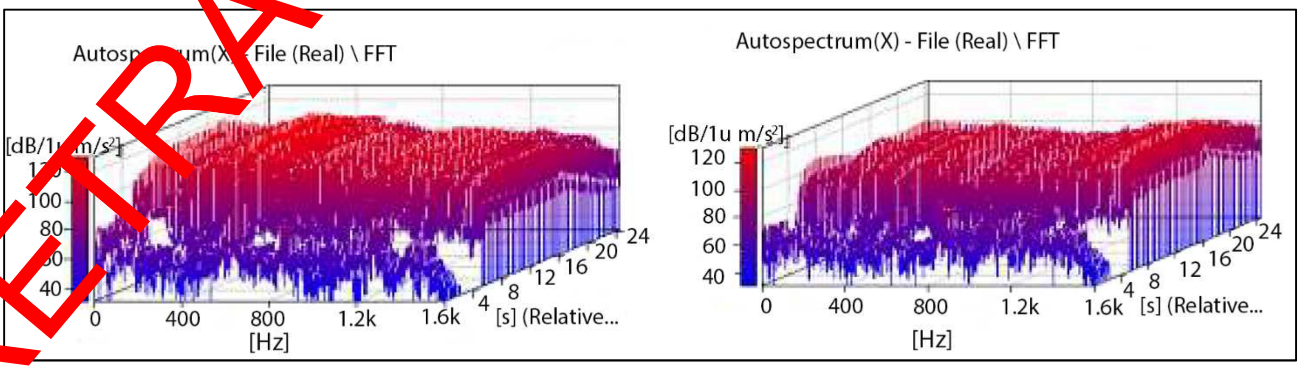

Fig. 8 The measurement results of machining vibration at room temperature

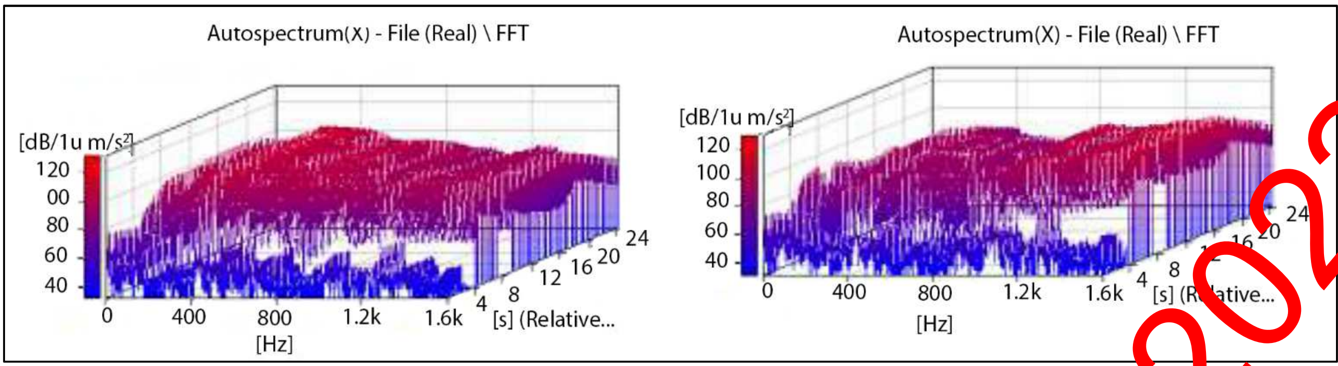

Fig.9 The measuring vibration results when thermal-assisted machining.

