In-process detection of cutting forces and cutting temperature signals in cryogenic assisted turning of titanium alloys: An analytical approach and experimental study (Postprint)

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Abstract

In-process detection of cutting forces, temperature, roughness, wear etc. during machining of titanium alloys are very important. The Finite element (FE) analysis plays an important role in monitoring and detection of machining responses. It offers a high accuracy in modeling of dry cutting processes and its performance in modeling of cryogenic machining process is a matter of interest. In this context, current investigation focuses on the dry turning and LN2/CO2 cooling assisted turning process of commonly used Ti6Al4V alloy. It is very useful material in the biomedical sector, and the simulation of cutting forces and cutting temperature via finite element method (FEM) has been performed. In addition, the simulation results are validated with experimental work. The results show that the deviations between FE modeling and experimental results for the cutting temperature are the average of 5.54%, 5.18% and 8.42% for the dry, LN2 and CO2 cooling conditions, respectively. On the other hand, the deviations from FE modeling and cutting force test results were 3.74%, 3.358%, and 3.03% under dry, LN2 and CO2 cooling conditions, respectively.

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Preamble

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In-process detection of cutting forces and cutting temperature signals in cryogenic assisted turning of titanium alloys: An analytical

approach and experimental study

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Keywords: Cutting force; Cutting temperature; Finite Element Method (FEM); Cryogenic cooling; Titanium alloys machining; In-process measurement

In-process detection of cutting forces, temperature, roughness, wear, etc. during machining of titanium alloys is very important. Finite element (FE) analysis plays an important role in monitoring and detection of machining responses. It offers high accuracy in modeling of dry cutting processes, and its performance in modeling cryogenic machining processes is a matter of interest. In this context, the current investigation focuses on the dry turning and LN_2/CO_2 cooling assisted turning process of the commonly used Ti6Al4V alloy, a very useful material in the biomedical sector, and the simulation of cutting forces and cutting temperature via finite element method (FEM) has been performed. In addition, the simulation results are validated with experimental work. The results show that the deviations between FE modeling and experimental results for cutting temperature average 5.54%, 5.18%, and 8.42% for dry, LN_2, and CO_2 cooling conditions, respectively. On the other hand, the deviations between FE modeling and cutting force test results were 3.74%, 3.35%, and 3.03% under dry, LN_2, and CO_2 cooling conditions, respectively.

Abbreviations: FEM, Finite Element Method; FE, Finite Element; LN_2/CO_2, Liquid nitrogen and carbon dioxide; F, vector matrix for the force at the element; U, Vector of the determined node displacement; K, Stiffness matrix; U, Node displacement vector refreshed with time change; M_1, Mass matrix; “˙U” , Node velocity (first derivative of the node displacement); M_2, Damping matrix; “¨U” , Node acceleration; ALE, Arbitrary Lagrangian-Eularian; σ_0, Flow stress; , Plastic deformation; ˙ , Deformation rate; ˙ $_0$, Reference plastic deformation rate; T, Workpiece temperature; T , Workpiece melting temperature; T , Room temperature; A, Yield strength; B, Hardness modulus; C, Strain rate sensitivity coefficient; N, Hardness coefficient; M, Thermal softening coefficient; P, Hydrostatic pressure; , Fracture strain during chip separation; D_1, D_2, D_3, D_4, D_5, Fracture constants in JC damage model; JC, Johnson-Cook; CVD, Chemical vapour deposition; Q, Heat transfer per unit time; C , Specific heat; M, Mass; dT/dt, Rate of temperature decrease per unit time; q, Heat flux of density; h, Heat transfer coefficient; T , Surface temperature; T , Cryogen temperature; Fc, Main cutting force; Ft, Tangential forces; α, Rake angle.

