# INFLUENCE OF COEFFICIENT OF FRICTION ON TI-6Al-4V TITANIUM ALLOY TURNING PROCESS – FEM ANALYSIS

## *Ocena wpływu współczynnika tarcia na przebieg procesu toczenia stopu tytanu Ti-6Al-4V – analiza MES*

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**Abstract:** The good properties of Ti-6Al-4V titanium alloy make it widely used, but at the same time, make it difficult to machine. One of the factors which influence the machinability of metal alloys is coefficient of friction, which can be lowered by multiple cooling and lubricating methods. In the present work the influence of coefficient of friction on the turning process of Ti-6Al-4V was analyzed based on the FEM simulations conducted in DEFORM 2D/3D software. It was proven that the coefficient of friction influenced the cutting force and thrust force. It was also shown that the coefficient of friction had a significant impact on the chip compression ratio.

**Keywords:** Ti-6Al-4V, turning, coefficient of friction, FEM analysis

**Streszczenie:** Dobre właściwości stopu tytanu Ti-6Al-4V decydują o jego szerokim zastosowaniu, lecz jednocześnie wpływają na trudnoobrabialność. Jednym z czynników, który wpływa na obrabialność stopów metali jest współczynnik tarcia, którego wartość może być obniżana dzięki zastosowaniu różnych metod chłodzenia i smarowania. W niniejszej pracy przeanalizowano wpływ wartości współczynnika tarcia na przebieg procesu toczenia stopu Ti-6Al-4V, na podstawie symulacji MES przeprowadzonych w programie DEFRORM 2D/3D. Pokazano, iż współczynnik tarcia ma wpływ na wartość siły skrawania i siły odporowej. Uwidoczniono również istotny wpływ wartości współczynnika tarcia na współczynnik spęczenia wióra.

**Słowa kluczowe:** Ti-6Al-4V, toczenie, współczynnik tarcia, analiza MES

## Introduction

Use of titanium alloys has been increasing in the recent years due to their excellent properties such as high specific strength, low density and exceptional corrosion resistance. The major field of application of titanium alloys includes aerospace, but they are also used in medical applications, automotive, marine industry and others [24].

Ti-6Al-4V is the most common titanium alloy accounting for more than 50 % of global production. The major fields of application (80%) is aerospace and medical industry [31]. Its particular characterization ($\alpha+\beta$ phase) provides unique strength due to the stable structure [18]. Table 1 shows some of the properties of Ti-6Al-4V titanium alloy at a room temperature.

Metal cutting process is one of the oldest methods of reducing a metal workpiece to a given shape and features in the manufacture of most of the items, also those made of titanium alloys [4]. However, the properties which cause the wide use of titanium alloys make them also hard-to-cut material [13, 26, 34]:

- Low thermal conductivity –the thermal conductivity of titanium materials is relatively low in comparison with steel and aluminum alloys. This causes heat concentration on the tool cutting edge and face.
- High chemical reactivity – titanium with common gases (oxygen, hydrogen and nitrogen) and cutting tool material at tool operation temperatures. Formation of oxides, hydrides and nitrides cause the embrittlement and decrease of the fatigue strength of the alloy.

Table 1. Properties of Ti-6Al-4V titanium alloy [22]

| Density $\rho$ [g/cm3] | Young’s modulus $E$ [GPa] | Tensile strength $R_m$ [MPa] | Yield strength $R_{p0.2}$ [MPa] | Elongation $A$ [%] |
|---|---|---|---|---|
| 4.42 | 106 – 114 | 987 – 1205 | 828 – 1075 | 10 – 18 |

Reactivity with cutting tool material causes galling, smearing and chipping of the workpiece surface and rapid tool wear.

