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INVESTIGATION OF CRYOGENIC COOLING EFFECT WITH FINITE ELEMENT METHOD IN MICRO MILLING OF Ti6Al4V MATERIAL

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Abstract

Original scientific paper

The objective of this study is to see for micro-milling of Ti6Al4V in the different parameters, how wear occurs on the face of the tool and how to evolve cutting temperature, forces, and chip formations with FEM. The effects of dry, liquid coolant and LN2-based cryogenic cooling applications at 50,100,150 m/s cutting speeds and 1,2,3 µm/dev feed rate were compared in micro-milling of Ti6Al4V alloy. At different parameters, internal and workpiece-cutting edges cryogenic (wacec) are simulated temperatures were observed. Cryogenic cooling, dry and liquid coolant applications perceived that tool wear, chip formation, strain, stresses, and shear forces interpreted with the FEM. Also, a mesh model based on Arbitrary Lagrangian-Eulerian (ALE) simulations and the Johnson-Cook Plasticity model for material plasticity failure criterion are used in this study. As a result, indicated that at the cutting velocity of 100 m/min, cryogenic cooling on the workpiece and cutting edges has caused into decreasing %57 of cutting temperature also by %54 lower tool wear was observed on the internal tool cryogenic, by %15 the shear stresses decreased on wacec in comparison to dry cutting.

Keywords: *Micro milling, finite element method (FEM), cryogenic cooling, Ti6Al4V.*

1 Introduction

Micro products are becoming a standard requirement for many product designs in response to the demand for high flexibility, accessibility, and cost reduction with advanced technology [1-2]. Micro-milling stands out with high production speed and efficiency in micro-manufacturing [3]. Micro-milling is using on microsensors, biomedical parts, and molds with the increase of innovative technologies [4].

Ti6Al4V alloy is used in many biomedical devices as it provides high hardness, low wear, and high corrosion resistance [5]. Micro-milling of Ti6Al4V alloy is poor due to the insufficient distribution of heat in the cutting zone causes tool wear [6]. This can lead to severe surface quality and dimensional accuracy breakdown, as well as micro milling tool dimension losses [7]. During micro-milling, coolant liquids have been using to reduce the cutting temperature and prevent tool wear, and improve surface quality [9].

However, it appears that the performance of coolant liquid applications in micro-milling is insufficient to reduce the cutting temperature because of overheating and low thermal conductivity. Overheating can causes evaporation without effective distribution into the cutting zone [10]. Alternative methods developed to prevent the formation of high temperatures in the cutting zone are cryogenic cooling and MQL(minimum quantity lubrication) cooling methods [11]. Although MQL cooling has good lubrication properties, they observed that MQL's cooling and chip removal properties are lower than cryogenic cooling [12]. The cryogenic cooling process is the process of applying non-oil-based cooling gases such as liquid nitrogen and carbon dioxide to the cutting zone. [13].

Under atmospheric pressure, liquid nitrogen and carbon dioxide evaporate at -196 °C and -78 °C, respectively, leaving no residue and contamination on the tool, workpiece, chip, and cutting area [14]. Therefore, in the processing of biomedical materials, cryogenic processing is more advantageous than other cooling methods that do not require secondary cleaning processes for cleaning the water and oil emulsion contaminated by the coolant. [15].

Micro milling with cryogenic cooling seems in the literature experimental approaches to examine during micromachining studies are expensive and time-consuming methods[16-18]. The numerical solution method is also a reliable technique used to obtain thermal changes on chips and tools during cryogenic machining [19].

