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FEM ANALYSIS OF THERMAL SOFTENING – INVESTIGATION OF THE INFLUENCE OF WORKPIECE TEMPERATURE ON CUTTING FORCE IN THE DEFORM ENVIRONMENT

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Abstract. This paper presents the findings from numerical modeling of the turning process of titanium alloys with preheating of the workpiece. This modelling was conducted using the DEFORM-2D software environment, which is based on the finite element method (FEM). The objective of this study is to investigate the influence of workpiece temperature on cutting force and to determine the optimal heating parameters for machining materials that are challenging to process.

The modelling was performed for the Ti-6Al-4V alloy at temperatures ranging from 25 °C to 700 °C. The results obtained demonstrate that an increase in the workpiece temperature results in a substantial reduction in cutting force, exceeding 60%, which is attributable to the thermal softening effect of the material. The most substantial decrease in intensity is observed within the temperature range of 400–600 °C, where phase transformations from α to β occur, diffusion slip is initiated, and dynamic recrystallization takes place.

The employment of DEFORM facilitated a comprehensive investigation into the stress-strain state within the cutting zone, the temperature distribution, and the contact conditions between the tool and the workpiece. The simulation results confirm the effectiveness of preheating for improving the machinability of titanium alloys. The optimal heating temperature, approximately 550°C, ensures minimal cutting forces while maintaining process stability.

The findings thus obtained can be used to optimise the technological parameters of turning hard-to-cut materials under industrial conditions.

Keywords: DEFORM, simulation, difficult-to-machine materials, cutting, hot turning, temperature, titanium alloys, preheating, thermal softening.

Introduction

One of the key directions in modern mechanical engineering is to improve the efficiency of machining processes for hard-to-cut materials, particularly titanium alloys. Titanium alloys, such as Ti-6Al-4V, are widely used in the aerospace, medical, and energy industries due to their combination of high strength, corrosion resistance, and low density. However, their low thermal conductivity, high chemical reactivity, and tendency to adhere to cutting tools lead to increased cutting forces, intensive heat generation in the cutting zone, and rapid tool wear. These factors significantly complicate the turning process and limit its productivity.

One of the promising approaches to reducing tool load and improving the machinability of titanium alloys is preheating of the workpiece (hot machining), in which the workpiece is heated to a certain temperature before cutting. This approach reduces the material's resistance to plastic deformation, resulting in lower cutting forces, improved surface quality, and extended tool life. Determining the optimal heating temperature is a complex task that requires a comprehensive analysis of the thermomechanical interaction between the tool and the workpiece [1, 2].

In this context, numerical modeling serves as a crucial research tool, enabling the reproduction of physical processes in the cutting zone without the need for extensive experimental studies. One of the most effective programs for this purpose is DEFORM, which is based on the finite element method (FEM). The software allows accounting for complex nonlinear effects, including friction, chip formation, heat transfer, and variations in material mechanical properties under heating.

The use of DEFORM-2D in the present study enabled the simulation of the turning process of a titanium workpiece at various temperatures, allowing for the determination of the dependence of cutting force on heating temperature. The modeling considered "tool–workpiece" contact interaction, feed rate and cutting speed parameters, as well as the real thermo-mechanical properties of the Ti-6Al-4V alloy.

The objective of this study is to investigate the effect of workpiece temperature on cutting force during the turning of titanium alloys using the DEFORM environment. To achieve this, a numerical model of the turning process was developed in DEFORM-2D. Simulations were conducted for various preheating temperatures, and the dependencies of cutting force were obtained. The mechanisms of thermal softening were also analyzed.

The simulation results provide a deeper understanding of the temperature's influence on the behavior of titanium alloys during cutting, identify optimal heating conditions to minimize cutting force, and enhance process stability. The obtained findings have practical significance for developing energy-efficient machining technologies for hard-to-cut materials and can be applied to further optimize thermally assisted machining processes under industrial conditions [3].