- Low elastic modulus – leads to a low rigidity and allows deflection of slender and thin-walled workpiece under tool pressure, including chatter and tolerance problems.
- High temperature hardness and strength – causing deformation of the cutting tool because of high cutting forces required.
- Work hardening – causes absence of built-up edge in front of the cutting tool and increase of the shearing angle, which in turn induces a thin chip to contact a relatively small area in the cutting face, resulting in high bearing loads per unit area. The high bearing stress, combined with the friction between the chip and bearing area causes a significant heat raises in a very small area of the cutting tool and production of cratering close to the cutting edge, resulting in rapid tool breakdown. However, the formation of built-up edge is referred to be detrimental for tool coating.

The friction between workpiece and tool is one of the factors that affect machinability. To reduce friction coefficient and therefore improve machinability, various cooling and lubricating methods are applied [17]. The impact of different coolants and different cooling strategies is of interest of many scientists [10, 14 , 20]. Deiab et al. [11] have revealed that the cooling strategies had an impact on the tool wear, surface roughness and energy consumption during turning Ti-6Al-4V. Bermingham et al. [6] compared the tool life during laser assisted milling, dry milling, milling with flood emulsion, milling with minimum quantity lubrication and a hybrid laser + MQL process. It was found that conventional coolants worked well at the standard cutting speeds recommended by the tooling manufacturer, but at higher cutting speeds the coolant deteriorated tool fife due to thermal shock/fatigue. Raza et al. [28] evaluated tool wear patterns when turning titanium alloy Ti6Al4V under six lubrication techniques: Flood Cooling, Dry Machining, Vegetable Oil MQL Machining, Cooled Air Lubrication, Cryogenic Machining (with liquid Nitrogen), Vegetable Oil + Cooled Air/MQCL machining. It has been concluded that vegetable oil is a sustainable alternative to synthetic cooling in terms of tool wear and surface roughness. Rahim and Sasahara [25] studied the effect of palm oil as MQL lubricant on high speed drilling of titanium alloy Ti-6Al-4V. It was concluded that MQL with palm oil produced lower cutting forces and workpiece temperatures than MQL with synthetic ester, almost equal to the flood condition.

Multitude of researches on the impact of different types of coolants and different cooling strategies leads to the conclusion that the coolant plays an important role during machining. However, there are only a few publications where results of machining tests were referred to the coefficient of friction obtained as a result of tribological tests for specific material pairs and cooling conditions.

The machinability of material can be assessed by analysis of cutting forces values and chip shape among others [33]. In this work, the impact of the coefficient of friction on cutting forces and chip shape during Ti-6Al-4V titanium alloy turning will be checked. It will be also checked if this effect changes with the cutting speed.

## Coefficient of friction in metal cutting

There are basically two types of friction: dry and viscous. Friction of dry and boundary- lubricated surfaces may be classified as Coulomb friction [30]:

$$\mu_f = \frac{F}{N} \tag{1}$$

where $N$ is the normal force acting at the considered interface and $F$ is the frictional force at this interface (Figure 1).

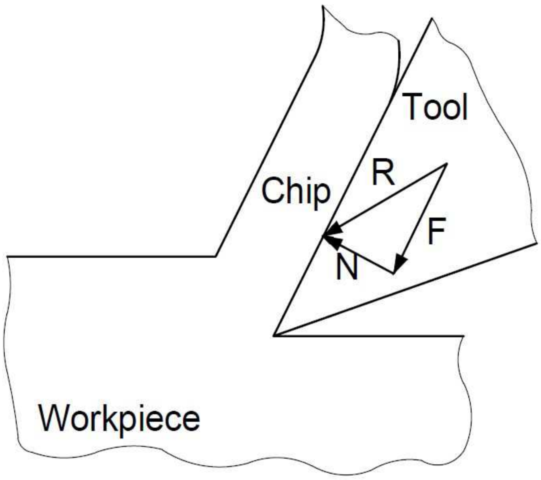

Fig 1. Normal force N and frictional force *F* in metal cutting (based on [2])

The regime of boundary lubrication is that the surfaces are separated by at most a few layers of lubrication molecules [23].