Researches on the subject examined; Caudill et al. (2019) observed the cutting forces and thermal fields as cryogenic and liquid-cooled during micro-milling of Ti6Al4V material with FEM (finite element model). When observed liquid nitrogen application in cryogenic processing reduces the cutting temperature by 40%, they saw an increase in tool life and machining efficiency [20]. Davoudinejad et al. (2019) compared the micro-milling of Ti6Al4V material by performing FEM (finite element

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analysis) and an experimental study. They proved that 8.5% error rate between experimental and FEM results [21]. Attanasio et al. (2018) analyzed the tool wear and chip flow of CuZn37 in micro milling and used FEM to determine the options of cycle number, feed, force, chip flow, and chip shape. They proved similarity with the experimental results of the cutting forces and chip formations in FEM [22]. Imbrogno et al. (2017) applied 3D FEM to observe cutting forces, temperature, and microstructure during Ti6Al4V turning in a dry and cryogenic. They observed that cryogenic cooling is increased the shear forces and contributed to the improvement in surface roughness [23]. Pashaki and Pouya (2017) studied the temperature changes in dry and cryogenic processing of aluminum alloy with FEM. They used the Johnson-Cook model for error analysis of thermal properties in their work. As a result, they saw that the cryogenic cutting of 10 m/s decreased the tool temperature to dry cutting by 60% [24]. Olleak and Özel (2017) analyzed dry and cryogenic processing in micro-milling of Ti6Al4V using FEM. They observed that tool stresses are lower in cryogenic machining compared to dry machining [25]. Imbrogno et al. (2017) applied the FEM for on-duty observation during the turning of Ti6Al4V alloy under dry cutting and cryogenic cooling. They observed that better surface integrity is achieved in cryogenic cooling with temperature reduction compared to dry cutting [26]. Mamedov and Lazoğlu (2016) compared the temperature obtained from the FEM model with the temperature measured using a milling experiment thermocouple. They found that the share of the difference between FEM and experimental is 12% [27]. In their research, Tounsi and El-Wardany (2015) examined the FEM connection when there are chip formation and residual stresses in the milling of Ti6Al4V alloy. The properties of chip morphology, strength, plastic deformation, and different distributions are analyzed. Residual stresses are showed to coincide with experimental results [28]. Rotella et al. (2014) performed a FEM application to determine the micro offer in the material after the dry and cryogenic cutting of Ti6Al4V.

They demonstrated the change in microprocessing during the cooling and lubrication process during cutting. The experimental results were in agreement with the FEM. They observed better surface integrity and hardness in cryogenic cooling [29].

In summarizing the studies, FEM draws attention to several different models of micro and macro cutting of metal using software such as Abaqus Deform, Advantage, ANSYS can analyze temperature, shear forces, stress, and strain [19-29].

Micro products produced from Ti6Al4V alloy, which is indispensable for modern engineering technologies, and micro surface roughness are gaining increasing importance. Since surface roughness is affected by cutting temperature, cutting speed and coolant are important research topics.

The FEM has gained importance today. It was seen that the finite element analysis confirmed the experimental analyzes with a small margin of error. At the same time, examining many experimental parameters can cause time and financial losses in experimental micro-milling.

In this study, a FEM using based on Arbitrary Lagrangian-Eulerian (ALE) simulations. Johnson-Cook plasticity failure criteria model is used to observe the chip removal method. Unlike the researches, the finite element model simulates dry, liquid coolant, internal tool, and the workpiece-cutting edges with liquid nitrogen cooling. This study discussed the effects of cooling methods on temperature, tool wear, strain, stress, chip formations, cutting forces at various cutting speeds, and feed rates.

2 Materials and Methods

2.1 Material and Cutting Tool Properties

A workpiece of Ti6Al4V material dimensions of 8 mm ×10 mm ×3 mm was modeled. Table 1 shows the physical characteristics of heat treatment Ti6Al4V.

Table 1. Physical characteristics of heat treatment Ti6Al4V [30].

Density Kg/m^3	Hardness (HB)	Melting point °C	Thermal Conduction (W/mK)	Elastic modul (GPa)	Poison
4430	195	1670	7.955	110	0.31

According to the literature, TiAlN coated WC (tungsten carbide) material tools recommended for the machining of hard materials were selected [20-24]. The geometric features of the 4-flute end mill tool are given in Table 2.

Table 2. Tool geometry of TiAlN coated WC

Tool diameter	0.5 mm
Helix angle	30°
Rake angle	15°
Clearance angle	5°
Cutting edge radius	0.5 µm

Fig.1 shows 3D design micro milling and view of the chip removed and temperature distribution on a tooth of micro tool.