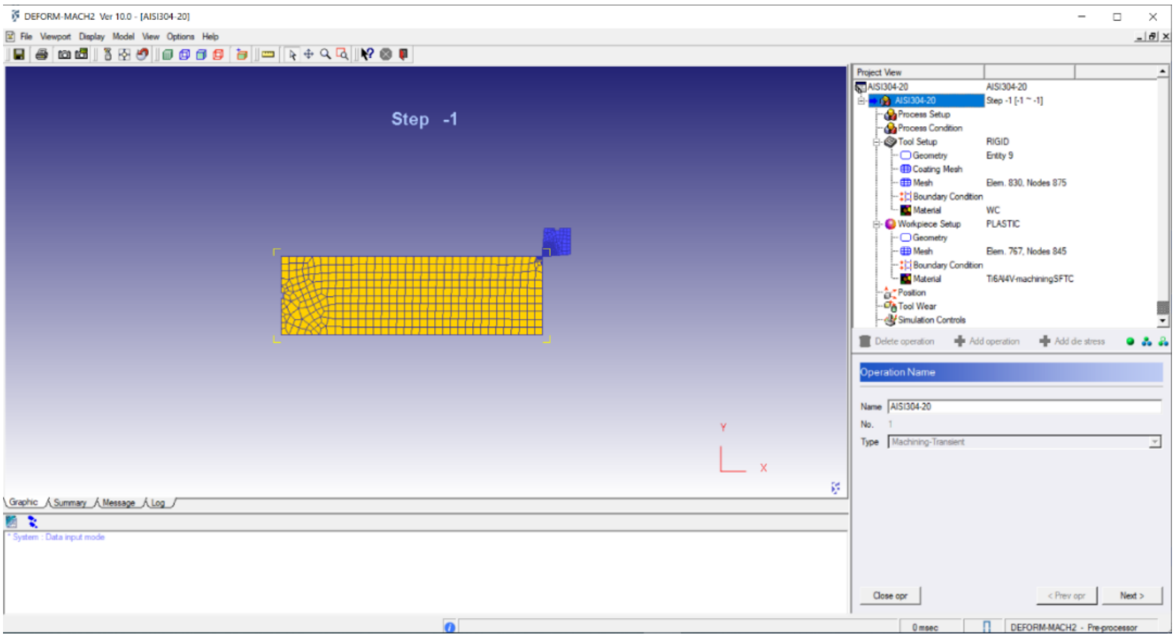

Fig. 1. Main settings window of the DEFORM-2D software

For this study, the DEFORM-2D software was selected. The turning process is complex in terms of tool–material interaction, as it simultaneously involves plastic deformation, friction, heat generation in the cutting zone, and heat conduction within the workpiece. DEFORM enables the consideration of all these factors, allowing for the creation of an accurate virtual model of the process that takes into account tool geometry, cutting speed, feed rate, heating temperature, and the physical and mechanical properties of the material [3].

Compared to general-purpose systems such as ANSYS, Abaqus, and LS-DYNA, DEFORM has a narrower specialization and requires less time for model setup. A particular advantage of using DEFORM (Fig. 2) is that the software allows the evaluation of the influence of temperature on cutting forces, the deformation characteristics of the material, and the thermal fields in the contact zone. This capability is crucial when turning hard-to-cut alloys such as Ti-6Al-4V, where increasing the temperature can significantly reduce cutting forces and tool wear. Additionally, DEFORM facilitates direct comparison between conventional turning and hot turning, allowing for the determination of optimal machining parameters.

