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EFFECT OF PREHEATING ON CUTTING FORCE AND MACHINING PERFORMANCE OF TITANIUM ALLOY TI-6AL-4V

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Abstract. The present paper examines the impact of preheating a titanium alloy on cutting force and surface quality during turning. The primary objective of the present study is to ascertain how variations in workpiece temperature prior to machining affect the technological parameters of the cutting process, specifically cutting force and the surface roughness parameter Ra. The experimental portion of the study involved the turning of a Ti-6Al-4V titanium alloy workpiece at numerous preheating temperatures, including room temperature, 300°C, 400°C, 500°C, and 600°C. Prior to the machining process, a preliminary step of preheating was conducted. The experimental procedure was executed employing the following set of cutting parameters: a feed rate of 0.1 mm/rev, a depth of cut of 0.5 mm, and a cutting speed of 150 m/min. The findings demonstrated a distinct pattern of decreasing cutting force with increasing workpiece size. The material's mechanical resistance decreased throughout the cutting process, as evidenced by the most notable force reduction at 600°C. In addition, an increase in surface roughness was observed, suggesting that this process may be conducive to the formation of chips and the establishment of a more pliant interface between the tool and the material. The findings corroborate the hypothesis that preheating can enhance surface quality and reduce tool load during machining of titanium alloys. It is noteworthy that this strategy does not necessitate substantial modifications to the existing machinery. Consequently, it has the potential to be advantageous in manufacturing settings where decreasing tool wear and enhancing productivity are imperative.

Keywords: difficult-to-machine materials, cutting, hot turning, temperature, surface roughness.

Introduction

In the contemporary realm of mechanical engineering, there is an escalating demand for machining materials that exhibit superior performance characteristics, including strength, heat resistance, corrosion resistance, and wear resistance. The materials in question include, in particular, titanium alloys, nickel-based alloys (e.g. Inconel, Monel), superalloys, and high-strength steels. However, it should be noted that these advantages are accompanied by significant challenges. These include poor machinability, low thermal conductivity, high strength at elevated temperatures, and a tendency for adhesive wear. These factors can result in rapid tool wear, reduced surface quality, and lower machining efficiency.

> *Masayuki Kono (Toyota engineer):*
> ***"The future of mechanical engineering lies in flexible, adaptive systems where machines learn alongside humans."***
> *(About the integration of AI in manufacturing processes)*

A promising approach to improving the machining of such materials is the application of hot turning, a cutting process performed with preheating or simultaneous heating of the workpiece. The mechanism of this method is predicated on the reduction of the material's hardness and strength in the cutting zone through thermal influence. This, in turn, engenders a reduction in cutting force, an improvement in chip formation, and a decrease in tool wear [1, 2].

The objective of this study is to explore the potential for enhancing machining productivity, mitigating tool wear, and conducting a comprehensive analysis of alterations in cutting force prior to and following the process of preheating.

Heating metals gives rise to complex physico-chemical processes, which in turn affect their mechanical properties. One of the pivotal factors determining changes in hardness with increasing temperature is the weakening of interatomic bonds within the crystal lattice. In typical circumstances, metal atoms are arranged in an ordered structure and are held together by interatomic forces that are characteristic of metals. As the temperature rises, atomic energy increases, causing more intense vibrations within the lattice. This phenomenon is attributed to a reduction in interatomic attraction, resulting in diminished mechanical strength and hardness [3].

Furthermore, an increase in temperature has been shown to activate diffusion processes, which in turn affect dislocation movement. Dislocations are defined as microscopic defects in the crystal lattice, and the mobility of these defects is a determining factor in the material's plasticity. In the low-temperature environment, dislocations persist in their pinned state within the structural framework, thereby conferring elevated levels of hardness and wear resistance. However, as the temperature rises, the dislocation mobility also increases, thus facilitating plastic deformation and reducing resistance to machining. It can thus be concluded that the application of heat results in a reduction of hardness and an increase in ductility.