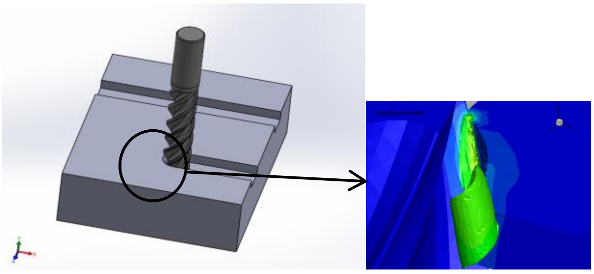


Figure 1. 3D Milling and view of the chip removed and temperature distribution on a tooth.

3D milling tool geometry was designed in the 2D orthogonal finite element method, micro tool, and workpiece. The dimensions of the orthogonal cutting tool are given in Fig. 2.

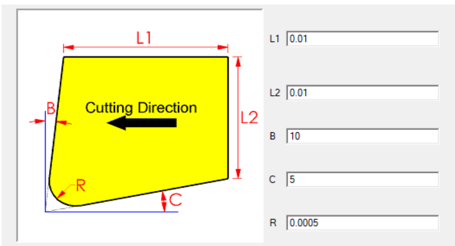


Figure 2. Dimensions of the orthogonal cutting tool.

2.2 Meshining

In this study, the mesh was applied using the Lagrangian approach to calculate chip formation with finite element software. The Arbitrary Lagrangian Euler's (ALE) approach using the clear integration solution is applied to reduce the typical element distortions of the Lagrangian approach.

In the ALE application of mesh to the part and the micro tool designed with the finite element method, 1575 elements meshed on 695 workpieces. Fig. 3 shows the mesh density applied before and during cutting.

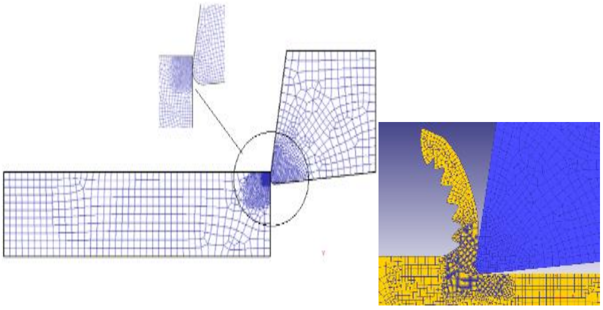


Figure 3. Tool and workpiece mesh distribution and mesh distribution during cutting.

2.3 Structural Modeling of the Material

Johnson-Cook (JC) model describes the plastic behavior of the workpiece material. Structural behavior in machining conditions is a substantial issue to make a reliable FEM. The Johnson-Cook (JC) constituent material model is considered to be a reliable model (Eq. 1) used in previous literature [31]. Chip flow stress, $\varepsilon\varepsilon$ plastic strain, ε 'strain rate, ε'0 reference strain rate. The material temperature is m melting point and a is room temperature. JC constants are respectively: yield stress A, pre-exponential factor B, stress rate factor C, work hardening exponent, and m thermal softening exponent.

$$\sigma = [A + B(\varepsilon)^n][1 + Cln(\frac{\varepsilon'}{\varepsilon'_0})[1 - \left(\frac{T-T_0}{Tm-T_0}\right)^m \quad (1)$$

The thermo-mechanical properties of the workpiece and the material constants used in modeling plastic behavior according to the JC model are given in Table 3

Table 3. Thermo-mechanical properties of Ti6Al4V [32].