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1. Introduction

The world of manufacturing, especially the machining sector, is undergoing a seismic shift from conventional to advanced processes. With this aim, Industry 4.0 supports systems that enable and reduce product costs. Ultimately, obtaining a high-quality product cannot be considered success alone; achieving the most affordable production is among the main goals and expectations in the context of the industrial revolution. To reduce production costs, the optimization of process parameters must be done well. Optimization of machining parameters, cutting tools, and cutting conditions reduces costs. Of course, in addition to all these, it is very common to demand manufacturing carried out under conditions that cause the least harm to the environment.

These days, application of sustainable cooling conditions (i.e., dry, cryogenics especially with liquid nitrogen and carbon dioxide) is used in machining of various materials. These cooling conditions significantly improve machining performance with less environmental effect. Research studies have been carried out to solve the above expectations, but every year there are technological developments in cutting tools, cutting conditions, and machine tools used in the manufacturing process. In parallel with these developments, the necessity of continuing research emerges. To reduce machining time in the turning process, obtain better quality surfaces, reduce costs, minimize environmental damage, and improve cutting tools used in turning have gained momentum in recent years.

Nath and Kurfess stated that cutting tools with different geometric features such as complex chip breaker form, tip angles of the cutting tip, and cutting tool tip radius have been produced and widely used in the industry. However, by considering these geometric features in cutting tools as a whole with cutting parameters, it is necessary to focus on complex problems such as the effect of chips formed during turning to reduce damage to the cutting tool and workpiece by breaking them in appropriate sizes, workpiece surface quality, and the effect on cutting forces and cutting temperatures during the cutting process. Thus, by determining suitable cutting conditions, it is aimed to contribute to obtaining products with minimal cost, time, and optimal quality.

In this context, there are many studies in the literature about finite element modeling of machining processes. Papazoglou et al. and Akgün and Demir focused on dry conditions. Zhou et al. predicted cutting forces in dry turning of Inconel 718 alloy with different tool nose radius and edge radius by finite element simulations, verifying cutting forces by the FE model with experimental studies in the range of 4% and 11%. Lotfi et al. developed a friction model under 3D dry turning of AISI 304 stainless steel, verifying that the created 3D friction model calculates friction value depending on cutting angle and force. Kumar et al. created a 2D FE model to investigate machinability performance of AISI 1045 steel via nanolayered coated WC-Co cutting insert in dry condition, finding that deviation between experimental and predicted force values varied from 1.8 to 3.8% for Fxz (uncoated tool) and 1.25 to 6% for coated tool. Yang et al. compared surface roughness values obtained experimentally and by FE models in dry turning of Al6061 alloy by PCD cutting tool, confirming good agreement between simulation and experimental responses. Vijayaraghavan et al. performed FE simulations of dry turning of Inconel 718 alloys by data analysis method, verifying that the developed FE model is suitable to achieve sustainable manufacturing goals. Parida and Maity carried out hot turning of Inconel 625 alloy experimentally and supported it by FEM, showing good relation and verification on chip formation and cutting forces between experimental values and FE results. Schindler et al. predicted thermal influences on Al2024 alloy by FE turning model, achieving good accuracy between experimental and FE results based on cutting forces and heat flows. Apart from these studies, a brief review of FEM studies for machining difficult-to-cut materials is given in Table 1 .

As can be seen from studies in the literature, FE studies were generally developed based on dry machining conditions. When cryogenic studies are performed, they are generally experimental, not finite element simulation type. To the best of the authors' knowledge, there are no or limited number of FE machining studies based on cryogenic cooling conditions in turning of Ti6Al4V alloys. Considering all these, the machining process is focused on Ti6Al4V, subjecting them to dry turning and LN_2/CO_2 cooling assisted turning process, and the simulation of this process with FEM has been performed. The findings and results are helpful for industrialists using such cooling technologies and researchers conducting research on these issues. In addition, it has been observed that there are differences between cooling technologies used in scientific studies and manufacturing industries. All studies examined in this section have shown that finite element model simulations made by simulation software can reach results compatible with experimental studies.