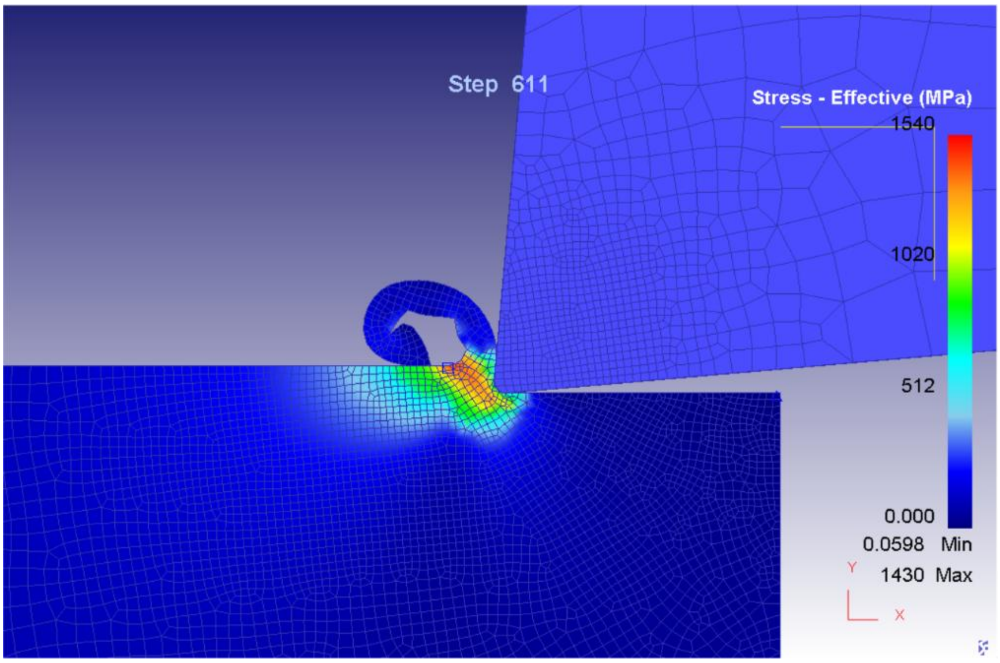

Fig. 2. Simulation window in the DEFORM-2D software

During the turning process, DEFORM-2D models the operation using a plane strain formulation. The workpiece is treated as a plastic body subjected to shear deformation under the action of the cutting tool. The tool is typically defined as a perfectly rigid body that moves relative to the workpiece at a constant feed rate. The contact between the tool and the workpiece is described through friction and heat transfer models. In the contact region, a shear zone forms, where intense plastic deformation occurs, resulting in chip formation.

In DEFORM-2D, during the simulation of turning with preheating of the workpiece (for example, up to 600 °C), the software simultaneously solves the mechanical and thermal equations within a coupled thermomechanical analysis [3].

The following equations are usually used to obtain the results of thermomechanical modeling:

Mechanical part – equilibrium equation

$$\nabla \cdot \sigma + \mathrm{f} = 0 \tag{1}$$

σ – stress tensor, f – body force vector (usually zero or gravity), ∇ – divergence operator.

For a 2D turning model, the plane strain formulation is used – that is, $\varepsilon_z = 0$, but $\sigma_z \neq 0$.

Flow rule

The mechanical behavior of the workpiece is described by the flow rule and a yield criterion. Most commonly, DEFORM uses a material model that relates stress to strain, strain rate, and temperature. One of the typical constitutive laws implemented in DEFORM is:

$$\sigma = [A + B\,\varepsilon^n][1 + C\ln\frac{\varepsilon}{\varepsilon_0}][1 - (\frac{T - T_{\mathrm{room}}}{T_{\mathrm{melt}} - T_{\mathrm{room}}})^m] \tag{2}$$

ε – plastic strain, ε – strain rate, T – current material temperature, A, B, C, n, m – material constants.

When the workpiece is heated to 600 °C, the software reduces the flow stress through the third term of the Johnson–Cook model (or table-based data), meaning the material becomes “softer,” and the cutting force decreases at the same cutting parameters [5].

Thermal part – heat conduction equation

DEFORM simultaneously solves the heat conduction equation, accounting for heat generated by plastic deformation and friction:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \beta\ \sigma : \varepsilon^p + Q_{\text{friction}} \tag{3}$$

ρ – density, c_p – heat capacity, k – thermal conductivity, $\beta \approx 0.9$ – fraction of plastic work converted into heat ?$\sigma : \varepsilon^p$– power of plastic deformation, Q_{friction} – frictional heat at the “tool–workpiece” interface.

Contact conditions

The contact between the tool and the workpiece is modeled using a friction law (most commonly Coulomb or shear friction models with coefficient μ or a limit shear stress). Thermal contact is defined by the heat transfer coefficient, h, which determines the amount of heat that flows between the workpiece and the tool.

Cutting force

The cutting force in DEFORM is computed automatically as the integral of contact stresses over the tool surface:

$$\mathrm{F} = \underset{S_{\text{contact}}}{} \sigma_{\text{contact}} \cdot \mathrm{n}\ dS \tag{4}$$

The software then decomposes it into components:

- tangential / cutting force,
- radial/thrust force.

When two simulations are run – one at room temperature and another at 600 °C – the only change is the initial thermal state of the workpiece. This affects the flow stress, heat distribution, and the behavior of the shear zone. As a result, the tool–chip contact conditions and the total cutting force change accordingly [4-6].

Modeling parameters in DEFORM-2D

Workpiece material: Ti-6Al-4V (titanium alloy)
Tool material: WC (tungsten carbide)
Cutting speed (surface speed): 100 m/min
Feed rate: 0.1 mm/rev
Cutting depth (depth of cut): 0.5 mm
Friction coefficient: set according to typical dry-cutting conditions for titanium (μ ≈ 0.4)
Workpiece initial temperature: 25°C (baseline case)

Simulation results

Titanium alloys, particularly Ti-6Al-4V, exhibit high sensitivity to temperature – even at 400–600 °C, a sharp decrease in yield strength occurs. This directly confirms the thermal softening effect obtained during the DEFORM simulation [7].