A (MPa)	B (MPa)	n	C	m	T_0 (°C)	Tm (°C)
782.7	498.4	0.28	0.028	1.0	20	1450

2.4 Model of Coulomb Friction

For the model of this section, the case of classical friction situation following Coulomb's law is assumed; frictional sliding force is proportional to the applied normal load. The ratio of these two is the coefficient of friction μ which is constant in all the contact lengths between chip and tool. The relation between frictional stresses τ and normal stresses can be expressed as: (2). The friction coefficient is taken as 0.3 constant throughout the analysis in all the contact lengths by Calamaz et al.[33] and Hong et al. [34].

$$\tau=\mu\sigma_n \quad (2)$$

2.5 Model of Tool Wear

The simulations of the micro-milling process, the workpiece, and the tool are not exposed to any external forces. A wear rate model based on the sliding wear mechanism that is mechanical contact pressure, sliding velocity and temperature-sensitive proposed by Usui et al. [35] has been used in this study. This tool wear rate model calculates the rate of volume loss on the tool per unit area per unit time. The wear equation constants are set to a = 1×10^{-5} b=1000. Interface temperature (T), P interface pressure, and sliding velocity (v_s) at the tool surface as inputs and yields a wear rate (dW/DT) distribution in the tool as shown in Eq. (3).

$$dW/dt = aPv_se^{-b/T} \quad (3)$$

Also, the tool coating affects the equivalent thermal conductivity, the heat capacity of the coated tool, and the friction coefficient at tool-chip contact.

2.6 Cooler Application Model

In this application, the cutting temperature is compared with cryogenic cooling, coolant, and dry cutting. The ambient temperature was chosen as 20 °C. Analyzes were carried out using the finite element method. The temperatures and surface transfer coefficient parameters in the cutting simulation are given in Table 4.

Table 4. Coolant temperatures and surface transfer coefficient table [20].

	Dry	Liquid	LN_2 cryogenic
Coolant temperatures °C	20	20	-196
Surface transfer coefficient W/m^2	45	2500	20000

In this simulation of the internal tool cryogenic cooling and equal to the workpiece, and the cutting edges are made according to the design in Fig 4. Three nozzles were used for cooling applied to the workpiece and cutting edges. Nozzle diameter and density of liquid nitrogen cryogenic liquid, flow rate, and application areas are given in Table 5.

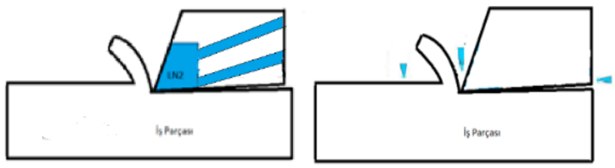


Figure 4. Internal cooling of the tool in the orthogonal cutting plane and cooling of the part and the cutting planes during cutting

Table 5. Application values of liquid nitrogen.

LN_2 density (kg/m^3)	808
Jet radius (mm)	0.01
Flow rate (kg/min)	0.2
Coolant applied location	Workpiece and cutting edges

3 Results and Discussion

With the tendency of cutting heat to accumulate on the cutting tool, there is a need to characterize the distribution of thermal fields on the tool and workpiece. Because of the low thermal conductivity exhibited by the Ti6Al4V material. Table 6 shows micro-milling simulation cutting parameters

Table 6. Cutting parameters

Cutting parameter	
Cutting speeds (m/min)	50,100,150
Feed rates (µm/dev)	1,2,3
Depth of cut (µm)	1
Coolant applications	LN_2 Cryogenic, Coolant liquid

To characterize cutting temperatures, the temperature distributions, strains, stresses, tool wear during dry, liquid coolant, and cryogenic cutting were shown in the orthogonal plane.

3.1 Effect of Cutting Speed on Cutting Temperature

The higher the cutting speed can cause more mechanical interaction and more chips remove per unit time. This increase in mechanical interaction increases the cutting temperature [38] as seen in Fig 5.

Additionally, it is seen in Fig.5 that cryogenic applications are affected more by the cutting speed than dry and coolant applications. The reason for reduced cutting temperature is due to the low cutting speed in cryogenic applications. Low contact time of the LN_2 fluid in the cutting zone causes friction and reduces the amount of heat transferred to the cutting tool [41]. In the simulation where we applied cryogenic LN_2 to the cutting areas and the part, it is seen that it obtained the best result at 50 m/ min cutting speed, while it obtained a temperature 80% lower than 150 speed. m / min. It is seen that this ratio is 42% in dry cutting, 44% in the cooler, and 62% in the internal cryogenic cooling of the tool.