2.1. Finite Element Method

Finite element analysis is a numerical approximation method that allows complex structures to be divided into particles, transformed into idealized structures, and mathematically solved. The finite element method includes systematic procedures of derivatives of finite elements that are sub-regions of approximation functions. Numerical solutions for variables at special points are called nodes of each element and are applied to the calculation of finite solutions for the whole geometry. Finite element analysis is useful in providing approaches for solving problems that are analytically difficult or impossible to solve.

Discretization of geometry is the first step in finite element analysis, where the geometry is divided into finite elements. Next, different types of elements are used, such as triangular, quadrilateral, and shallow defined, with element properties depending on what is required for the analysis. The stiffness matrix is used to define element properties, expressing the force-displacement relationships of the element under load. After defining the stiffness matrix, loading conditions such as pressure, force, and velocity are defined throughout the boundary conditions at specific nodes. Finally, the expression of the element, applied loads, and boundary conditions are adapted to form the matrix. The established equations are solved numerically for unknown values. Stress, strain, and other properties of interest can be defined depending on the result of node displacement.

The equilibrium equations for general linear or nonlinear static problems of finite element analysis can be expressed as Eq. (1):

$$\{F\} = [K] \cdot \{U\}$$

where F is the vector matrix for the force at the element, K is the stiffness matrix, and U is the vector of the determined node displacement.

However, dynamical analysis requires a different form for dynamical problems independent of time as shown in Eq. (2):

$$\{F(t)\} = [K]\{U\} + [M_1]\{\dot{U}\} + [M_2]\{\ddot{U}\}$$

Here K refers to the stiffness matrix, U to the node displacement vector refreshed with time change, M_1 to the mass matrix, $\dot{U}$ to the node velocity (first derivative of node displacement), M_2 to the damping matrix, and $\ddot{U}$ to the node acceleration (second derivative of node displacement).

In finite element formulation, Lagrangian, Eulerian, and Arbitrary Lagrangian-Eulerian mesh structures are widely used. When these mesh structures are compared, differences between them become apparent. In the Eulerian mesh structure, the finite element mesh remains constant during material flow, with only points displaced. The benefit of the Eulerian mesh structure is that the shape of elements does not change over time, so there is no distortion. However, it is imperative to consider the free surface of the chip as the starting shape, and the chip formation process cannot be modeled.

On the other hand, in the Lagrangian method, the mesh is fixed to the material and moves with it. However, it is difficult to accommodate shape changes of elements during material flow. Therefore, the deformed mesh may need regeneration. Thus, when using such mesh structures, the mesh needs re-meshing or adaptive meshing, and chip separation criteria are required for shaping chips.

In the Arbitrary Lagrangian-Eulerian (ALE) mesh structure, points on the surface are fixed neither to the material nor to the area—these points move arbitrarily. In other words, material flow is independent of points. According to Savidis et al., ALE gives better results when compared with both mesh structures.

ALE mesh algorithms are used in many software packages for machining, such as ABAQUS, DEFORM, Third Wave AdvantEdge, and ANSYS LS-DYNA, and give better results. However, Third Wave AdvantEdge is machining-specific simulation software, while ABAQUS, DEFORM, or LS-DYNA are general plastic deformation process simulation software. For this reason, Third Wave AdvantEdge was selected due to its being specialized FE simulation software that is easy to process. Grzesik indicated that the remeshing method used in some of these software packages increases the sensitivity and accuracy of analysis.

Some important boundary conditions are required to use the finite element method for analysis of chip formation in metal cutting. These boundary conditions help define limits and loading conditions to solve the problem. By applying these boundary conditions, determining the deformation rate of the material, and understanding how the workpiece material will behave during plastic deformation, it is possible to model chip formation by selecting the appropriate modeling technique. To capture the dynamic behavior of the model, the strain rate and thermal effects of the constitutive equations should be selected. Stress in metals changes as a function of strain, strain rate, and temperature. According to Xu et al., the Johnson-Cook constitutive equation is one of the first equations involving strain and thermal effects. Using these equations, material models such as rigid plastic, elastic-plastic, thermo-elastoplastic, and thermo visco-plastic can be created. The formulation of Johnson-Cook' s constitutive equation used by Third Wave AdvantEdge is presented in Eq. (3):

$$\sigma_0 = (A + B(\varepsilon_p)^n)\left(1 + C\ln\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0}\right)\left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right)$$