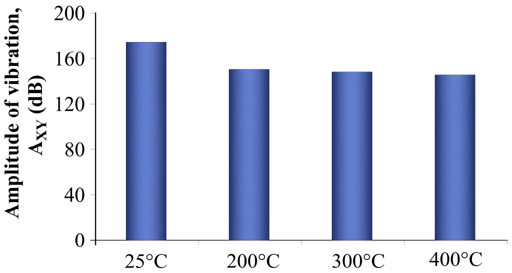

Fig.10 Amplitude of vibration when machining at different temperature conditions

The amplitude of vibration and its reduction when milling SKD11 steel at different temperature conditions compared with conventional methods are presented in Table VII and Fig.10. The results show that the amplitude of vibration decreased by 13.2%, 14.9% and 15.8% respectively when machining at 200°C, 300°C and 400°C. This shows that the SKD11 steel processing is more stability when machining at high temperature. The reason is that, under the effect of high temperature, the bonds between metal particles are reduced, making the cutting process easier. However, the decrease in vibration amplitude varies slightly when the high-temperature change in the cutting process.

IV. Conclusion

The experimental research on the impacts of the thermal-assisted machining of SKD11 steel materials has given the following results: The material's microscopic structure does not change under the thermal-assisted process's effect with a temperature range from 200°C - 400°C. The heated workpiece is naturally cooled with air is the same hardness as the original sample. Chip geometry changes compared to conventional machining with the heating support. Chips obtained at normal machining at room temperature are purple-black. Chips are bright white when heated to 200oC, 300oC and yellow when heated to 400oC. The bigger diameter of chip twist when heated. Cutting force during the thermal-assisted machining is significantly reduced compared to conventional machining. Cutting force up to 67.1% when heated to 400°C with cutting mode V = 235m/min, f = 305mm/min, t = 1.5mm. The chip shrinkage coefficient is increased by 31.7% when heated 400°C with cutting mode V = 235m/min, f = 305mm/min, t = 1.5mm. Roughness is significantly reduced in comparison with popular machining. The roughness is reduced by 47.1% when heated to 400°C with the cutting mode V = 190m/min, f = 230mm/min, t = 0.5mm. Compared to popular machining methods, the reduced vibration amplitude shows the more stability of the machining process. However, the variation in vibration amplitude during high-temperature changes that supports the machining process is negligible.

References

[1] C.-W. Chang and C.-P. Kuo, "Evaluation of surface roughness in laser-assisted machining of aluminum oxide ceramics with Taguchi method," *Int. J. Mach. Tools Manuf.*, vol. 47, no. 1, pp. 141–147, 2007.

[2] M. Q. Chau, "Modeling 3D surface milling process using a ball-end milling cutter," *J. Mech. Eng. Res. Dev.*, vol. 43, no. 3, pp. 50–63, 2020.

[3] A. Shams, A. Pramanik, and T. T. Chandratilleke, "Thermal-assisted machining of titanium alloys," in *Advanced manufacturing technologies*, Springer, 2017, pp. 49–76.

[4] S. Lei and F. Pfefferkorn, "A review on thermally assisted machining," in *International Manufacturing Science and Engineering Conference*, 2007, vol. 42908, pp. 325–336.

[5] M. Feng, Z. Hua, G. Qingshan, and K. K. B. Hon, "A novel energy evaluation approach of machining processes based on data analysis," *Energy Sources, Part A Recover. Util. Environ. Eff.*, pp. 1–15, Sep. 2019, doi: 10.1080/15567036.2019.1670761.

[6] Y. Gao, R. L. Sun, Y. N. Chen, and J. Leopold, "Mechanical and thermal modeling of modulation-assisted machining," *Int. J. Adv. Manuf. Technol.*, vol. 86, no. 9–12, pp. 2945–2959, 2016.

[7] A. Kristanto, A. Agung, and K. Suryopratomo, "Thermal-Hydraulics Operation Parameters Modeling and Analysis of KLT-40S Reactor at Steady-State and Transient Condition using RELAP5-3D," *Int. J. Adv. Sci. Eng. Inf. Technol.*, vol. 10, no. 3, pp. 937–944, 2020.

[8] M. Q. Chau, "An overview study on the laser technology and applications in the mechanical and machine manufacturing industry," *J. Mech. Eng. Res. Dev.*, vol. 42, no. 5, pp. 16–20, 2019, doi: 10.26480/jmerd.05.2019.16.20.