The dissolution of carbides and other hard phases represents a significant mechanism for material softening. In nickel-based alloys exhibiting high heat resistance, such as Inconel 718, heating to temperatures ranging from 600 to 800°C can result in the dissolution of the strengthening γ' particles. This phenomenon, known as the "breakdown of strengthening γ' particles," has been observed to concurrently decrease the hardness of the material and enhance its machinability. Analogous processes have been observed in high-alloy chromium steels, wherein the dissolution of chromium carbides leads to a reduction in overall hardness and an increase in material plasticity [3,4,5,6].

Therefore, the softening of metal during heating can be attributed to a combination of physical processes, including the weakening of interatomic bonds, increased dislocation mobility, phase transformations, carbide dissolution, and changes in the crystal structure.

In the domain of mechanical engineering, a range of methodologies are employed to facilitate the process of preheating during the turning operation. These methodologies include:

- flame heating (oxy-acetylene, oxy-propane flame)
- induction heating
- plasma heating
- laser heating
- arc heating

Literature Review

In Study 1, B. Maher et al. (2023) obtained promising results from experiments involving the titanium alloy Ti-5553. The cutting force decreased by 13% at 500°C and by 34% at 750°C. The experiments conducted utilised the process of induction heating. The optimal temperature range for hot turning Ti-5553 was determined to be 500–600°C, while overheating in the range of 600–750°C resulted in substantial tool wear. Excessive heating resulted in combined tool wear. The tool's flank exhibited crater wear, which is typical of high-temperature conditions. Meanwhile, the rake face experienced material loss due to active titanium diffusion into the tool material, leading to brittleness. A substantial enhancement in surface roughness was observed, with the Rauthenberg parameter (Ra) decreasing from 1.6 μm (in the context of cold cutting) to 0.8 μm at a temperature of 400°C. However, at 750°C, a significant deterioration in surface quality was observed, attributable to oxidation and overheating. Furthermore, the researchers discovered that at temperatures in excess of 640°C, irreversible microstructural alterations occurred within the material, which had the potential to degrade the mechanical properties of the finished component. It has been hypothesised that excessive heating may have a detrimental effect on the machining process and, moreover, compromise the final properties of the part [7].

In Study A. K. Parida and K. P. Maity conducted experiments involving the heating of the following alloys: Inconel 718, Inconel 625, and Monel 400. The experiments were conducted on a lathe, where the workpieces were preheated to 300°C and 600°C using a propane-oxygen torch to heat the surface during turning. The efficacy of the process was evident in the substantial reduction in cutting force and the consequent enhancement of tool life. The findings of the study demonstrated that the process of hot turning resulted in a significant enhancement of tool life, with an increase of 160% observed in Inconel 718, 238% in Inconel 625, and 107% in Monel 400. Inconel 718 was identified as the most challenging material to machine due to its elevated strength and reduced thermal conductivity. Despite a marked decline in cutting force, Inconel 718 continues to pose significant challenges during processing. The predominant wear mechanism was diffusion wear, whereby tool particles dissolved into the workpiece material. Monel 400 was the most amenable to machining due to its superior thermal conductivity, which facilitated more uniform heat distribution. Furthermore, the process yielded chips that were more manageable, thereby mitigating the risk of built-up edge formation. Inconel 625 demonstrated a predominant occurrence of notch wear, while Monel 400 exhibited a preponderance of adhesive and abrasive wear. As the temperature increased from 200 to 600°C, the surface roughness of the three different materials (Inconel 718, Inconel 625 and Monel 400) was found to decrease, with a 23% decrease observed for the former material, a 42% decrease observed for the latter material, and a 50% decrease observed for the latter material [8].

In the article entitled "Hybrid machining process: experimental and numerical analysis of hot ultrasonically assisted turning", the authors explored a novel method for improving the turning of difficult-to-machine materials, particularly titanium alloys. The fundamental concept underpinning the innovation was the integration of two distinct technologies. Firstly, the workpiece was subjected to preheating, and secondly, ultrasonic vibrations were applied to the cutting tool. This combination of techniques was designed to facilitate the cutting process.