Here σ_0 represents flow stress, plastic deformation, $\dot{\varepsilon}_p$ deformation rate, $\dot{\varepsilon}_0$ reference plastic deformation rate, T workpiece temperature, T workpiece melting temperature, and T room temperature. The coefficient A indicates yield strength (MPa), B hardness modulus (MPa), C strain rate sensitivity coefficient, n hardness coefficient, and m thermal softening coefficient.

Moreover, for chip separation, a damage model is required. The general JC damage model equation for equivalent fracture strain is expressed in Eq. (4):

$$\varepsilon_f = \left(D_1 + D_2\exp(D_3\frac{P}{\sigma})\right)\left(1 + D_4\ln\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0}\right)\left(1 + D_5\frac{T - T_r}{T_m - T_r}\right)$$

In Eq. (4), P/σ shows the stress triaxiality where P is the hydrostatic pressure (average of three-dimensional normal stresses). _f is the fracture strain during chip separation, which is a dynamic process of machining. The fracture constants D_1, D_2, D_3, D_4, D_5 in the JC damage model equation represent the initial failure strain, exponential factor, triaxial factor, strain rate factor, and temperature factor, respectively.

The general geometric structure for finite element analysis with Third Wave AdvantEdge is presented in Fig. 1 [Figure 1: see original paper]. As the turning method, 3D nose turning was preferred.

2.2. Material Details

The numerical analysis of machining is directly related to accurate adaptation of the material model into the software. Therefore, modeling success is possible by determining material properties well and adapting them as input. During finite element analysis, Ti6Al4V workpiece material with dimensions of 1$×1×$3 mm was selected. The JC parameters and fracture constants previously used by Xu et al., chemical compositions by Gupta et al., and other mechanical features of Ti6Al4V alloys used by Du et al. are given in Tables 2-5, respectively.

The cutting insert was selected as CVD (chemical vapour deposition) type TiC-Al_2O_3-TiN (each assumed as 1 µm thickness) coated carbide inserts with ISO code CNMG 120408, as shown in Fig. 2 [Figure 2: see original paper]. The properties of carbide cutting tools previously used by Du et al. are provided in Table 6 .

2.3. Cooling Systems

Cryogenics is generally defined as the study of low temperature situations. When analyzing a system operating under cryogenic conditions, thermal features of materials changing with temperature must be considered. Specific heat, thermal conductivity, and especially heat transfer coefficient values for gases and liquids are important thermal properties for heat transfer calculations at cryogenic temperatures.

The calculation of heat transfer per unit time (Q) is given in Eq. (5):

$$Q = C_v \cdot m \cdot \frac{dT}{dt}$$

In Eq. (5), C , m, and dT/dt specify specific heat, mass, and rate of temperature decrease per unit time, respectively. By substituting “m = A • δ • ” in Eq. (6):

$$Q = C_v \cdot A \cdot \delta \cdot \rho \cdot \frac{dT}{dt}$$

The heat flux density q equals Q/A. So Eq. (6) takes the form of Eq. (7) by Newton’ s heat transfer law:

$$q = \rho \cdot C_v \cdot \delta \cdot \frac{dT}{dt}$$

From Eq. (7), dT/dt is known as the ratio of temperature differences like the cooling rate (T_2-T_1)/(t_2-t_1). The heat transfer coefficient h is calculated by Eq. (8):

$$q = h(T_w - T_f)$$

In Eq. (8), h is the heat transfer coefficient (W/m^2K), T is the surface temperature, and T is the cryogen temperature of LN_2 and CO_2, respectively. Moreover, the heat transfer coefficients for LN_2 and CO_2 are adapted as 309 W/m^2K and 78.5 W/m^2K, with cryogen temperatures of -196.5°C and -78.5°C, respectively.

