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Abstract

Aluminium alloys are widely utilized in modern engineering applications such as automotive and aerospace industries due to their advantageous properties. However, machining of these alloys is considered challenging owing to their adhesive and soft nature, low thermal conductivity, and strain-hardening effects. While cooling conditions applied in the cutting zone can enhance machining performance, experimental machining trials necessitate significant resources, material consumption, and skilled labor. Therefore, simulation of process parameters using Finite Element Modelling (FEM) during machining has emerged as a highly active research domain. In this study, FEM simulation was conducted using AdvantEdge software as a novel measurement science approach, and prediction models were developed to evaluate cutting forces and cutting temperatures in machining of AA2024-T351 alloy under dry, liquid nitrogen (LN2), and carbon dioxide (CO2) conditions. Initially, a 3D turning model was established and validated against experimental results. The simulation outcomes showed close agreement with experimental data, with a minimum deviation of 0.67 (5.7%) for cutting forces and 4.58 (6.16%) for cutting temperature. Thus, it is noteworthy that the 3D FE model is efficient and effective for predicting measurement results with minimal error.

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Cutting forces and temperature measurements in cryogenic assisted turning of AA2024-T351 alloy: An experimentally validated simulation approach

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Keywords: Aluminum alloy, Cooling conditions, Cutting forces, Cutting temperature, Machining, Simulation

Abstract

Aluminium alloys are widely used in modern engineering applications such as automobile and aerospace industries because of their favorable characteristics. However, the machining of aluminium alloys is considered difficult due to their sticky and soft nature, low thermal conductivity, strain hardening effects, and other factors. While cooling conditions employed at the cutting zone can improve machining performance, they require significant resources, material consumption, and skilled labor for experimental implementation. Therefore, simulation of process parameters using Finite Element Modelling (FEM) during machining has become a highly researched topic. In this work, a novel approach from measurement science—FEM simulation—was performed with AdvantEdge software, and prediction models were developed for evaluating cutting forces and cutting temperature while machining AA2024-T351 alloy under dry, liquid nitrogen (LN_2), and carbon dioxide (CO_2) conditions. Initially, a 3D turning model was developed and the results were compared with experimental findings. The simulation results showed very close agreement with experimental data, with minimum standard values of 0.67 (5.7%) for cutting forces and 4.58 (6.16%) for cutting temperature. Thus, it is worthy to mention that the 3D FE model is efficient and effective for predicting measurement results with minimal error.

1. Introduction

Aluminum is one of the most used materials in engineering after steel and cast iron [?]. In particular, Al-Cu alloys are increasingly employed in aircraft and automotive industries due to their low density (2.7 gm/cm^3), higher strength (18-26 kg/mm^2) compared to other Al alloys, and heat treatment applicability [?, ?]. In general, metal materials are not used in their natural state as they have low mechanical properties (hardness, rupture strength, wear resistance, etc.) in their pure form, such as pure aluminum.

Various methods are applied to improve the mechanical properties of materials, with alloying and heat treatment being common approaches [?]. AA2024-T351 is produced by adding alloying elements to pure aluminum and then tempering via the T351 process, which means solution heat-treated and stress-relieved with a controlled amount of stretching [?].

In addition to the positive aspects of enhanced mechanical properties, there are also negative consequences. Mechanical properties directly affect material shaping processes (machining, cutting, bending, etc.) [?]. Material shaping by chip removal (turning, milling, drilling, etc.) represents a significant portion of the manufacturing industry [?]. Machinability is of great importance regarding cutting tools, cutting forces, and surface roughness [?]. Recent studies have categorized materials as either easy to machine or difficult to cut [?]. The machinability of a material depends directly on its mechanical properties (flow stress, rupture strength, hardness, etc.) and cutting parameters. Materials with high mechanical properties (e.g., high hardness) are difficult to process, while those with lower properties may be easier to machine. Processing materials with high mechanical properties may generate higher cutting forces and consequently higher temperatures [?]. Although machining materials with low mechanical properties might seem problem-free regarding cutting forces and tool wear, some materials can cause issues such as chip adhesion on the cutting insert and deterioration of surface quality. Especially in machining aluminum alloys under dry cutting conditions, negative effects such as deterioration of the machined surface due to Built-up-Edge (BUE) formation and increased cutting forces are frequently observed [?]. Apart from material properties, improperly selected cutting parameters (cutting speed, feed, depth of cut, etc.) can also cause negative effects such as increased cutting forces, reduced tool life, and poor surface roughness [?, ?]. For these reasons, cryogenic cooling processes are needed to avoid these negativities in machining aluminum alloys [?, ?]. In cryogenic cooling, materials are cooled to very low temperatures (around -196°C) to achieve desired metallurgical and microstructural properties [?, ?].

Temperature reduction is possible by feeding the system with controlled liquid nitrogen (N_2) or CO_2 and using suitable insulation materials [?, ?]. Important studies on cryogenic cooling in machining various alloys are summarized below.

Chetan et al. [?] analyzed the tribological performance of Ti6Al4V alloy under wet and cryogenic cooling conditions, concluding that cryogenic cooling is superior to wet conditions based on tool wear, carbon emissions, and machining cost. Ding and Hong [?] studied cryogenic machining of AISI1008 steel, considering tool wear, temperature, and surface quality, finding cryogenic processing superior for better surface quality and reduced tool temperature and wear. Sivaiah and Chakradhar [?] examined the machinability of 17-4 PH stainless steel with coated carbide tools under cryogenic conditions, indicating that cryogenic cooling successfully decreases cutting zone temperature and can be recommended for difficult-to-cut materials. Jebaraj et al. [?] compared LN_2 and CO_2 coolants in cryogenic machining of AISI L6 steel using TiAlN coated carbide tools, suggesting CO_2 coolants are better for surface quality while LN_2 is superior regarding cutting forces. Khanna et al. [?] associated dry, flood, MQL, and cryogenic cooling conditions in machining stainless steel with carbide inserts, revealing that cryogenic cooling is superior to MQL in terms of surface quality, energy consumption, and tool wear. Outerio et al. [?] researched surface integrity in turning AZ31B-O magnesium alloy under dry and cryogenic conditions, showing cryogenic cooling is better than dry conditions based on cutting forces. Kaynak [?] evaluated machinability of Inconel718 under dry, MQL, and cryogenic conditions, finding cryogenic the best for tool wear and cutting zone temperature, while MQL was best for surface quality. Eapen et al. [?] studied dry and cryogenic machining of AA6063 aluminum alloy, concluding that cryogenic conditions are more suitable than dry conditions for higher surface quality.

As mentioned above, these experimental studies are costly, wasteful of materials, and not eco-friendly. Therefore, numerical methods have been suggested for the research field, with the finite element method being the most widely used in machining processes. The finite element (FE) method is a popular and effective approach for solving complicated problems in various engineering applications [?]. Complex engineering problems involve complex solutions that can distract from solution sensitivity. The finite element method can solve complex problems in the shortest way with results closest to the correct solution. Main finite element software used in the machining industry includes DEFORM 3D, LS-Dyna, ABAQUS, and Thirdwave AdvantEdge. Several critical studies on FE machining of aluminum alloys are summarized below.