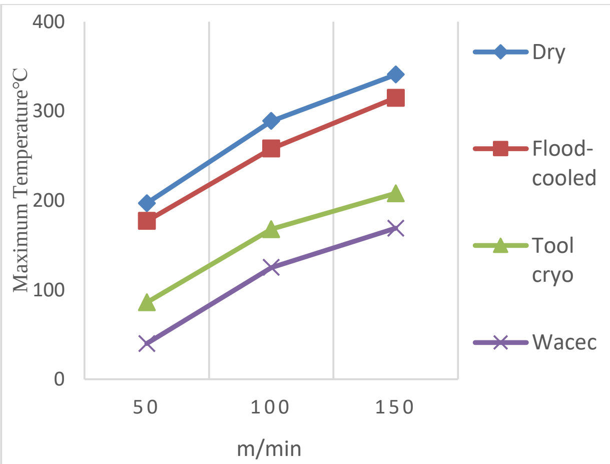


Figure 5. 2µm / dev feed on the effect of coolant applications at different cutting speeds on temperature.

Temperature distributions in the tool and the workpiece analysis results of FEM were shown in Fig 6. It is seen that as the cutting speed increases, the chip temperatures increase, and ductile chip formation is observed.

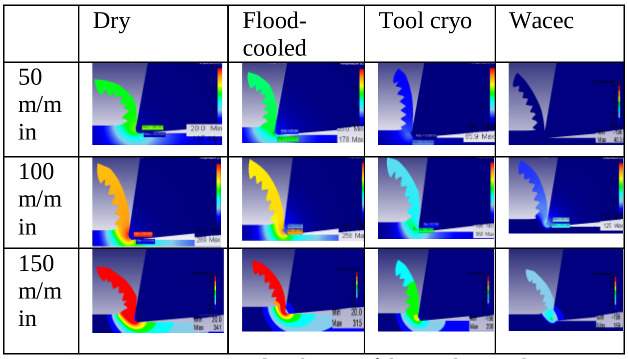


Figure 6. Temperature distribution of dry, coolant, and cryogenic applications at different cutting speeds on 2µm / rev feed.

3.2 Impact of Feed Rate

The graphs of the maximum temperatures at 150 m / min in 1,2,3 µm/rev progress are given in Fig. 7. In the same cooler applications, the feed rate affects the temperature between 5-19%. The feed rate effect is higher in cryogenic applications. It is noticed from the change of temperatures in Fig. 7 that alteration is between 11-19% in the cryogenic cooling applied to the cutting edges and the workpiece, and between 5-9% change in dry cutting on the different feed rate.

Increasing the cutting speed causes decreases the effect of the feed rate on the temperature in cryogenic applications. It is seen that the cutting speed effect on the temperature is higher than the feed rate when Fig. 5 and 7 are compared.

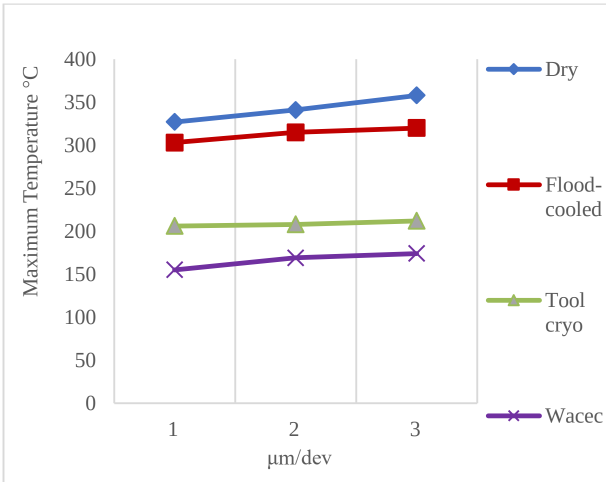


Figure 7. The effect of coolant applications on the temperature at different feed rates on 150 m/s cutting speed.

The temperature distributions formed in the tool and the workpiece simulations made with finite element methods are shown in fig. 8. In the application of dry and coolant, it is seen in the chip formations in fig. 8 that the temperatures in the chips are higher, as a result of which the chip formation is more ductile. When compared the temperature distributions and chip shapes in Fig. 6 and Fig. 8, it is seen that the cutting speed increases can affect the chip ductility and cutting temperature more than the feed rate.