2.4. Meshing

The mesh structure created in finite element analysis directly affects the analysis results. The main goal is to select a mesh structure that can represent the geometry as accurately as possible. The density of finite elements is an essential measure used to confirm analysis accuracy (element type and morphology also affect accuracy). Assuming the model has no singularity region, higher density mesh produces outcomes with higher precision. However, very dense element mesh requires substantial computer memory and long execution time, often occurring under multiple repeating conditions, especially for nonlinear and transitional analysis.

Comparing findings to test data or theoretical values is one approach to assess finite element mesh quality. Unfortunately, in early research stages, test data and theoretical conclusions are frequently unavailable. Therefore, different tools are required to assess mesh quality, with mesh sensitivity analysis being the most important. For the current study, the minimum element size for the workpiece and cutting tool was optimized as 0.15 mm by mesh sensitivity analysis with re-meshing method shown in Table 7 .

Simulations were performed on a computer with 16 GB RAM, 6 GB client cache, and 2.4 GHz processor speed. All 8 cores were used for parallel processing to solve FE analysis faster, meaning 8 FE simulations could be performed simultaneously in the same solving period. Initially, element sizes of 1, 0.5, and 0.25 mm were used in FE analysis, yielding cutting forces of 320.1, 298.4, and 285.3 N with computing times of 0.7, 1.5, and 3.3 hours, respectively. This showed that element size should be further decreased due to higher values of change in cutting forces relative to small computing time differences. Afterwards, element size was decreased stepwise to 0.1 mm. The change in cutting force became negligible but computing time increased by about 70%. For this reason, element size was determined as 0.15 mm (Fig. 4 [Figure 4: see original paper]) with a computing time of 6.1 hours for a simple test simulation.

2.5. Friction Model

In FE simulation of the turning process, Ozel suggested that the Coulomb friction model may be quite efficient on the tool flank surface. The average friction coefficient between tool and chip in orthogonal turning was computed from measured cutting forces as presented in Eq. (9) from simple turning tests for each condition. As a result, the average friction coefficient ( ) was found to be 0.46, 0.42, and 0.37 for dry, LN_2, and CO_2 conditions, respectively.

$$\mu = \frac{F_t + F_c \cdot \tan\alpha}{F_c - F_t \cdot \tan\alpha}$$

In Eq. (9), Fc and Ft are the main cutting and tangential forces obtained experimentally with a dynamometer while α is the rake angle. For instance, average friction coefficient ( ) is calculated as 0.46 when Fc, Ft, and α are 270.5 N, 159 N, and -6°, respectively. Tangential forces were measured but not recorded in the previous study of Gupta et al.

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3. Experimental Procedure for Verification

In this work, the same experimental conditions of Gupta et al. were adopted for performing simulations. Machining of commercially used Ti6Al4V alloy was performed with CVD type TiCn-Al_2O_3-TiN coated carbide inserts with ISO code CNMG 120408 rhombic shaped inserts. The workpiece dimensions were 30 mm diameter and 100 mm length. An initial layer of 0.5 mm was removed to maintain workpiece uniformity. The side cutting edge angle (principle cutting angle) used had 0.8 mm nose radius. Further experiments were performed under the same conditions as FE simulations using a CNC lathe machine with Siemens control system. Specifications of the CNC center and parameters for the cryogenic cooling system by Gupta et al. are given in Table 8 .

Levels of feed rate and cutting speed under dry, LN_2, and CO_2 conditions were selected based on previous work of Gupta et al. As mentioned earlier, the same machining conditions were adopted and the experimental design is shown in Annexure 1. Cutting depth of 0.5 mm and machining time of 60 s were used throughout experiments. These parameters were selected following tool manufacturer guidelines and preliminary studies. Details of machining parameters are listed in Table 9 . Cutting temperature and cutting forces were evaluated with a Fluke thermal camera and Kistler 9257A dynamometer. All measurements were performed online and the Dynoware package was utilized to extract cutting forces from the system. The complete process methodology is given in Fig. 5 [Figure 5: see original paper].