Li et al. [?] verified a finite element model of high-speed machining with AA6061-T6 aluminum alloy, confirming the Johnson-Cook model parameters previously determined experimentally under high strain rates. Mali et al. [?] validated simulated cutting forces with experimental results by performing dry turning of AA7075 aluminum alloys, also comparing and confirming tool wear, chip behavior, and stresses on cutting inserts from the FE model. Lima et al. [?] compared cutting temperatures between FE and experimental results in milling AISI D2 steel using thermocouple methods, finally verifying the FE model experimentally. Baraheni et al. [?] developed a FE model for ultrasonic drilling of 7075 aluminum alloy, verifying it through experimental drilling tests with higher than 80% accuracy. Khajehzadeh et al. [?] compared experimental and FE results for ultrasonic turning of AISI 4140 steel, verifying FE thrust forces and residual stress via experimental drilling tests with 91% and 87% accuracy, respectively. Huang et al. [?] created a FE model for high-speed milling of aluminum 7075 alloy and confirmed the model with experimental milling processes under the same conditions with high accuracy.

It is evident that studies on FE machining based on cryogenic cooling conditions for AA2024-T351 alloy are very limited in the literature. Although this alloy is highly used in aerospace applications, work on simulation under different cooling conditions remains quite limited. Therefore, the purpose of this research is to develop a FE model based on dry and LN_2/CO_2 cryogenic turning and evaluate machinability performance in terms of cutting forces and cutting temperature for AA2024-T351 alloy. Moreover, the main aim is to contribute to solving important problems mentioned in related manufacturing research. It is observed that differences exist in cooling techniques used between scientific research and manufacturing. In this regard, the results of this study are intended to be directly applicable to both manufacturing and scientific research. Initially, the 3D cryogenic model was developed with FEM practice and responses were predicted. Then, comparison was made with experimental results. The complete analysis of this work is shown in the following sections.

2. Formulation of 3D Cryogenic Assisted Johnson-Cook Turning Model

2.1. Introduction of FE Model

One of the most widely used solutions in recent years is finite element analysis, which divides complicated systems into particles, transforms them into idealized structures, and solves them mathematically [?]. For derivatives of finite elements, which are subcomponents of approximation functions, the finite element approach follows specific procedures [?]. The numerical solution procedure for parameters at specific points is defined as the nodes of each element and is applied to compute finite solutions when determining the solution for the entire geometry [?]. Finite element analysis (FEA) is considered an effective method for solving problems that are difficult or impossible to solve analytically [?]. The initial stage in finite element analysis is to discretize the geometry, after which the geometry is split into finite elements. The Arbitrary Lagrangian-Eulerian (ALE) mesh does not fix points on the geometry surface to the material or to a specific region; instead, it is based on arbitrary movement of points, making material flow point-independent. Compared to other mesh topologies, ALE produces better outcomes [?]. ALE network algorithms are used in multiple software packages to solve metal cutting problems, including ABAQUS, DEFORM, Third Wave AdvantEdge, and ANSYS LS-DYNA, from which users obtain very good results. The re-meshing technique employed in several software packages helps further reduce errors in the analysis [?].

Tetrahedral meshes used in this FE study are utilized in various applications, including fracture analysis, haptics, solid modeling, surgical simulations, and modeling of biological tissue such as brain, knee, and adipose tissue, as well as machining simulations. To analyze chip formation using the finite element method in machining operations, certain boundary conditions need to be defined [?]. The entered boundary conditions play an active role in defining limits and loading conditions to solve the problem. It is feasible to simulate chip formation by selecting the right modeling approach, establishing boundary conditions, calculating material deformation rate, and understanding how the workpiece material will react during plastic deformation [?]. The strain rate and heat effects of the constitutive equations must be set to define the model's dynamic behavior [?]. In metallic materials, stress, strain, and strain rate vary with temperature [?]. One of the most important models considering strain and heat effects in metallic materials is the Johnson-Cook (JC) constitutive model [?]. Moreover, it is possible to create material models such as rigid-plastic, elastic-plastic, thermo-elastoplastic, and thermo-viscoplastic using these models [?]. The Johnson-Cook constitutive model employed by Third Wave AdvantEdge [?] can be seen in Eq. (1).

σ_0 = (A + B( )^n) 1 + Cln 1 (cid:0) T (cid:0) Tr Tm (cid:0) Tr

In Eq. (1), σ_0, , ˙ , ˙ $_0$, T, Tm, and Tr represent flow stress, plastic deformation, deformation rate, reference plastic deformation rate, workpiece temperature, workpiece melting temperature, and room temperature, respectively. The coefficients A, B, C, n, and m represent yield strength in MPa, hardness modulus in MPa, strain rate sensitivity coefficient, hardness coefficient, and thermal softening coefficient, respectively [?]. Additionally, a damage model is needed for chip separation. For equivalent fracture strain, the JC damage model [?] is used as seen in Eq. (2).

D$_1$ + D$_2$exp(D$_3$ 1 + D$_4$ln 1 + D$_5$ T (cid:0) Tr Tm (cid:0) Tr

Here, stress triaxiality is represented by P/σ, where P refers to hydrostatic pressure, which is the mean of three-dimensional normal stresses. f denotes the fracture strain experienced at chip separation, which is part of dynamic metal cutting processes. In addition, D$_1$, D$_2$, D$_3$, D$_4$, and D$_5$ are constants for 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]. The 3D nose turning method shown was preferred for the turning process. Fig. 1 illustrates the overall geometric framework for finite element analysis using Third Wave AdvantEdge.

2.2. Workpiece and Cooling Condition Details

The appropriate transfer of the material model to the software is critical for successful numerical analysis of machining. For this reason, correct determination of material properties and their adaptation as inputs reflects modeling success. In the present study, AA2024-T351 workpiece material with dimensions of 1$×1×$3 mm was used for finite element analysis. The JC parameters are shown in Table 1 , fracture constants in Table 2 , chemical composition in Table 3 , and mechanical and thermal properties of AA2024-T351 alloy in Table 4 .

As illustrated in Fig. 2 [Figure 2: see original paper], the cutting tool was a CVD coated TiC-Al_2O_3-TiN carbide insert (each presumed to be 1 m thickness

[?]) with an ISO designation of CNMG 120408. Table 5 lists the characteristics of the utilized carbide cutting insert.