The resulting graph clearly demonstrates the dependence of cutting force on the workpiece temperature: as the temperature increases from 25 °C to 700 °C, the cutting force decreases by more than 60% for both components (F_x and F_y). This indicates the dominant influence of thermal softening processes in the material.

In the range of 25–400 °C, the cutting force decreases moderately (approximately 25%), corresponding to the onset of thermal softening. With a further increase in temperature to 500–700 °C, an intensive drop in cutting force (up to 60%) is observed, caused by a sharp reduction in the strength of the α-phase and the development of dynamic recrystallization. At 500 °C, the self-diffusion coefficient for α-titanium is approximately 10^{-19} m²/s, while for β-titanium it is about 10^{-18} m²/s. This means that above 500

°C, diffusion processes become highly active, leading to: increased dislocation mobility, reduced resistance to plastic deformation, activation of diffusion creep mechanisms, and enhanced recrystallization or subrecrystallization, which collectively soften the material.

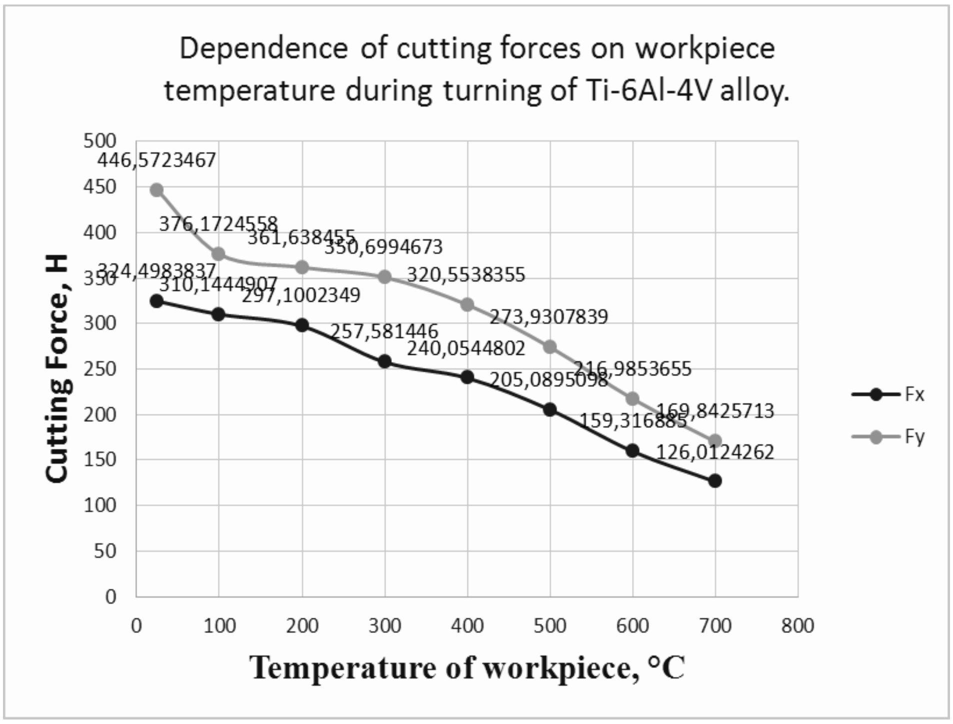

Fig. 3. Dependence of cutting forces on workpiece temperature

Cutting forces and their reduction percentage at different workpiece temperatures

°C	25	100	200	300	400	500	600	700
F(x)	324.5	310.1	297.1	257.6	240.1	205.1	159.3	126.0
%	**0**	**4.4**	**8.4**	**20.6**	**26**	**36.8**	**50.9**	**61.2**
F(y)	446.6	376.2	361.6	350.7	320.6	273.9	217	169.8
%	**0**	**15.8**	**19**	**21.5**	**28.2**	**38.7**	**51.4**	**62**

In addition to the reduction of yield stress, the shear viscosity and friction coefficient in the “chip–tool” contact zone decrease within this temperature range, further reducing the overall cutting force. However, as noted by Leyens and Peters [28], at temperatures above 600 °C, Ti-6Al-4V may experience thermoplastic instability, forming adiabatic shear bands, which reduce process stability. This explains why, after 600 °C, the cutting force continues to decrease but at a slower rate, and the process becomes less predictable.