4.1. FE Simulation Results

The simulation study performed with Thirdwave Advantage software using process parameters and boundary conditions detailed above analyzed 3D turning and developed a new finite element model. Fig. 6 [Figure 6: see original paper] shows a sample finite element simulation for feed rate of 0.1 mm/rev and cutting speed of 50 m/min.

4.2. Main Cutting Forces

In metal cutting processes, cutting force is the force necessary to remove material from a resistive body. The principle cutting force and its components are affected by various variables. Cutting parameters, workpiece material, cutting tool properties, and cutting environment are the most basic factors known to affect cutting force according to Yang et al. Knowing cutting force is helpful for sizing cutting tools, estimating power requirements, optimizing cutting parameters, etc. Consequently, minimal cutting force is often desirable in machining operations.

In this section, the influence of cutting parameters and cutting environment on main cutting force was determined via finite element analysis, with results presented graphically in Fig. 7 [Figure 7: see original paper]. With increasing cutting speed, an increase in cutting force was observed in all three feed rates and cutting environments. For example, when calculated according to each increasing level of cutting speed, the increase in cutting force ranged between 16.56% and 23.70% at 0.1 mm/rev feed, between 18.24% and 28.17% at 0.15 mm/rev feed, and between 14.23% and 26.36% at 0.20 mm/rev feed. In many previous studies, unlike this study, Pathak et al. and Şeker et al. proved that there is a reduction in cutting force with increased cutting speed in machining of Al-(1-2)Fe-1V-1Si alloy and St44 steel, respectively. Ravi and Pradeep Kumar stated that this situation results from thermal softening of the work material due to heat generated by rising cutting speed in machining of titanium alloys. However, in the current work, force ascends with elevated cutting speed. Generally, when workpiece materials are subjected to deformation, strain hardening occurs in addition to thermal softening. An increase in cutting force can be observed if the strain hardening effect exceeds the thermal softening effect. Therefore, in this study, the rise in force versus cutting speed was associated with strain hardening, similar to observations by Hou et al. and Shi et al.

As seen in Fig. 7, a rise in feed triggered an increase in cutting force. Depending on feed increase, cutting force increased from 6.72% to 23.11%. However, compared to cutting speed influence, feed had lower impact on cutting force. This phenomenon may be associated with higher feed rate increasing contact area at the tool-chip interface as more material is removed per unit time, as mentioned by Kim et al.

Examining Fig. 7 reveals that the cutting environment offering the lowest cutting force for each cutting parameter is LN_2 cooling, followed by CO_2 and dry environments. Compared to dry cutting, 21.01% to 34.95% less cutting force can be achieved with LN_2 assisted cutting. Additionally, CO_2 assisted cutting can provide improvement up to 14.41%. Improved strength and hardness of tool material, decreased tool wear, and eliminated adhesion between tool-chip and tool-workpiece interfaces gained by reducing cutting temperature may result in lower cutting forces achieved by LN_2 and CO_2 assisted machining. Since LN_2 has a lower boiling temperature than CO_2, it prevents cutting tool overheating during machining and offers more effective cooling ability, as thought by Pusavec et al. Hong et al. indicated that outstanding LN_2 cooling performance may result from the liquid/gas buffer across the contact surface absorbing generated heat and providing a lubricating effect that evaporates quickly and reduces friction.

4.3. Cutting Temperature

Cutting temperatures are highly dependent on machining parameters, workpiece material, and tool material characteristics. Particularly, characteristics of the machined material are vital in determining cutting temperature ranges. Singh et al. demonstrated that titanium alloys, which have much lower thermal conductivity than steels, lead to higher cutting temperatures during machining. Because Ti6Al4V has limited thermal conductivity, roughly 80% of heat generated stays in the cutting zone. In contrast, during machining of materials like aluminum, Pramanik declared that more heat is carried away with chips.