Cryogenic basically refers to very low temperatures [?]. Although several assumptions exist, the temperature that separates cryogenic from ordinary cooling is usually regarded as -150°C. Based on this assumption, cryogens with boiling temperatures above -150°C, used in local cooling such as air conditioning and freezers, are classified as conventional coolers, whereas cryogens with boiling temperatures below -150°C, such as hydrogen, CO_2, and LN_2, are classified as non-conventional coolers. When studying systems operating at cryogenic temperatures, it is important to remember that materials' thermal characteristics fluctuate with temperature. For heat transfer calculations at cryogenic temperatures, specific heat, thermal conductivity, and notably heat transfer coefficient values for gases and liquids are significant thermal characteristics. Eq. (3) gives the formula for calculating heat transfer per unit time (Q) [?].

$$Q = Cv \times m \times (dT/dt)$$

Here, Cv, m, and dT/dt represent specific heat, mass, and cooling rate $(T_2\text{-}T_1)/(t_2\text{-}t_1)$, respectively. By substituting “$m = A\times\delta\times$ ” in Eq. (4):

$$Q = Cv \times A \times \delta \times \quad \times (dT/dt)$$

The heat flux density “q” can be obtained from “Q/A” . Therefore, as a result of Newton’ s heat transfer rules, Eq. (3) takes the form of Eq. (5):

$$q = \quad \times Cv \times \delta \times (dT/dt)$$

In Eq. (6), “h” represents the heat transfer coefficient in W/m^2K, and Tw and Tf indicate the surface temperature and cryogen temperature of LN_2 (-196.5°C) and CO_2 (-78.5°C), respectively. Additionally, as illustrated in Fig. 3 [Figure 3: see original paper], the heat transfer coefficients for LN_2 and CO_2 were inputted as 309 W/m^2K and 165 W/m^2K [?].

2.3. Meshing Details

The mesh structure used in finite element analysis has a significant impact on final findings [?]. The basic objective is to create a mesh structure that accurately reflects the geometry. The density of finite elements is an important metric for determining study correctness, and accuracy is also influenced by element type and morphology. Assuming no singularity area exists in the model, greater mesh density provides highly precise results. However, extremely dense element meshes require large amounts of computer memory and lengthy execution times, especially prevalent in nonlinear and transitional analysis with many recurring circumstances. One method for evaluating finite element mesh quality is comparing results to test data or theoretical values, though these are typically unavailable in early research stages. Consequently, new tools for evaluating mesh quality are necessary, with mesh sensitivity analysis being the most significant. In this paper, mesh sensitivity analysis using the re-meshing approach provided in Table 6 was used to reduce the minimum element size for the workpiece and cutting tool to 0.15 mm. The software ran on a machine with 16 GB RAM, 6 GB client cache, and a CPU speed of 2.4 GHz. To solve FE analysis faster, all 8 cores were employed for parallel processing. Initially, element sizes of 1, 0.5, and 0.25 mm were utilized, yielding cutting forces of 105.7, 95.9, and 87.2 N, respectively, with computation times of 0.6, 1.3, and 3.8 hours. Due to greater changes in cutting forces relative to small computation time differences, the element size was reduced. Subsequently, element size was gradually decreased to 0.1 mm. Although the difference in cutting force became negligible, calculation time increased by approximately 84%. As a result, the element size was set to 0.15 mm for basic test simulation with a computing time of 6.1 hours, as shown in Table 6.

2.4. Friction Model Details

The Coulomb friction model can provide accurate results on the tool flank face in FE simulations of the turning process [?]. In the present investigation of orthogonal turning, the average friction coefficient ( ) between tool and chip was assumed as 0.45. Fig. 4 [Figure 4: see original paper] depicts the standard flow chart for FE simulations.

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3. Results and Discussions

In this simulation study, 3D turning was analyzed and a new finite element model was developed with Thirdwave AdvantEdge software using the process parameters and boundary conditions detailed above. Simulation results are presented below.

3.1. Analysis of Predicted Cutting Forces

Determination of cutting forces is very important for machine tool design. Cutting parameters, workpiece material, cutting tool properties, and cutting environment are the most basic factors that significantly affect cutting force values [?]. Moreover, cutting forces are helpful for estimating cutting power, surface roughness, and tool wear values. Therefore, minimum cutting forces are required in all machining operations to obtain sound machining characteristics. Finite element analysis results of cutting forces and their influences are presented graphically in Fig. 5 [Figure 5: see original paper].

In general, FEM-obtained cutting force variations tended to be similar for all cutting media and increased with increasing feed rate. This result can be associated with increased contact area at the tool-chip interface and removal of more material per unit time, as stated in Refs. [?, ?]. It is also thought that increasing friction in the feed direction contributes to cutting force increases [?]. However, lower cutting forces in LN_2 and CO_2 environments can be explained by decreased negative effects of friction in the second deformation zone. Thanks to the cooling and lubricating effects of LN_2 and CO_2 gases, minimum BUE and sticking zones resulted in lower cutting forces. On the other hand, contrary to expectations, cutting forces increased with increasing cutting speed in FEM simulations. This can be explained by metallurgical changes occurring with thermo-mechanical effects during material deformation. Increased heat during deformation can cause both strain hardening and softening effects in the workpiece. When the shear rate is not high enough to cause thermal softening, the strain hardening effect exceeds the softening effect, leading to increased material strength and consequently increased shear forces. Similar observations were made by Hou et al. [?] and Shi et al. [?]. Moreover, Paresi et al. [?] proved that the strength of AA2024-T351 material increased due to strain hardening up to 200°C at high deformation rates.

From Fig. 5, the minimum cutting forces were determined under LN_2 cooling, followed by CO_2 and dry environments. Liquid nitrogen cooling reduces forces up to 5.05% and carbon dioxide reduces forces up to 1.58% compared with dry machining. This may be attributed to the fact that low cutting temperatures under liquid nitrogen cooling improve cutting tool hardness with lower tool wear, resulting in less adhesion at the tool-chip interface [?]. Another factor is that liquid nitrogen' s boiling temperature is significantly lower than carbon dioxide' s, preventing workpiece and tool material from overheating [?]. Additionally, liquid nitrogen absorbs heat very quickly and provides good lubrication at the cutting zone [?].

3.2. Analysis of Predicted Cutting Temperature

To examine machining performance, it is very important to determine temperature at the cutting zone during machining operations. Aluminum is as soft as titanium alloy but has low thermal conductivity [?], resulting in higher cutting temperatures at the cutting zone. The poor thermal conductivity of Al alloys means that only 20% of generated heat is removed from the machining area [?]. Fig. 5 also demonstrates FEM results of cutting temperature while machining aluminum alloy under different cooling conditions. During machining of soft materials like aluminum alloys, heat is not evacuated from the cutting zone, causing built-up edge formation to accelerate with increasing cutting speed [?]. Similarly, feed rate is a dominant factor affecting cutting temperature values, and when feed rate increases, cutting temperature also increases up to 10%. This can be attributed to greater feed promoting energy in the system and producing more friction between the machined workpiece material and cutting insert, supporting literature findings [?, ?].