The behavior of titanium at different temperatures is well illustrated by the temperature dependence of Young’s modulus (E). The Young’s modulus (in GPa) represents the material’s stiffness, i.e., its resistance to elastic deformation.

As can be seen, the Young’s modulus decreases with increasing temperature, meaning that the material becomes “softer” (less stiff). This indicates the thermal softening of titanium alloys, which occurs due to the weakening of interatomic bonds in the crystal lattice during heating [7].

Here are several key factors that influence the thermal softening of metals:
The figure shows the microstructure of the Ti-6Al-4V titanium alloy at temperatures of 25 °C and 700 °C, illustrating the effect of thermal exposure on the material’s condition during machining. At room temperature (25 °C), the structure is characterized by elongated α-phase grains oriented along the direction

of deformation. Such a structure is typical for alloys subjected to intensive plastic deformation without thermal softening. It indicates high hardness, residual stresses, and a significant dislocation density, which complicate metal cutting and accelerate tool wear.

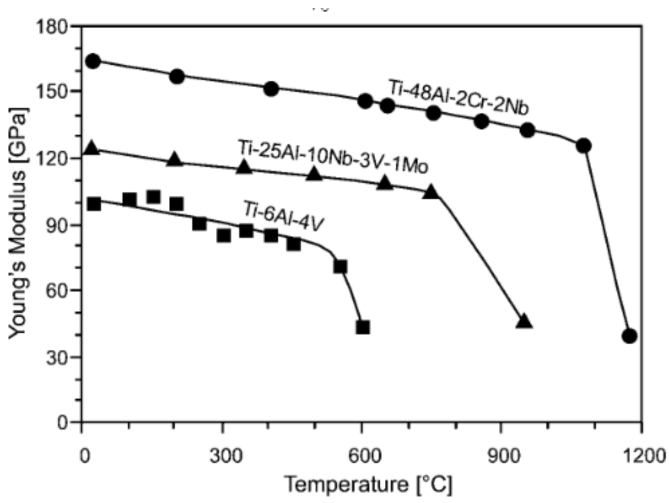

Fig. 4. Young's modulus [27]

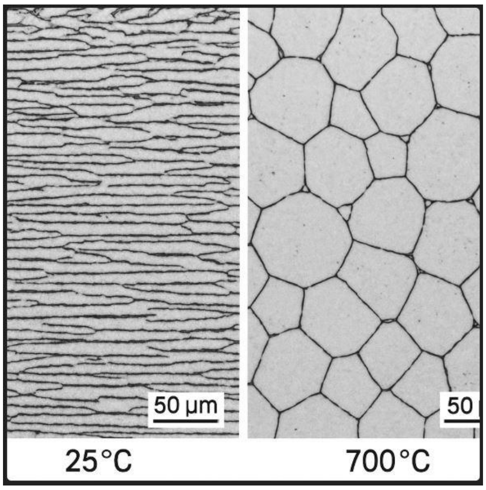

Fig. 5. Microstructure of the titanium alloy Ti-6Al-4V at 25°C and 700°C [28]

When the temperature increases to 700 °C, recrystallization occurs, resulting in grains acquiring an equiaxed polygonal shape and the structure becoming more homogeneous. The reduction of internal stresses and dislocation density decreases the resistance to plastic deformation, thereby facilitating the machining process of the material.

A partial α → β phase transformation can account for up to 20–25% of the reduction in cutting force. The Ti-6Al-4V titanium alloy (an α+β alloy) consists of two phases: the α-phase (hexagonal close-packed, HCP) – hard, less ductile, and stable up to approximately 880 °C; and the β-phase (body-centered cubic, BCC) – more ductile and active at elevated temperatures. When heated, the alloy transitions from a predominantly α-structured state to an α+β mixture, and further (≈995 °C) almost completely to the β-phase. During this process, thermal softening mechanisms occur, which reduce the material's cutting force, strength, and hardness [1].

Dislocation mobility is another significant factor, accounting for up to 30% of the reduction in cutting force. As temperature increases, atomic vibrations within the crystal lattice intensify, lowering the energy required for dislocation motion.