In this section, the effect of cutting parameters and cutting environment on cutting temperature was determined via finite element analysis, with outcomes provided graphically in Fig. 8 [Figure 8: see original paper]. The upward effect of cutting speed on temperature is noticeable, with this effect varying between 23.61% and 81.25% depending on feed rate and cutting environment. Generally, higher cutting speed accelerates cutting temperature buildup due to more heat produced per unit time and less time available for heat evacuation from the region. Feed rate was found to have lesser effect on cutting temperature, with temperature increase up to 16.89% in response to feed increase from 0.1 to 0.2 mm/rev. This is most likely due to increased feed causing more friction between removed material and cutting tool, increasing system energy and raising cutting temperature. This finding is consistent with prior research by He et al.

With machining under LN_2, cutting temperature is drastically reduced compared to dry and CO_2 machining. LN_2 lowered temperature from 58.43% to 73.53% compared to dry, and from 40.32% to 57.14% compared to CO_2. Another observation is the slowing of LN_2 temperature reduction rate with increasing cutting speed and feed, evidence that LN_2 cooling efficiency decreases at elevated cutting speeds and feed rates. Since LN_2 has lower boiling temperature than CO_2, Pusavec et al. stated that it prevents cutting tool overheating during machining and offers more effective cooling ability.

To verify data in Fig. 8, steps of a simple finite element simulation for evaluation of maximum cutting temperature are given in Figs. 9-11 for dry, LN_2, and CO_2 cooling conditions, respectively. As shown, there is maximum temperature on the contact surface of the cutting tool. Heat generated between tool and chip affects tool performance and machined workpiece surface quality. Friction in the slip zone also affects mechanical properties of machined material and causes tool wear and higher cutting forces due to heat generated in tool, chip-tool, and workpiece contact area. Moreover, the relation between cutting forces and cutting temperature is well explained in Fig. 12 [Figure 12: see original paper].

4.4. Verification of FE Analysis Results by Turning Experiments

Fig. 12 shows graphical comparison of cutting temperature and cutting forces from experimental study and FE analysis. The results are very close to each other and the curves are quite consistent, showing that experimental results verify FE model results with high accuracy.

Based on Fig. 12a-c-e, deviations between FEM and experimental results for cutting temperature average 5.54%, 5.18%, and 8.42% for dry, LN_2, and CO_2 cooling conditions, respectively. Deviations between FEM and cutting force test results in Fig. 12b-d-f average 3.74%, 3.35%, and 3.03% under dry, LN_2, and CO_2 cooling conditions, respectively. In literature, most FE machining studies consider deviation less than about 10% as acceptable between finite element model results and experimental validation, as mentioned by Ozel et al.

After verification of the FE model, possible wear regions of cutting inserts were evaluated for each cutting condition. Fig. 13 [Figure 13: see original paper] shows possible wear regions evaluated by FE model and actual wear regions after experimental turning previously documented by Gupta et al. The experimental and FE images of cutting inserts are also similar with respect to tool wear, further verifying the FE model developed for cryogenic turning of Ti6Al4V alloy.

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5. Comparison of the Results

The most common reasons for deviations between FE model and experimental results are meshing accuracy and friction model, since these parameters are only assumed in the FE model. Another possible reason is that Johnson-Cook parameters adapted for the workpiece material model are obtained from literature. However, mechanical properties of the workpiece material used in this study may differ from the same materials in literature due to different microstructures caused by different manufacturing methods or heat treatments, as thought by Guo et al. Mechanical properties are mainly due to interatomic bond strengths, though internal structure (microstructure) also affects them. This makes it possible to obtain different mechanical properties (tensile, compressive strength, hardness, toughness) in the same material by changing microstructure. Moreover, there may be different tensile strength values for the same material under identical tensile test conditions, which is why the average of 3-5 tensile strength values from identical test situations is generally taken.