On the other hand, cutting temperature values are lower with carbon dioxide cooling because when CO_2 is transferred to the tool-chip contact area, the cryogenic liquid absorbs heat and dissipates quickly from the region, which is the main factor in further lowering cutting temperature. Therefore, temperature drops under CO_2 conditions were observed from 11% and 26% respectively compared with LN_2 and dry environments. This also evidences that CO_2 cooling efficiency decreases at elevated cutting speeds and feed rates. Moreover, application of both cryogenic cooling conditions helps break chips into small pieces. With this phenomenon, chip rubbing against the cutting tool is reduced, generating less friction at the tool-chip interface as mentioned by Danish et al. [**?**]. Hence, temperature is reduced compared with dry machining. The complete mechanism of chip breakage is also shown in Fig. 6 [Figure 6: see original paper].

3.3. Verification of FE by Turning Experiments

3.3.1. Experimental Procedure for Verification The simulation was carried out under the same experimental test conditions. Machining of commercially available AA2024-T351 alloy was performed using CVD TiCn-Al_2O_3-TiN coated carbide cutting tools with ISO designation CNMG 120408. The workpiece had a diameter of 30 mm and length of 100 mm. To reduce work hardening effects, the first 0.5 mm layer was removed. The tool had a 0.8 mm nose radius and a side cutting edge angle (principal cutting angle) of 90°. Actual tests were carried out under the same conditions as FE simulations using a CNC lathe machine. Table 7 lists the machine tool and cryogenic cooling system characteristics. Process parameter levels were chosen using a tool manufacturer' s handbook and preliminary tests. The experimental design is shown in Annexure 1. During experiments, a depth of cut of 0.5 mm was used and machining time of 60 s was considered.

Table 8 lists the cutting parameters in detail. Cutting temperature and cutting forces were measured using a Fluke thermal camera and Kistler 9257A dynamometer. The thermal camera was positioned at the rake face to measure temperature from the main cutting zone or primary shear zone. During temperature measurements with the thermal camera, the main problem is usually measuring temperature on the outer plane of the flowing chip, whereas the FEM model evaluates direct temperature in the cutting zone. Thus, comparing temperatures measured in distinct zones is difficult. To address this, temperatures were initially measured and calibrated with simulation results, and overall cutting temperature values during machining experiments were considered for comparison. All measurements were taken five times and average values were used for analysis. Measurements were performed online and Dynoware software was used to transfer cutting force data to computer. Fig. 7 [Figure 7: see original paper] depicts the study' s overall flow diagram.

3.3.2. Analysis of Results The experimental, simulation, and deviation results are shown in Figs. 8 and 9. From Fig. 8 [Figure 8: see original paper] (a)-(c), Fc values obtained with FEM are relatively larger than experimental data when the feed rate is 0.2 mm/rev. This can be explained by pressure formed in the second deformation zone as feed increases. Segmented chip formation [**?**] increases with feed, raising pressure created by friction at the tool-chip interface and thus increasing cutting forces. When experimental and numerical results are examined, the cutting medium offering the lowest cutting forces is LN_2 cooling, followed by CO_2 and dry environments. The lowest cutting force was found at 0.1 mm/rev feed, 100 m/min cutting speed, and LN_2 cutting environment. Compared to dry cutting, an average of 8.8% less cutting force was obtained in LN_2 assisted machining and 4.4% less in CO_2 assisted machining. Additionally, experiment run #4 (cutting speed of 150 m/min, feed rate of 0.20 mm/rev, dry conditions) shown in Fig. 8(c) provides the minimum standard deviation value of 0.67 and average deviation of 5.71. Therefore, it is worthy to mention that the simulation model developed for cutting forces is very close to experimental values. Hence, the developed model is suitable for predicting cutting forces under specified cutting conditions.

Similarly, experimental, simulation, and standard deviation values of cutting temperature are shown in Fig. 9 [Figure 9: see original paper] (a)-(c). Cutting temperatures obtained in experimental and FEM simulation remain within the temperature threshold mentioned in the literature. When compared across cutting media, the highest increase in cutting temperature with increasing cutting speed is 22°C in LN_2 and CO_2 cutting environments. When cutting temperatures are compared experimentally and numerically, the smallest temperature value was obtained in the CO_2 environment at the lowest feed and cutting speed. In light of all evaluations, average deviations of 5.7% and 6.16% between experimental and cutting simulations for cutting force and cutting temperature, respectively, indicate the suitability of the JC material model, coefficient of friction, and FEM simulations. In literature, most FE machining studies consider deviation less than about 10% as acceptable between finite element model results and experimental validation [**?**, **?**]. Additionally, experiment run #11 (cutting speed of 100 m/min, feed rate of 0.20 mm/rev, CO_2 cooling conditions) shown in Fig. 9(c) provides the minimum standard deviation value of 4.58 and average deviation of 6.16. Therefore, it is worthy to mention that the simulation model developed for cutting temperature is very close to experimental values. Hence, the developed model is suitable for predicting cutting temperature under specified cutting conditions.

3.3.3. Discussion and Comparison of Results During comparison of FEM and experimental results, development of the friction model and meshing accuracy plays an important role. Apart from these, selection of Johnson-Cook parameters that specifically match material properties is highly important for obtaining accurate results. However, the mechanical features, microstructure, and other characteristics of the workpiece material employed in this study may differ from those reported in literature for the same material [**?**]. The strength of interatomic connections is primarily responsible for mechanical qualities, and the material' s microstructure has a major impact. Different mechanical properties such as tensile strength, compressive strength, hardness, and toughness of the same material can be achieved by modifying the microstructure [**?**]. Additionally, the same material can have different tensile strength values, which is why researchers consider the average of 4-5 tensile strength values from the same test situation [?, ?]. Moreover, precipitation hardening properties play an active role in differentiating the texture of same materials. Material strength increases because particles separate from the main phase [?]. This process is mostly used to increase strength of non-ferrous materials such as Ti, Al, and Mg [?]. The prevention of displacement movement of precipitates created by supersaturated melts is the major explanation for enhanced strength with precipitation hardening.

However, compatible material in finite element software can behave similarly using certain parameters such as JC inputs, constants, tensile parameters, Young' s modulus, etc. No special conditions can be defined for material structure in certain software. Therefore, a mean deviation of 5-6% can be due to these factors. It was emphasized by [?] that deviation can be caused by less accurate engagement and friction models. Similar findings were reported by Korkmaz et al. [?], with researchers attributing inconsistency to both structure and hardness of the workpiece material. Additional reasons include the depth of cut being less than the radius of the cutting edge, which FE software cannot model. Under cryogenic conditions, the heat transfer coefficient is assumed constant. Since cutting and cooling is a thermodynamic process, it should be modeled dynamically [?] or as a function of temperature [?]. However, solving a simple FE simulation under cryogenic conditions can be very time-consuming, which is why heat transfer coefficients are kept constant.