The experiment was conducted on Ti-15V-3Al-3Cr-3Sn alloy, which has high strength and heat resistance. The workpiece was preheated to 300°C, while the tool was subjected to ultrasonic vibration at a frequency of 20 kHz and an amplitude of 0.08 mm. Consequently, the cutting zone exhibited an influence from both thermal energy and mechanical micro-vibration. The findings were remarkable: in comparison with traditional turning, the hybrid method diminished total cutting force by 75–85%, with the most substantial reduction occurring in the tangential direction, thereby enabling more efficient tool movement. Surface roughness (Ra) was reduced by an average of 62%, indicating a considerable enhancement in surface quality that obviated the necessity for additional finishing processes. It is interesting to note that, despite the elevated cutting zone temperature resulting from preheating, no instances of overheating, recrystallization, or degradation of mechanical properties in the surface layer were observed. A further noteworthy finding was that the chip morphology was subject to change when ultrasonic assistance was employed; the chips became thinner, more uniform, and easier to evacuate from the cutting zone. The enhanced process stability demonstrated in this study has been shown to reduce the risk of tool jamming and prolong tool life [9].

Experimental Procedure

In this study, the method of preheating the workpiece was determined to be flame heating. For this purpose, a gasoline blowtorch was utilized, with a flame temperature capable of reaching up to 1200°C. The test specimen was composed of the titanium alloy Ti-6Al-4V, also referred to as VT6 or Grade 5, which is among the most renowned and extensively utilized titanium alloys on a global scale. The composition of the alloy is primarily titanium, constituting approximately 90% of the total mixture, with the addition of approximately 6% aluminum and 4% vanadium. The combination of aluminum and vanadium in these two alloying elements endows the material with its distinctive properties. Specifically, aluminum contributes to enhancing the material's strength, while vanadium ensures its effective thermal stability.

The combination of high strength, low weight, and corrosion resistance that Ti-6Al-4V exhibits renders it a suitable material for critical applications. This material is utilized extensively in the aerospace and aviation industries for components such as turbine blades, fuselage panels, and landing gear. In these areas, the reduction of weight without compromising reliability is of the essence. This alloy exhibits a number of noteworthy characteristics. For instance, the material demonstrates notable strength at elevated temperatures, rendering it well-suited for high thermal load environments, such as those found in jet engine turbines. Despite its strength being comparable to steel, its weight is approximately 45% less. However, machining the material is notoriously difficult due to its low thermal conductivity. This characteristic leads to rapid heat accumulation at the cutting tool, which in turn accelerates tool wear.

Table 1

Table of Key Properties of Titanium Alloy Grade Ti-6Al-4V

Parameter	Value
Hardness (HRC)	36–41
Tensile Strength (MPa)	900–1000 MPa
Yield Strength (MPa)	800–880 MPa
Density (g/cm³)	4.43
Thermal Conductivity (W/(m·K))	6.7

Experimental Setup

The experimental setup consists of the following main components:

1. Dynamometer with strain gauge sensors (FlexiForce40X)
2. Pyrometer
3. Blowtorch
4. Profilometer
5. Cutting tool – single-point turning tool
6. Workpiece – cylindrical specimen made of Ti-6Al-4V, with a diameter of 25 mm and a length of 300 mm.

Description of the design of the dynamometer FlexiForce40X

The author has developed a dynamometer for measuring cutting forces under conditions of preventive heating of the workpiece, based on a mechanical system that includes a main fixed carrier frame 1, which is fixed on the lathe toolholder, load cells for fixing force effects 4, a movable block two and a cutting tool 3 (Fig. 3). Software based on the Arduino platform was developed to control the process of data collection and processing, and a corresponding calibration system for calibrating the measuring system.