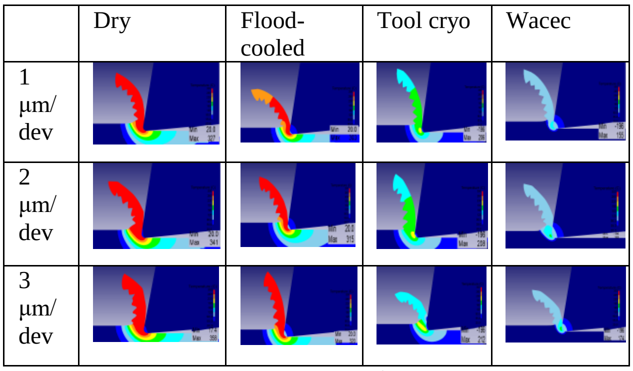


Figure 8. Temperature distribution of coolant applications in the workpiece and tool at different feed rates on 150 m/s cutting speed

3.3 Effect of cryogenic applications

Low cutting speed and feed rates are more effective in lowering temperatures in the application where the workpiece and cutting edges are cryogenic cooled. Fig. 9 shows temperature differences of the internal cryogenic, workpiece-cutting edges cryogenic coolings. The maximum temperature drop was achieved by up to 57% compared to the internal tool and wacec at 50 m/min cutting speed and 1 µm/rev feed rate. The lowest temperature change was measured at 150 m/min cutting speed and 3 µm/rev feed rate by up to 18% compared to the internal tool and wacec. This is because fluid is applied directly to the cutting planes. Slow cutting speed and feed rate can reduce cutting temperatures significantly due to more cutting zones interaction.

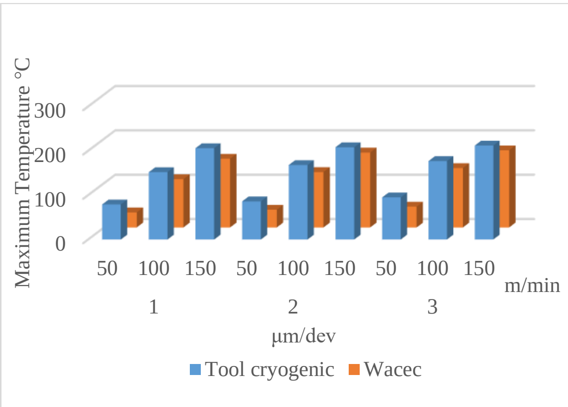


Figure 9. Maximum temperature change in LN_2 applications

3.4 Effect of cutting speed and coolant applications on tool wear

The amount of wear and distribution of cutting tools caused by micro-milling at 50, 100, and 150 m/min is shown in Fig. 10. Cryogenic cooling on workpieces had hardened the Ti6Al4V metarials Ahmed et al [42]. The hardening of the material increases tool wear. When the graphic in Fig. 10 is examined, it is seen that internal cryogenic applications executed lesser wearing than other cutting applications on different cutting speeds. Also, it is seen that cryogenic applications decrease tool wear. At the same time, the internal cryogenic application gives the tool high hardness and wear resistance. It was observed that as the cutting speed increased, the amount of wear increased in parallel with the cutting temperature.

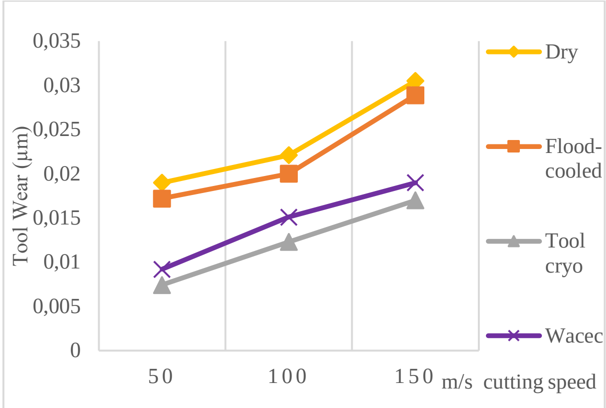


Figure 10. The amount of wear on the tool in 1 µm/dev feed at different cutting speeds and cooling applications

LN_2 application is expected to significantly decrease the rate of tool-wear during high speed milling of Ti6Al4V Caudill et.al [20]. As a result of the analysis made with finite element methods, the wears and the wear distributions in the set were shown in Fig. 11. The lowest wear is observed in the internal cryogenic cooling of the tool at 50 m/s cutting speed. The highest wear is seen in dry cutting with a cutting speed of 150 m/s.