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4. Conclusions

This study focuses on the AA2024-T351 turning process under LN_2/CO_2 cooling and uses FEM to model this process. The purpose is to analyze the extent to which widely adopted LN_2/CO_2 cooling technology performs its intended function to meet requirements for sustainable processing. Additionally, based on FEM data, this study aims to validate the FEM simulation through experimental turning processes. The main results can be summarized as follows:

- Liquid nitrogen cooling lowers cutting forces up to 5.05% and carbon dioxide cooling reduces cutting forces up to 1.58% compared with dry conditions.
- When CO_2 is injected into the tool-chip contact region, it absorbs heat and evaporates rapidly from the area, causing cutting temperature to drop. CO_2 produces the lowest cutting temperature compared to LN_2 and dry environments by 11% and 26%, respectively. This evidences that CO_2 cooling efficiency decreases at elevated cutting speeds and feed rates.
- The lowest cutting force was found at 0.1 mm/rev feed, 100 m/min cutting speed, and LN_2 cutting environment. Compared to dry cutting, an average of 8.8% less cutting force was obtained in LN_2 assisted machining and 4.4% less in CO_2 assisted machining.

- The highest increase in cutting temperature with increasing cutting speed is 22°C in LN_2 and CO_2 cutting environments. When cutting temperatures are compared experimentally and numerically, the smallest temperature value was obtained in the CO_2 environment at the lowest feed and cutting speed.
- In light of all evaluations, average deviations of 5.7% and 6.16% between experimental and cutting simulations were observed, indicating the suitability of the JC material model, coefficient of friction, and FEM simulations.

CRediT Authorship Contribution Statement

Munish Kumar Gupta: Investigation, Formal analysis, Conceptualization, Writing –review & editing.
Mehmet Erdi Korkmaz: Investigation, Formal analysis, Conceptualization, Writing –review & editing.
Murat Sarıkaya: Investigation, Formal analysis, Conceptualization, Writing –review & editing.
Grzegorz M. Krolczyk: Conceptualization, Writing –review & editing, Supervision.
Mustafa Günay: Conceptualization, Writing –review & editing, Supervision.
Szymon Wojciechowski: Conceptualization, Writing –review & editing, Supervision.

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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Appendix A

Exp. No.	Cutting speed, vc (m/min)	Feed, f (mm/rev)	Cooling Conditions

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References

[1] H.A. Al-Tameemi, T. Al-Dulaimi, M.O. Awe, S. Sharma, D.Y. Pimenov, U. Koklu, K. Giasin, Evaluation of cutting-tool coating on the surface roughness and hole dimensional tolerances during drilling of Al6061-T651 alloy, Mater. 14 (2021), https://doi.org/10.3390/ma14071783.
[2] M. Sánchez-Carrilero, J.M. Sánchez-Sola, J.M. González, J.P. Contreras, M. Marcos, Cutting forces compatibility based on a plasticity model: application to the oblique cutting of the AA2024 alloy, Int. J. Mach. Tools Manuf 42 (5) (2002) 559–565, https://doi.org/10.1016/S0890-6955(01)00157-2.
[3] G. List, M. Nouari, D. Géhin, S. Gomez, J.P. Manaud, Y. Le Petitcorps, F. Girot, Wear behaviour of cemented carbide tools in dry machining of aluminium alloy, Wear 259 (7-12) (2005) 1177–1189, https://doi.org/10.1016/j.wear.2005.02.056.
[4] H.-S. Kim, J. Chen, H.B. Lee, J.H. Shin, B.S. Kong, S. Oh, H. Jang, C. Jang, Effect of heat treatment on grain boundary carbides and primary water stress corrosion cracking resistance of Alloy 182 weld, Corros. Sci. (2021) 109730, https://doi.org/10.1016/j.corsci.2021.109730.
[5] Q. Sun, X. Liu, Q. Han, J. Li, R. Xu, K. Zhao, A comparison of AA2024 and AA7150 subjected to ultrasonic shot peening: microstructure, surface segregation and corrosion, Surf. Coatings Technol. 337 (2018) 552–560, https://doi.org/10.1016/j.surfcoat.2018.01.072.
[6] A. Iqbal, H. Suhaimi, W. Zhao, M. Jamil, M.M. Nauman, N. He, J. Zaini, Sustainable milling of Ti-6Al-4V: investigating the effects of milling orientation, cutter helix angle, and type of cryogenic coolant, Metals (Basel). 10 (2020), https://doi.org/10.3390/met10020258.
[7] M. Kurt, Y. Kaynak, E. Bagci, Evaluation of drilled hole quality in Al 2024 alloy, Int. J. Adv. Manuf. Technol. 37 (2008) 1051–1060, https://doi.org/10.1007/s00170-007-1035-7.
[8] A.T. Abbas, D.Y. Pimenov, I.N. Erdakov, M.A. Taha, M.M. El Rayes, M.S. Soliman, Artificial intelligence monitoring of hardening methods and cutting conditions and their effects on surface roughness, performance, and finish turning costs of solid-state recycled aluminum alloy 6061 chips, Met. 8 (2018), https://doi.org/10.3390/met8060394.
[9] A. Shokrani, V. Dhokia, S.T. Newman, Environmentally conscious machining of difficult-to-machine materials with regard to cutting fluids, Int. J. Mach. Tools Manuf. 57 (2012) 83–101, https://doi.org/10.1016/j.ijmachtools.2012.02.002.
[10] S. Sun, M. Brandt, M.S. Dargusch, Thermally enhanced machining of hard-to-machine materials—a review, Int. J. Mach. Tools Manuf 50 (8) (2010) 663–680, https://doi.org/10.1016/j.ijmachtools.2010.04.008.
[11] M.S. Carrilero, R. Bienvenido, J.M. Sánchez, M. Alvarez, A. González, M.

Marcos, A SEM and EDS insight into the BUL and BUE differences in the turning processes of AA2024 Al–Cu alloy, Int. J. Mach. Tools Manuf. 42 (2) (2002) 215–220, https://doi.org/10.1016/S0890-6955(01)00112-2.

[12] I. Puertas Arbizu, C.J. Luis Pérez, Surface roughness prediction by factorial design of experiments in turning processes, J. Mater. Process. Technol. 143-144 (2003) 390–396, https://doi.org/10.1016/S0924-0136(03)00407-2.

[13] M. Nouari, G. List, F. Girot, D. Géhin, Effect of machining parameters and coating on wear mechanisms in dry drilling of aluminium alloys, Int. J. Mach. Tools Manuf. 45 (12-13) (2005) 1436–1442, https://doi.org/10.1016/j.ijmachtools.2005.01.026.

[14] M. Danish, T. Ginta, B.A. Wahjoedi, Enhanced functional properties of Mg alloys by cryogenic machining, Int. J. Appl. Eng. Res. 11 (2016) 5055-5059.

[15] N.S. Kalsi, R. Sehgal, V.S. Sharma, Cryogenic treatment of tool materials: a review, Mater. Manuf. Process. 25 (10) (2010) 1077–1100, https://doi.org/10.1080/10426914.2010.480075.