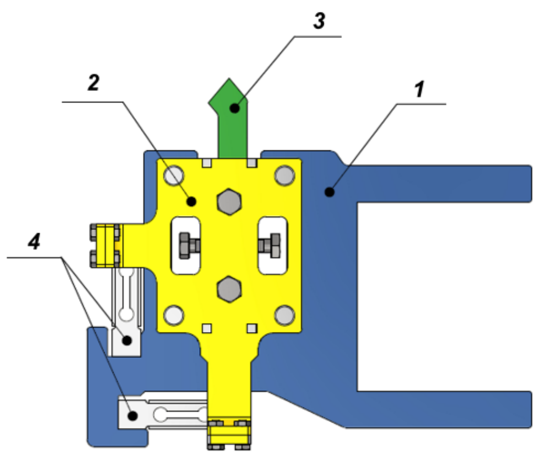

Fig. 1. Schematic diagram of the dynamometer FlexiForce40X

The primary structural elements of the dynamometer facilitate the following functions (Fig. 1):

1. The main bearing frame constitutes the foundation for the metrological system, providing rigidity and stability. The apparatus under discussion is designed to facilitate the repair of other components of the dynamometer. The strength and stability of this component are critical to minimizing vibrations and deformations during measurement, which is essential for ensuring measurement accuracy.

2. The movable unit constitutes an element affixed to the primary support frame by means of damping bushings. This mounting system enables the block to exhibit slight movement in response to applied loads, thereby ensuring equivalent force transmission to the load cells while mitigating the impact of vibrations and sharp shocks. The soft bushings act as dampers, mitigating mechanical impacts and protecting both the sensors and the entire structure from excessive deformation. This increases the reliability and durability of the dynamometer.

3. A cutter is defined as a cutting tool that directly interacts with the workpiece during the cutting process. The force exerted on the cutter is transmitted through the movable block and the mounting system to the load cells.

4. Load cells represent a critical component of the measuring system. The design utilizes strain gauges, which possess a measuring range of up to 1000 N. These sensors are strategically positioned in regions where the anticipated deformation is expected to be the most significant during the cutting process. This approach enables the acquisition of precise force load readings. The operation of strain gauges is predicated on the principle of strain measurement. The application of cutting force to the material upon which the strain gauges are mounted induces deformation, thereby altering the resistance of the gauges. These resistance changes are then converted into an electrical signal, which is transmitted to the controller [10].

Experimental Procedure

In the course of the experiment, the workpiece was exposed to temperatures of 300°C, 400°C, 500°C, and 600°C. At each stage of the process, a specific section of the material was machined. To enhance the precision of the measurement, each temperature condition was evaluated on two separate occasions. The cutting tool traversed the workpiece at distinct positions, and the mean cutting force was computed for the corresponding temperature.

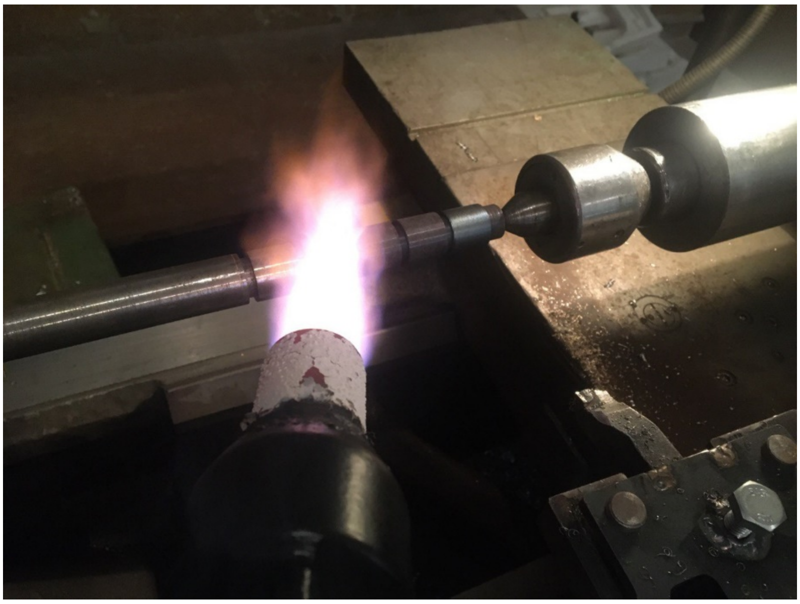

Fig. 2. Experimental Procedure

Subsequent to each machining stage, the cutting tool was replaced with a new one. This approach prevented the accumulation of tool wear and ensured the reliability of the comparative analysis.