[9] B. K. Shanmugam, H. Vardhan, M. G. Raj, M. Kaza, R. Sah, and H. H, "Screening performance of coal of different size fractions with variation in design and operational flexibilities of the new screening machine," *Energy Sources, Part A Recover. Util. Environ. Eff.*, pp. 1–9, Sep. 2019, doi: 10.1080/15567036.2019.1670291.

[10] K. Iwai, T. Tamura, D. T. Nguyen, and K. Taguchi, "The development of a flexible battery by using a stainless mesh anode," *Int. J. Renew. Energy Dev.*, vol. 8, no. 3, pp. 225–229, 2019, doi: 10.14710/ijred.8.3.225-229.

[11] A. T. Hoang, T. T. Van Tran, and D. N. Nguyen, "Effect of Heat Treatment Process on The Microstructure and Mechanical Properties of The Spray Coating Ni-Cr on CT38 Steel," *Int. J. Adv. Sci. Eng. Inf. Technol.*, vol. 9, no. 2, pp. 560–568, 2019.

[12] C. Wang, F. Ding, D. Tang, L. Zheng, S. Li, and Y. Xie, "Modeling and simulation of the high-speed milling of hardened steel SKD11 (62 HRC) based on SHPB technology," *Int. J. Mach. Tools Manuf.*, 2016, doi: 10.1016/j.ijmachtools.2016.05.005.

[13] W. Ming *et al.*, "Investigating the energy distribution of workpiece and optimizing process parameters during the EDM of Al6061, Inconel718, and SKD11," *Int. J. Adv. Manuf. Technol.*, 2017, doi: 10.1007/s00170-017-0488-6.

[14] N. Lusi, D. R. Pamuji, A. Afandi, and G. S. Prayogo, "Optimization Design of Electrochemical Machining Process of SKD11 Tool Steel Using Weighted Principal Component Analysis (WPCA)," 2020, doi: 10.1088/1757-899X/854/1/012024.

[15] X. P. Nguyen and D. K. Pham Nguyen, "Experimental Research on the Impact of Anchor-Cable Tensions in Mooring Ship at Vung Tau Anchorage Area," *Int. J. Adv. Sci. Eng. Inf. Technol.*, vol. 9, no. 6, pp. 1892–1899, 2019.

[16] M. Q. Chau, "A study on the factors affecting the flare of the weld when welding the steel wire," *J. Mech. Eng. Res. Dev.*, vol. 41, no. 03, pp. 71–75, 2019, doi: 10.26480/jmerd.03.2019.71.75.

[17] L. Özler, A. Inan, and C. Özel, "Theoretical and experimental determination of tool life in hot machining of austenitic manganese steel," *Int. J. Mach. Tools Manuf.*, vol. 41, no. 2, pp. 163–172, 2001.

[18] K. A. Mohammed, M. N. M. Al-Sabbagh, A. A. F. Ogaili, and E. S. Al-Ameen, "Experimental analysis of hot machining parameters in surface finishing of crankshaft," *J. Mech. Eng. Res. Dev.*, vol. 43, no. 4, pp. 105–114, 2020.

[19] A. S. Alwan and A. A. Jaddoa, "Effect of thermochemical and mechanical surface treatments on metallographic of biomaterial stainless steel grad 316l," *J. Mech. Eng. Res. Dev.*, vol. 43, no. 3, pp. 312–320, 2020.

[20] P. V. Vinay, C. Srinivasa Rao, and K. Pavan Kumar, "An analysis of cutting force and surface finish in surface grinding of aisi H13 Steel," *J. Mech. Eng. Res. Dev.*, vol. 41, no. 1, pp. 177–189, 2018, doi: 10.7508/jmerd.2018.01.021.

[21] T. N. Le, M. K. Pham, A. T. Hoang, T. N. M. Bui, and D. N. Nguyen, "Microstructure Change For Multi-Pass Welding Between Austenitic Stainless," *J. Mech. Eng. Res. Dev.*, vol. 41, no. 2, pp. 97–102, 2018.