[16] M. Danish, T.L. Ginta, K. Habib, A.M. Abdul Rani, B.B. Saha, Effect of cryogenic cooling on heat transfer during turning of AZ31C magnesium alloy, Heat Transf. Eng. 40 (12) (2019) 1023-1032, https://doi.org/10.1080/01457632.2018.1461917.

[17] M. Dogra, V.S. Sharma, A. Sachdeva, N.M. Suri, J.S. Dureja, Performance evaluation of CBN, coated carbide, cryogenically treated uncoated/coated carbide inserts in finish-turning of hardened steel, Int. J. Adv. Manuf. Technol. 57 (5-8) (2011) 541–553, https://doi.org/10.1007/s00170-011-3320-8.

[18] M. Danish, T.L. Ginta, A.M. Abdul Rani, D. Carou, J.P. Davim, S. Rubaiee, S. Ghazali, Investigation of surface integrity induced on AZ31C magnesium alloy turned under cryogenic and dry conditions, Procedia Manuf. 41 (2019) 476–483, https://doi.org/10.1016/j.promfg.2019.09.035.

[19] N.S. Kalsi, R. Sehgal, V.S. Sharma, Effect of tempering after cryogenic treatment of tungsten carbide-cobalt bounded inserts, Bull. Mater. Sci. 37 (2) (2014) 327–335, https://doi.org/10.1007/s12034-014-0634-9.

[20] C. Agrawal, J. Wadhwa, A. Pitroda, C.I. Pruncu, M. Sarikaya, N. Khanna, Comprehensive analysis of tool wear, tool life, surface roughness, costing and carbon emissions in turning Ti–6Al–4V titanium alloy: Cryogenic versus wet machining, Tribol. Int. 153 (2021) 106597, https://doi.org/10.1016/j.triboint.2020.106597.

[21] S.Y. Hong, Y. Ding, Micro-temperature manipulation in cryogenic machining of low carbon steel, J. Mater. Process. Technol. 116 (1) (2001) 22–30, https://doi.org/10.1016/S0924-0136(01)00836-6.

[22] P. Sivaiah, D. Chakradhar, Performance improvement of cryogenic turning process during machining of 17-4 PH stainless steel using multi-objective optimization techniques, Measurement 136 (2019) 326–336, https://doi.org/10.1016/j.measurement.2018.12.094.

[23] M. Jebaraj, M. Pradeep Kumar, R. Anburaj, Effect of LN_2 and CO_2 coolants in milling of 55NiCrMoV7 steel, J. Manuf. Process. 53 (2020) 318-327, https://doi.org/10.1016/j.jmapro.2020.02.040.

[24] N. Khanna, P. Shah, Chetan, Comparative analysis of dry, flood, MQL

and cryogenic CO_2 techniques during machining of 15-5-PH SS alloy, Tribol. Int. 146 (2020) 106196, https://doi.org/10.1016/j.triboint.2020.106196.

[25] J.C. Outeiro, F. Rossi, G. Fromentin, G. Poulachon, G. Germain, A.C. Batista, Process mechanics and surface integrity induced by dry and cryogenic machining of AZ31B-O magnesium alloy, Procedia CIRP. 8 (2013) 487-492, https://doi.org/10.1016/j.procir.2013.06.138.

[26] Y. Kaynak, Evaluation of machining performance in cryogenic machining of Inconel 718 and comparison with dry and MQL machining, Int. J. Adv. Manuf. Technol. 72 (5-8) (2014) 919-933, https://doi.org/10.1007/s00170-014-5683-0.

[27] J. Eapen, S. Murugappan, S. Arul, A study on chip morphology of aluminum alloy 6063 during turning under pre-cooled cryogenic and dry environments, Mater. Today:. Proc. 4 (8) (2017) 7686-7693, https://doi.org/10.1016/j.matpr.2017.07.103.

[28] D.Y. Pimenov, V.I. Guzeev, Mathematical model of plowing forces to account for flank wear using FME modeling for orthogonal cutting scheme, Int. J. Adv. Manuf. Technol. 89 (9-12) (2017) 3149-3159, https://doi.org/10.1007/s00170-016-9216-x.

[29] S. Li, J. Sui, F. Ding, S. Wu, W. Chen, C. Wang, Optimization of milling aluminum alloy 6061-T6 using modified Johnson-cook model, Simul. Model. Pract. Theory 111 (2021) 102330, https://doi.org/10.1016/j.simpat.2021.102330.

[30] R.A. Mali, M.D. Agrahari, T.V.K. Gupta, FE based simulation and experimental validation of forces in dry turning of aluminium 7075, Mater. Today:. Proc. 27 (2020) 2319-2323, https://doi.org/10.1016/j.matpr.2019.09.120.

[31] H.V. Lima, A.F.V. Campidelli, A.A.T. Maia, A.M. Abrão, Temperature assessment when milling AISI D2 cold work die steel using tool-chip thermocouple, implanted thermocouple and finite element simulation, Appl. Therm. Eng. 143 (2018) 532-541, https://doi.org/10.1016/j.applthermaleng.2018.07.107.

[32] M. Baraheni, A. Bagheri Bami, A. Alaei, S. Amini, Ultrasonic-assisted friction drilling process of aerospace aluminum alloy (AA7075): FEA and experimental study, Int. J. Light. Mater. Manuf. 4 (2021) 315-322, https://doi.org/10.1016/j.ijlmm.2021.03.001.

[33] M. Khajehzadeh, O. Boostanipour, M. Reza Razfar, Finite element simulation and experimental investigation of residual stresses in ultrasonic assisted turning, Ultrasonics 108 (2020) 106208, https://doi.org/10.1016/j.ultras.2020.106208.

[34] X. Huang, J. Xu, M. Chen, F. Ren, Finite element modeling of high-speed milling 7050-T7451 alloys, Procedia Manuf. 43 (2020) 471-478, https://doi.org/10.1016/j.promfg.2020.02.186.

[35] J.-H. Urrea-Quintero, M. Marino, H. Hernandez, S. Ochoa, Multiscale modeling of a free-radical emulsion polymerization process: numerical approximation by the Finite Element Method, Comput. Chem. Eng. 140 (2020) 106974, https://doi.org/10.1016/j.compchemeng.2020.106974.

[36] K.O. Coelho, P.R.B. Devloo, S.M. Gomes, Error estimates for the Scaled Boundary Finite Element Method, Comput. Methods Appl. Mech. Eng. 379 (2021) 113765, https://doi.org/10.1016/j.cma.2021.113765.