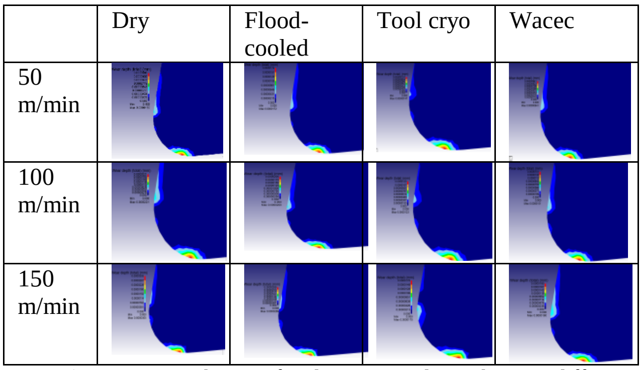


Figure 11. Distribution of tool wear in analyzes shown at different cutting speed.

3.5 Effect on chip formation and stress

As cutting temperatures increase, chip ductility and chip thickness increase [36-37]. As seen in Fig. 12, the top and hole distances decrease in chip thickness cooling applications. Chip thicknesses that decrease while the temperature decreases are indicators of the formation of brittleness in the chip. Chip thickness in the matter of valley heights reduced with cryogenic cooling Davoudinejad et.al. [43].

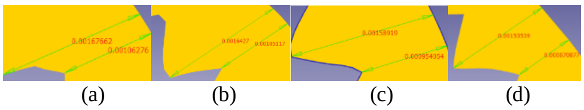
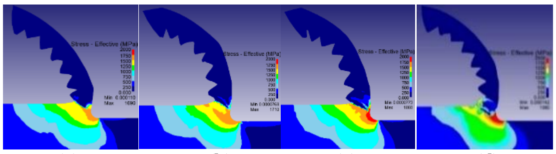


Figure 12. Compare to peak and valley heights of chip thicknesses a) Dry b) flood-cooling,c) internal cryogenic d) wacec, peak, and dimple heights of chip thickness.

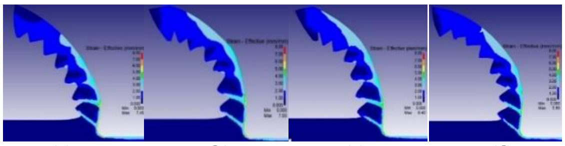
Due to the cooling effect of LN_2, which lowers the cutting temperature and increases the brittleness [37]. Also, the cryogenic process. Fig. 13 shows that the stresses are higher in cryogenic cooling applications than in dry cutting. Stress increased inversely with temperature While machining, a pre-stress area is formed on the cutting plane, which overlaps inversely with the stress field created by the force and heat Umberello et al [44].



(a) (b) (c) (d)

Figure 13. Compare to stress distributions a) Dry b) flood-cooling, c) internal cryogenic d) Wacec.

As is well known, cutting force and cutting heat interrelate during the milling shear slip and plastic deformation would occur in the cutting area due to the cutting force [40]. The temperature rises as the result of which the work of the plastic deformation and the friction turns into heat, thereby causing thermal strain and then softening the material Peng et al [45]. While cryogenic cooling limits the deformation in the chip by reducing the cutting zone temperature, that causes decreases in the amount of strain as shown in Fig. 14. Micro-machining is applied at high speeds to accelerate production. Material processing at high speeds causes continuous chip formation. Decreased strain can make brittle chip formation and prevent unwanted continuous chip formation [39]. Chip breakability was appreciable, and the acceptable forms of chips were produced in cryogenic machining conditions when compared to dry and wet machining environments Jerold and Kumar [46].