Subsequent analysis of the machined samples was conducted to assess surface roughness. The workpiece temperature was meticulously monitored using a laser pyrometer, while the cutting force was recorded using a dynamometer equipped with strain gauge sensors.

Machining Parameters

- Cutting speed (v): 100 m/min
- Depth of cut (a): 0.5 mm
- Feed rate (f): 0.1 mm/rev
- Temperature modes: the experiment was conducted at different preheating temperatures — 20 °C (room temperature), 300 °C, 400 °C, 500 °C, and 600 °C.

Results of the study

During the experimental investigation, the effect of preheating temperature on cutting force and surface roughness parameters during the machining of the material was determined.

Table 2

°C	F(y), N	Reduction F(x), %	F(x), N	Reduction F(y), %
20	51	0	38	0
300	48.5	5	37.5	1.3
400	46	10	36	5.3
500	45	13	33	13.9
600	40.5	23	31	21.2

The study showed that increasing the processing temperature leads to a significant reduction in cutting force. As seen from the tables and graphs, when the temperature was increased from 20°C to 600°C, the cutting force F(x) decreased from 51 N to 40.5 N, which corresponds to a reduction of 23%. A similar trend was observed for the cutting force F(y), which decreased by 31.4% at maximum heating. This can be explained by the reduction in material hardness in the cutting zone, which facilitates chip formation and reduces the load on the cutting tool.