[37] N. Yaşar, Thrust force modelling and surface roughness optimization in drilling of AA-7075: FEM and GRA, J. Mech. Sci. Technol. 33 (10) (2019)

4771–4781, https://doi.org/10.1007/s12206-019-0918-5.
[38] K. Gok, Development of three-dimensional finite element model to calculate the turning processing parameters in turning operations, Measurement 75 (2015) 57–68, https://doi.org/10.1016/J.MEASUREMENT.2015.07.034.
[39] S. Savidis, D. Aubram, F. Rackwitz, Arbitrary Lagrangian-Eulerian finite element formulation for geotechnical construction processes, J. Theor. Appl. Mech. 38 (2008) 165–194.
[40] W. Grzesik, Chapter Nine -Heat in Metal Cutting, in: W.B.T.-A.M.P. of M.M. Grzesik (Eds.), Adv. Mach. Process. Met. Mater., second ed., Elsevier, 2017, pp. 163–182. https://doi.org/10.1016/B978-0-444-63711-6.00009-0.
[41] F. Jafarian, M. Imaz Ciaran, D. Umbrello, P.J. Arrazola, L. Filice, H. Amirabadi, Finite element simulation of machining Inconel 718 alloy including microstructure changes, Int. J. Mech. Sci. 88 (2014) 110–121, https://doi.org/10.1016/j.ijmecsci.2014.08.007.
[42] S.K. Mishra, S. Ghosh, S. Aravindan, 3D finite element investigations on textured tools with different geometrical shapes for dry machining of titanium alloys, Int. J. Mech. Sci. 141 (2018) 424–449, https://doi.org/10.1016/j.ijmecsci.2018.04.011.
[43] M.E. Korkmaz, P. Verleysen, M. Günay, Identification of constitutive model refinement induced by dynamic recrystallization of Ti6Al4V alloy during high speed machining, J. Mater. Process. Technol. 286 (2020) 116834, https://doi.org/10.1016/j.jmatprotec.2020.116834.
[44] M.E. Korkmaz, M. Günay, P. Verleysen, Investigation of tensile Johnson-Cook model parameters for Nimonic 80A superalloy, J. Alloys Compd. 801 (2019) 542–549, https://doi.org/10.1016/J.JALLCOM.2019.06.153.
[45] X. Xu, J. Zhang, J. Outeiro, B. Xu, W. Zhao, Multiscale simulation of grain parameters for nimonic 80A superalloy, Trans. Indian Inst. Met. 71 (12) (2018) 2945–2952, https://doi.org/10.1007/s12666-018-1394-9.
[46] X. Xie, G. Kang, Q. Kan, C. Yu, Phase-field theory based finite element simulation on thermo-mechanical cyclic deformation of polycrystalline superelastic NiTi shape memory alloy, Comput. Mater. Sci. 184 (2020) 109899, https://doi.org/10.1016/j.commatsci.2020.109899.
[47] M.E. Korkmaz, N. Yaşar, M. Günay, Numerical and experimental investigation of cutting forces in turning of Nimonic 80A superalloy, Eng. Sci. Technol. an Int. J. 23 (3) (2020) 664–673, https://doi.org/10.1016/j.jestch.2020.02.001.
[48] S.K. Josyula, S.K.R. Narala, Study of TiC particle distribution in Al-MMCs using finite element modeling, Int. J. Mech. Sci. 141 (2018) 341–358, https://doi.org/10.1016/j.ijmecsci.2018.04.004.
[49] B. Haddag, S. Atlati, M. Nouari, A. Moufki, Dry machining aeronautical aluminum alloy AA2024-T351: analysis of cutting forces, chip segmentation and built-up edge formation, Met. 6 (2016), https://doi.org/10.3390/met6090197.
[50] S. Canovic, B. Ljungberg, C. Björnander, M. Halvarsson, CVD TiC/alumina and TiN/alumina multilayer coatings grown on sapphire single crystals, Int. J. Refract Metal Hard Mater. 28 (2) (2010) 163–173, https://doi.org/10.1016/j.ijrmhm.2009.08.001.
[51] M. Du, Z. Cheng, S. Wang, Finite element modeling of friction at the

tool-chip-workpiece interface in high speed machining of Ti6Al4V, Int. J. Mech. Sci. 163 (2019) 105100, https://doi.org/10.1016/j.ijmecsci.2019.105100.

[52] M. Akgün, H. Demir, Optimization of cutting parameters affecting surface roughness in turning of inconel 625 superalloy by cryogenically treated tungsten carbide inserts, SN Appl. Sci. 3 (2021) 277, https://doi.org/10.1007/s42452-021-04249-2.

[53] H. Kaya, O. Uluer, E. Kocaoğlu, V. Kirmaci, Experimental analysis of cooling and heating performance of serial and parallel connected counter-flow Ranquee-Hilsch vortex tube systems using carbon dioxide as a working fluid, Int. J. Refrig. 106 (2019) 297–307, https://doi.org/10.1016/j.ijrefrig.2019.07.004.

[54] M.K. Gupta, Q. Song, Z. Liu, M. Sarikaya, M. Mia, M. Jamil, A.K. Singla, A. Bansal, D.Y. Pimenov, M. Kuntoğlu, Tribological performance based machinability investigations in cryogenic cooling assisted turning of α-β titanium Alloy, Tribol. Int. 160 (2021) 107032, https://doi.org/10.1016/j.triboint.2021.107032.

[55] Y.M. Arisoy, C. Guo, B. Kaftanoğlu, T. Ozel, Investigations on microstructural changes in machining of Inconel 100 alloy using face turning experiments and 3D finite element simulations, Int. J. Mech. Sci. 107 (2016) 80–92, https://doi.org/10.1016/j.ijmecsci.2016.01.009.

[56] Y. Yang, L. Jin, J. Zhu, J. Kong, L. Li, Study on cutting force, cutting temperature and machining residual stress in precision turning of pure iron with different grain sizes, Chin. J. Mech. Eng. 33 (2020) 53, https://doi.org/10.1186/s10033-020-00455-8.

[57] B.N. Pathak, K.L. Sahoo, M. Mishra, Effect of machining parameters on cutting forces and surface roughness in Al-(1-2) Fe-1V-1Si alloys, Mater. Manuf. Process. 28 (4) (2013) 463–469, https://doi.org/10.1080/10426914.2013.763952.

[58] U. Şeker, A. Kurt, İ. Çiftçi, The effect of feed rate on the cutting forces when machining with linear motion, J. Mater. Process. Technol. 146 (3) (2004) 403–407, https://doi.org/10.1016/j.jmatprotec.2003.12.001.

[59] M.A.P. Juárez, E.A. Gómez, H. Plascencia-Mora, E.L. Orozco, J.F.R. Arredondo, M.L.C. Silva, Finite element simulation and experimental analysis of cutting forces in orthogonal turning in AISI-1045 steel, Comput. y Sist. 23 (2019) 7.

[60] J. Hou, W. Zhou, H. Duan, G. Yang, H. Xu, N. Zhao, Influence of cutting speed on cutting force, flank temperature, and tool wear in end milling of Ti-6Al-4V alloy, Int. J. Adv. Manuf. Technol. 70 (9-12) (2014) 1835–1845, https://doi.org/10.1007/s00170-013-5433-8.