[22] M. K. Pham, D. N. Nguyen, and A. T. Hoang, "Influence of Vanadium Content on the Microstructure and Mechanical Properties of High-Manganese Steel," *Int. J. Mech. Mechatronics Eng.*, vol. 18, no. 2, pp. 141–147, 2018.

[23] T. L. Ginta and A. K. M. N. Amin, "Thermally-assisted end milling of titanium alloy Ti-6Al-4V using induction heating," *Int. J. Mach. Mach. Mater.*, vol. 14, no. 2, pp. 194–212, 2013.

[24] X. D. Pham, A. T. Hoang, and D. N. Nguyen, "A Study on the Effect of the Change of Tempering Temperature on the Microstructure Transformation of Cu-Ni-Sn Alloy," *Int. J. Mech. Mechatronics Eng.*, vol. 18, no. 04, pp. 27–34, 2018.

[25] A. T. Hoang, M. Q. Chau, and Q. B. Le, "Parameters affecting fiber quality and productivity of coir spinning machines," *J. Mech. Eng. Res. Dev.*, vol. 43, no. 5, pp. 122–145, 2020.

[26] M. Q. Chau and V. T. Nguyen, "Effects of frequency and mass of eccentric balls on picking force of the coffee fruit for the as-fabricated harvesting machines," *Int. J. Adv. Sci. Eng. Inf. Technol.*, vol. 9, no. 3, pp. 1039–1045, 2019, doi: 10.18517/ijaseit.9.3.8578.

[27] M. Baili, V. Wagner, G. Dessein, J. Sallaberry, and D. Lallement, "An experimental investigation of hot machining with induction to improve Ti-5553 machinability," in *Applied mechanics and Materials*, 2011, vol. 62, pp. 67–76.

[28] V. V. Pham and A. T. Hoang, "Technological Perspective for Reducing Emissions from Marine Engines," *Int. J. Adv. Sci. Eng. Inf. Technol.*, vol. 9, no. 6, pp. 1989–2000, 2019.

[29] R. M. H. Prajapati, "Experimental Investigation on Effect of Machining Parameters on Surface Roughness in Thermally Assisted Turning of mild steel," *Int. Conf. Multidiscip. Res. Pract.*, vol. 1, no. 8, pp. 488–489, 2014.

[30] A. S. Alwan, E. A. Khalid, and A. A. Jaddoa, "Improvement the corrosion behavior and wear characteristics of aisi 304 stainless steel by using Nd -yag laser surface treatment," *J. Mech. Eng. Res. Dev.*, vol. 43, no. 4, pp. 50–59, 2020.

[31] A. T. Hoang, D. N. Nguyen, and V. V. Pham, "Heat Treatment Furnace For Improving The Weld Mechanical Properties: Design and Fabrication," *Int. J. Mech. Eng. Technol.*, vol. 9, no. 6, pp. 496–506, 2018.

[32] S. Cho, I. Jo, H. Kim, H. T. Kwon, S. K. Lee, and S. B. Lee, "Effect of TiC addition on surface oxidation behavior of SKD11 tool steel composites," *Appl. Surf. Sci.*, 2017, doi: 10.1016/j.apsusc.2016.11.164.

[33] G. Zhang, Z. Zhang, W. Ming, J. Guo, Y. Huang, and X. Shao, "The multi-objective optimization of medium-speed WEDM process parameters for machining SKD11 steel by the hybrid method of RSM and NSGA-II," *Int. J. Adv. Manuf. Technol.*, 2014, doi: 10.1007/s00170-013-5427-6.

[34] Z. Liao, D. A. Axinte, and D. Gao, "A novel cutting tool design to avoid surface damage in bone machining," *Int. J. Mach. Tools Manuf.*, 2017, doi: 10.1016/j.ijmachtools.2017.01.003.

[35] F. A. Putro, S. H. Pranolo, J. Waluyo, and A. Setyawan, "Thermodynamic Study of Palm Kernel Shell Gasification for Aggregate Heating in an Asphalt Mixing Plant," *Int. J. Renew. Energy Dev.*, vol. 9, no. 2, pp. 311–317, 2020, doi: 10.14710/ijred.9.2.311-317.