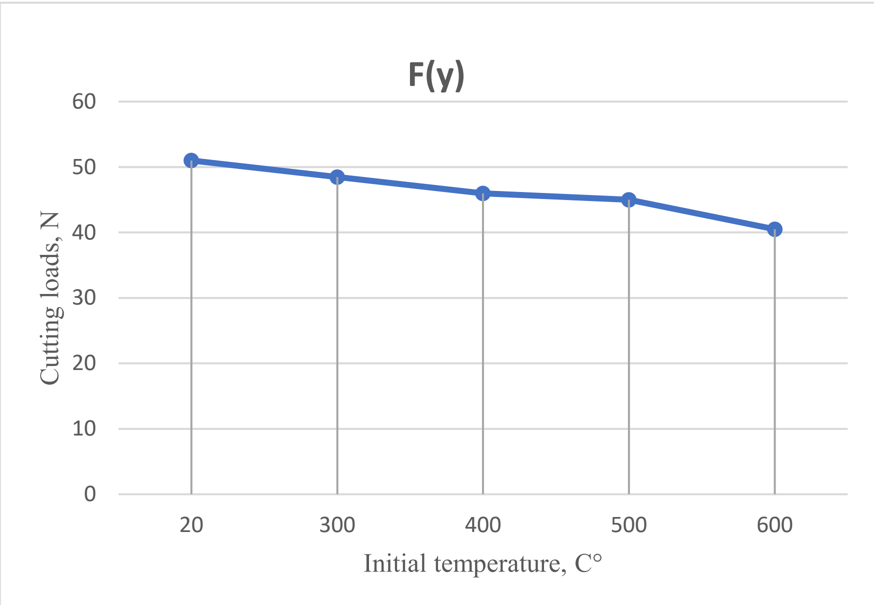

Fig. 3. Variation of cutting force along the F(y) axis

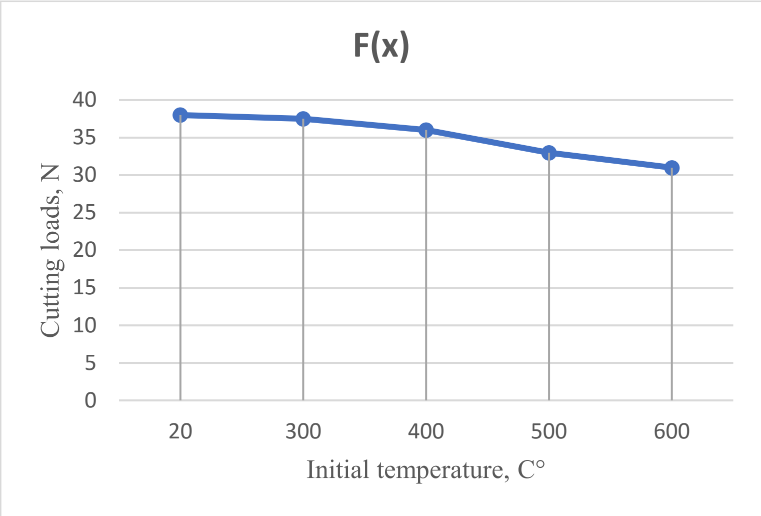

Fig. 4. Variation of cutting force along the F(x) axis

Effect of temperature on surface roughness

The findings of the study suggest a positive correlation between elevated temperatures and enhanced surface quality in machining operations. As the temperature increased from 20°C to 600°C, the surface roughness parameter Ra decreased from 2.1 µm to 1.7 µm, corresponding to an improvement of 31.25%. The phenomenon can be elucidated by the principle that elevated temperatures result in a diminution of cutting forces, thereby fostering the development of a more refined surface and a reduction in microdefects.

Table 4

Surface Roughness, Ra

Temperature (°C)	Ra (µm)	Improvement, %
20	2.1	0.0
300	2.0	6.3
400	1.9	12.5
500	1.7	25.0
600	1.65	28.1

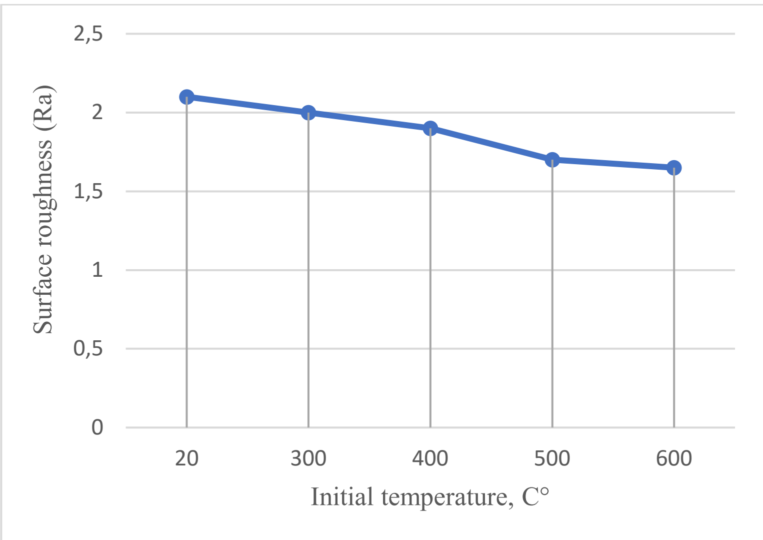

Fig. 5. Variation of surface roughness

Conclusions

The present study analyzes the effect of preheating a VT6 titanium workpiece on cutting force and the quality of the machined surface during turning. The primary objective of this study was to ascertain whether preheating the workpiece prior to machining could exert a favorable influence on the technological characteristics of the cutting process and contribute to the mitigation of the load on the cutting tool.

The findings of the research allow us to draw several important conclusions:

1. Preheating the workpiece has been demonstrated to exert a substantial influence on the cutting force. A comparison of the cutting force values for non-heated workpieces and those heated to 200°C, 400°C, and 600°C revealed a significant reduction in forces. This phenomenon suggests that as the temperature rises, the workpiece undergoes a loss of hardness, thereby facilitating the tool's ability to penetrate the material.

2. A reduction in tool wear was observed. Although direct measurement of cutting-edge wear was not conducted in this study, the reduction in cutting force can be interpreted as an indirect indicator of decreased tool load, which in turn leads to reduced wear and extended tool life.

3. The quality of the machined surface is enhanced. As the preheating temperature increased, the Ra surface roughness parameter demonstrated a marked improvement. The optimal temperature for achieving the greatest outcomes was determined to be 600°C, a finding that signifies enhanced process stability, diminished vibrations, and more uniform material removal.

In summary, preheating the workpiece is an effective technological approach that allows the optimization of the machining process for titanium alloys, improves the final product quality, and reduces operational costs. Subsequent research endeavors may concentrate on the analysis of the impact of heating on the microstructure of the machined surface, the tool's lifespan, and the economic efficiency of the process.

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