[61] Q. Shi, L. Li, N. He, W. Zhao, X. Liu, Experimental study in high speed milling of titanium alloy TC21, Int. J. Adv. Manuf. Technol. 64 (1-4) (2013) 49–54, https://doi.org/10.1007/s00170-012-3997-3.

[62] P.R. Paresi, Y. Lou, A. Narayanan, J.W. Yoon, Enhanced constitutive model for aeronautic aluminium alloy (AA2024-T351) under high strain rates and elevated temperatures, Int. J. Automot. Technol. 20 (S1) (2019) 79–87, https://doi.org/10.1007/s12239-019-0130-8.

[63] S. Ravi, M. Pradeep Kumar, Experimental investigations on cryogenic cooling by liquid nitrogen in the end milling of hardened steel, Cryogenics (Guildf) 51 (9) (2011) 509–515, https://doi.org/10.1016/j.cryogenics.2011.06.006.

[64] F. Pusavec, A. Deshpande, S. Yang, R. M' Saoubi, J. Kopac, O.W. Dillon, I.S. Jawahir, Sustainable machining of high temperature Nickel alloy -inconel 718: part 1 -predictive performance models, J. Clean. Prod. 81 (2014) 255-269, https://doi.org/10.1016/j.jclepro.2014.06.040.

[65] S.Y. Hong, Y. Ding, W. Cheol Jeong, Friction and cutting forces in cryogenic machining of Ti-6Al-4V, Int. J. Mach. Tools Manuf. (2001), https://doi.org/10.1016/S0890-6955(01)00029-3.

[66] P. Singh, H. Pungotra, N.S. Kalsi, On the complexities in machining titanium alloys, in: D.K. Mandal, C.S. Syan (Eds.), CAD/CAM, Robot. Factories Futur., Springer India, New Delhi, 2016, pp. 499-507.

[67] A. Pramanik, Problems and solutions in machining of titanium alloys, Int. J. Adv. Manuf. Technol. 70 (5-8) (2014) 919-928, https://doi.org/10.1007/s00170-013-5326-x.

[68] Kiprawi, Mohammad Ashaari, Yassin, Abdullah, Syed Shazali, Syed Tarmizi, Islam, M. Shahidul, Mohd Said, Mohd Azrin, Study of cutting edge temperature and cutting force of end mill tool in high speed machining, in: MATEC Web Conf. vol. 87, 2017, pp. 2030. https://doi.org/10.1051/matecconf/20178702030.

[69] J. Hua, R. Shivpuri, X. Cheng, V. Bedekar, Y. Matsumoto, F. Hashimoto, T. R. Watkins, Effect of feed rate, workpiece hardness and cutting edge on subsurface residual stress in hard turning of bearing steel using chamfer+hone cutting edge geometry, Mater. Sci. Eng., A 394 (1-2) (2005) 238-248, https://doi.org/10.1016/j.msea.2004.11.011.

[70] H.-B. He, H.-Y. Li, J. Yang, X.-Y. Zhang, Q.-B. Yue, X. Jiang, S.-ki. Lyu, A study on major factors influencing dry cutting temperature of AISI 304 stainless steel, Int. J. Precis. Eng. Manuf. 18 (10) (2017) 1387-1392, https://doi.org/10.1007/s12541-017-0190-9.

[71] M. Danish, T.L. Ginta, K. Habib, D. Carou, A.M.A. Rani, B.B. Saha, Thermal analysis during turning of AZ31 magnesium alloy under dry and cryogenic conditions, Int. J. Adv. Manuf. Technol. 91 (5-8) (2017) 2855-2868, https://doi.org/10.1007/s00170-016-9893-5.

[72] T. Ozel, M. Sima, A.K. Srivastava, B. Kaftanoglu, Investigations on the effects of multi-layered coated inserts in machining Ti-6Al-4V alloy with experiments and finite element simulations, CIRP Ann. 59 (1) (2010) 77-82, https://doi.org/10.1016/j.cirp.2010.03.055.

[73] T. Ozel, D. Ulutan, Prediction of machining induced residual stresses in turning of titanium and nickel based alloys with experiments and finite element simulations, CIRP Ann. 61 (1) (2012) 547-550, https://doi.org/10.1016/j.cirp.2012.03.100.

[74] Y. Guo, G. Quan, M. Celikin, L. Ren, Y. Zhan, L. Fan, H. Pan, Effect of heat treatment on the microstructure and mechanical properties of AZ80M magnesium alloy fabricated by wire arc additive manufacturing, J. Magnes. Alloy. (2021), https://doi.org/10.1016/j.jma.2021.04.006.

[75] L. Li, M. Mahmoodian, C.-Q. Li, D. Robert, Effect of corrosion and hydrogen embrittlement on microstructure and mechanical properties of mild steel, Constr. Build. Mater. 170 (2018) 78-90, https://doi.org/10.1016/j.conbuildmat.2018.03.023.

[76] L. Wang, S. Jia, Y. Yi, G. Liu, L. Sun, L. Shi, S. Ma, Effects of damage evolution on tensile strength measurement of nuclear graphite material by ring compression test, J. Nucl. Mater. 555 (2021) 153128, https://doi.org/10.1016/j.jnucmat.2021.153128.

[77] Q. Zheng, T. Furushima, Evaluation of high-temperature tensile behavior for metal foils by a novel resistance heating assisted tensile testing system using samples with optimized structures, J. Mater. Sci. Technol. 94 (2021) 216–229, https://doi.org/10.1016/j.jmst.2021.03.061.

[78] M. Abdel-Salam, S. El-Hadad, W. Khalifa, Effects of microstructure and alloy composition on hydroxyapatite precipitation on alkaline treated α/β titanium alloys, Mater. Sci. Eng., C 104 (2019) 109974, https://doi.org/10.1016/j.msec.2019.109974.

[79] B. Fu, H. Wang, C. Zou, Z. Wei, The influence of Zr content on microstructure and precipitation of silicide in as-cast near α titanium alloys, Mater. Charact. 99 (2015) 17–24, https://doi.org/10.1016/j.matchar.2014.09.015.

[80] S. Schindler, M. Zimmermann, J.C. Aurich, P. Steinmann, Thermo-elastic deformations of the workpiece when dry turning aluminum alloys - A finite element model to predict thermal effects in the workpiece, CIRP J. Manuf. Sci. Technol. 7 (3) (2014) 233–245, https://doi.org/10.1016/j.cirpj.2014.04.006.

[81] C. Wang, H. Ding, H. Wang, Thermodynamic model and dynamic temperature compensation in positive-pressure-based sonic nozzle gas flow standard, IEEE Trans. Instrum. Meas. 62 (5) (2013) 1154–1165, https://doi.org/10.1109/TIM.2012.2234599.

[82] R. Zimmerschied, R. Isermann, Nonlinear time constant estimation and dynamic compensation of temperature sensors, Control Eng. Pract. 18 (3) (2010) 300–310, https://doi.org/10.1016/j.conengprac.2009.11.008.

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