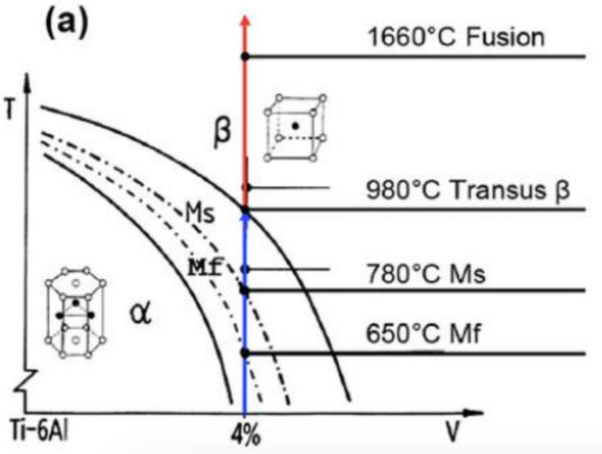

Fig. 6. Phase transformation diagram
of the titanium alloy Ti-6Al-4V [28]

In Ti-6Al-4V, dislocations in the α-phase (HCP) usually move with difficulty due to the limited number of slip planes. However, at approximately 400–600 °C, additional slip systems (such as prismatic and basal planes) become activated, making deformation easier. In the β-phase (BCC), dislocation motion is even easier – the structure is more ductile, leading to an overall reduction in deformation resistance.

Moreover, at temperatures above 400 °C, diffusion creep mechanisms become active in titanium alloys. This means that part of the plastic deformation occurs not through conventional dislocation slip but through slow atomic diffusion in the lattice – the so-called Nabarro–Herring (volume diffusion) and Coble (grain boundary diffusion) mechanisms. Such diffusion creep leads to gradual "creep-like" material flow, which further reduces resistance to plastic deformation and contributes to lower cutting forces at high temperatures.

Additionally, since the α-phase has fewer active slip planes, titanium deforms with difficulty at lower temperatures. However, after the activation of additional prismatic and basal slip systems (around 500 °C), deformation becomes easier. The β-phase, with its cubic structure, possesses 12 slip systems, resulting in significantly higher ductility. This explains the intensive reduction in cutting force in the 400–600 °C range, when a two-phase α+β structure is formed.

According to Leyens [28], the diffusion coefficient in β-titanium at 1000 °C is about 1000 times higher than that in α-titanium at 500 °C, meaning that at elevated temperatures, diffusion creep and dynamic recrystallization mechanisms are strongly activated, producing the observed thermal softening effect – precisely what was simulated in DEFORM.

There are also several secondary factors that contribute, to a lesser extent, to the reduction of cutting force at elevated temperatures. Among them are recrystallization (grain formation), where accumulated dislocations and stresses are eliminated by the formation of new equilibrium grains (dynamic recrystallization). In the cutting or deformation zone, at approximately 500–700 °C, fine equiaxed β-phase grains are formed. This structural "renewal" reduces dislocation density, making the material softer.

Coarsening or dissolution of strengthening phases also contributes to titanium softening. In Ti-6Al-4V, strengthening is provided by fine α-lamellae within the β-matrix. These α-lamellae coarsen (coagulate), and some partially dissolve in the β-phase, leading to the loss of dispersion strengthening, and consequently, a reduction in yield strength [1, 7-9].

If the material has undergone prior plastic deformation (cold working), heating causes the relaxation of accumulated defects and reduces the effect of work hardening, which also softens the metal

Conclusions

As a result of the FEM simulation of the turning process of Ti-6Al-4V titanium alloys in the DEFORM-2D environment, a significant influence of the workpiece temperature on the cutting force was established. Increasing the temperature from 25°C to 700°C results in a reduction of more than 60% in cutting force, confirming the effect of thermal softening on the material. The most intensive decrease is observed in the range of 400–600°C, where $\alpha \rightarrow \beta$ phase transformations, dynamic recrystallization, and diffusion creep become active.

Analysis of the mechanisms revealed that the main factors contributing to the reduction in cutting force are: increased dislocation mobility (approximately 30%), phase transformations (approximately 25%), as well as diffusion creep and recrystallization processes, which further weaken the alloy structure. In addition, at elevated temperatures, the friction coefficient in the "chip–tool" contact zone decreases, further reducing the cutting resistance.

The optimal heating temperature was determined to be around 500°C, as this temperature provides the minimum cutting force while maintaining process stability without the occurrence of thermoplastic instability.

The obtained results confirm the effectiveness of thermally assisted turning for improving the machinability of titanium alloys and can be used to optimize machining parameters for hard-to-cut materials in industrial applications.

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