(a) (b) (c) (d)

Figure 14. Compare to strain distributions a) Dry b) flood-cooling,c) internal cryogenic d)Wacec

3.6 Effect of coolant applications on forces

Since cryogenic cooling causes hardening in the material, it increases the cutting forces Shokrani et al. [47] There is uncertainty in the literature regarding the effect of cryogenic cooling on measured shear forces. Some empirical-based studies have concluded that cryogenic application in Ti6Al4V processing leads to an increase in shear force [20-24] due to an increase in hardness and strength in the workpiece.

Other studies have concluded that some force components are increased while using cryogenic cooling, while other components are decreased or not affected [25-28]. The force reduction may occur because of changes in the low-temperature friction behavior or a reduction in tool-chip contact length due to physical chip removal. All these possibilities are directly affected by the experimental methodology as the LN_2 application is quite sensitive. Numerical simulations within the deform and the model created to apply cryogenic cooling cannot physically calculate the effect of chip removal. In Fig. 15, the shear forces in the x and y direction in dry, flood-coolant, and cryogenic cooling applications at a speed of 1µm advance and 100 m/min are given in Fig. 15. It has been observed that the shear forces increase in cryogenic uses.

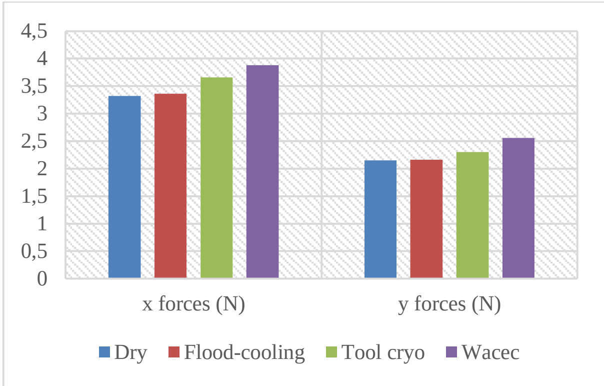


Figure 15. Effect of shear forces (N) in x and y direction in dry, cooler, and cryogenic cooling.

4 Conclusion

Using cryogenic in the machining process increases tool life, dimensional accuracy and provides better roughness. Results of reduced temperature create low energy consumption and increase productivity. Therefore, in this study, the finite element model of micro-milling Ti6Al4V alloy by different cutting parameters and cooling applications. Based on simulation results, it can be concluded that;

- A significant decrease in cutting temperatures is noticed in cryogenic applications. In wacec %57, internal tool cryogenic % 42, and liquid coolant %11, temperature drops were observed against dry cutting.
- In cryogenic cooling on the workpiece and cutting edges, The temperature significantly increased as the cutting speed and the amount of feed increased, and the highest temperatures 174 °C were seen at 3 µm / rev at 150 m / min and the lowest temperatures 34°C were seen at 50 m/min,1 µm/rev.
- It has been observed that keeping the cutting speed low increases the effect of the cryogenic application on the temperature during cutting and is more effective in the cooling application applied to the part and cutting areas.
- Internal tool cryogenic cooling gave %18 better tool wear results compared to the cooling of the workpiece and cutting edges. It is showed that internal cooling can reduce tool wear.
- Cryogenic cooling of the workpiece and cutting edges showed 44% less wear and 54% less internal tool wear compared to dry cutting. Tool wear can be reduced depending on the predicted temperatures, tool wear was predicted, showing that LN_2 cryogenic cooling can significantly improve tool life.
- Considering the production times of micromachining, production is made at high speeds. Material processing at high speeds causes continuous chip formation. Cryogenic cooling has been found to make the chips brittle. It is predicted that the continuous chip formation that damages the tool and the part can be reduced by cryogenic applications.

It has been seen that the cutting forces %15 increase with cryogenic cooling. However, numerical simulation of micro-milling is limited by the number of factors that can be effectively analyzed. Thus, more experimentation is necessary to make any conclusive statement.

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