Another method for differing microstructure of the same material is precipitation hardening. Abdel-Salam et al. defined precipitation hardening as ensuring the second phase, present in less amount in the material, precipitates in particle form in the main phase, thereby increasing material strength. According to Fu et al., this is one of the most important methods for increasing material strength and is generally used in non-ferrous metal alloys (Al, Ti, Mg). The main reason for strength increase in precipitation hardening is limitation of dislocation movements by precipitates formed from supersaturated melt. However, adapted material in finite element software may behave only according to certain adapted parameters (JC parameters, damage constants, tensile parameters, elastic modulus, etc.). Special conditions within material structure cannot be defined in the software. For this reason, average deviations of 6-7% may be attributed to these circumstances.

Korkmaz et al. investigated cutting force in dry turning of Nimonic 80 alloy both experimentally and with FE model, finding about 6% deviations between results. The researchers commented that deviation may be attributed to both microstructure and hardness of workpiece material, and also to experimental ploughing effect due to smaller depth of cut than tool nose radius. However, it is not possible to model this effect in FE software.

For cryogenic conditions, heat transfer coefficients are assumed constant in FE software. Wang et al. thought that cutting and cooling is a thermodynamic process and should actually be modeled dynamically or temperature-dependently, but Zimmerschied and Isermann demonstrated that this would take excessive time to solve simple FE simulations in cryogenic conditions. Therefore, in this FE study, heat transfer coefficients and cooling temperatures of LN_2 and CO_2 cryogens were adapted as constant. This issue may contribute to deviations between FE model and experimental results in cryogenic conditions.

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6. Conclusions

This study focused on dry turning and LN_2/CO_2 cooling assisted turning of Ti6Al4V and simulation of this process by finite element method modeling. The aim was to verify FEM simulation with experimental turning process and show estimation of obtainable machining results. Prominent findings are summarized as follows:

- Cutting force increased with cutting speed. The increase versus cutting speed was associated with strain hardening. Depending on cutting speed increase, cutting force increased between 16.56% and 23.70% at 0.1 mm/rev feed, between 18.24% and 28.17% at 0.15 mm/rev feed, and between 14.23% and 26.36% at 0.20 mm/rev feed. Additionally, feed increase triggered cutting force increase ranging from 6.72% to 23.11%.
- The cutting environment offering lowest cutting force for each cutting parameter is LN_2 cooling, followed by CO_2 and dry environments. Compared to dry cutting, 21.01% to 34.95% less cutting force can be achieved with LN_2 assisted cutting. CO_2 assisted cutting can provide improvement up to 14.41%.
- Cutting speed had upward effect on temperature varying between 23.61% and 81.25% depending on feed rate and cutting environment. Feed rate had lesser effect on cutting temperature, with temperature increase up to 16.89% in response to feed increase from 0.1 to 0.2 mm/rev.
- LN_2 machining drastically reduced cutting temperature compared to dry and CO_2 machining. LN_2 lowered temperature from 58.43% to 73.53% compared to dry, and from 40.32% to 57.14% compared to CO_2. The LN_2 temperature reduction rate slowed with increasing cutting speed and feed, evidence that LN_2 cooling efficiency decreases at high cutting speeds and feed rates.
- Experimental results verified FE model results with high accuracy. Deviations between FE modeling and experimental results for cutting temperature averaged 5.54%, 5.18%, and 8.42% for dry, LN_2, and CO_2 cooling conditions, respectively. Deviations between FE modeling and cutting force test results were 3.74%, 3.35%, and 3.03% under dry, LN_2, and CO_2 cooling conditions, respectively.
- Although deviation between experimental and FE model results is within acceptable limits, complete agreement is not possible. Since heat transfer coefficients and cooling temperatures of LN_2 and CO_2 cryogens were adapted as constant, this may contribute to deviations between FE model and experimental results in cryogenic conditions.
- This research will help research & development centers in machining industries, especially those working on improvement of cooling technologies in machining of biomedical materials.

CRediT Authorship Contribution Statement

Munish Kumar Gupta: Investigation, Formal analysis, Conceptualization, Writing –review & editing.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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