It is well-known that the contact between the two bodies is limited to only few microscopic high points (asperities). However, the stresses are customarily calculated by assuming that the forces are distributed over the total contact area. Due to a high contact pressure in real machining, the actual and apparent contact areas are practically the same. Therefore, the above approximation is not far from reality and numerator and denominator from of equation (1) can be divided over the tool-chip contact area $A_c$ and then recalling than the mean normal stress at the interface is $\sigma_c = N/A_c$ and the mean shear (frictional) stress at the interface is $\tau_c = F/A_c$, one can obtain [3]:

$$\mu_f = \frac{\tau_c}{\sigma_c} \qquad (2)$$

Values for coefficient of friction are conveniently tabulated and incorporated into engineering books. However, the engineers and scientists confronted with real friction problems in machinery or industrial processes often find this simple approach insufficient to explain observations or to enable them to select from among numerous candidate materials and lubricants. Furthermore, different tabulations of friction data list different values even for (supposedly) the same sliding materials with the same lubricant (Table 2) [7].

Table 2. Values of coefficient of friction for material pair Ti-6Al-4V / WC-Co with various lubricants

| Lubricant | Testing method | Coefficient of friction | References |
|---|---|---|---|
| Dry | ball-on-flat | 0.42 | [21] |
| Dry | tribometer based on a numerically controlled lathe | 0.2-0.35 depending on sliding velocity (apparent friction coefficient) | [12] |
| Water | ball-on-flat | 0.26 | [21] |
| Deionized water | block on ring | 0.34 | [35] |
| Water | ball on disc | 0.7 | [37] |
| Water | ball on disc | 0.47 | [38] |
| Water | ball on disc | 0.7 | [36] |
| Commercial emulsion diluted to the concentration of 5 wt% | ball on disc | 0.2 | [38] |
| polyalkylene glycol (PAG) dissolved in deionized water at concentration of 10% | ball on disc | 0.6 | [37] |
| Castor oil sulfated sodium salt (CSS) aqueous solution at low concentration (5 wt%) | ball on disc | 0.18 | [37] |
| Pure castor oil | ball on disc | 0.2 | [37] |
| Cryogenic cooling | calculated on the base of cutting forces | 0.42-0.54 dependent on the cutting parameters | [5] |
| Cryogenic cooling | rotating disk rubs<br>on a flat specimen with a controlled normal force | 0.12-0.18 depending on the method of feeding LN2 | [16] |
| Paraffin | ball on disc | 0.66 | [36] |
| PAO40 | ball on disc | 0.5 | [36] |
| self-emulsifying ester (SEE) | ball on disc | 0.2 | [36] |
| SEE aqueous solution with small concentration of 1 wt% | ball on disc | 0.17 | [36] |
| Nonylphenol polyoxyethylene ether phosphate ester (PPE) diluted to the concentration of 1 wt% by deionized water. | ball on disc | 0.14 | [38] |

### Experimental Design

The experiment was designed with three-level factors in Statistica software (Table 3). Basing on literature review the range of cutting speed was assumed as 60-150 m/min [15, 27, 29] and the range of coefficient of friction was assumed as 0.12-0.7 (based on the Table 2). Other parameters such as heat convection coefficient and tool geometry (rake angle = 7°, flank angle = 7° and cutting edge radius = 0.04 mm) have not changed in individual cases. The feed was at constant level of 0.1 mm/rev.

Table 3. The design of experiment with Statistica software

| Standard Run | Cutting speed $v_c$ [m/min] | Coefficient of friction $\mu$ |
|---|---|---|
| 5 | 115 | 0.41 |
| 7 | 150 | 0.12 |
| 9 | 150 | 0.70 |
| 1 | 80 | 0.12 |
| 3 | 80 | 0.70 |
| 2 | 80 | 0.41 |
| 8 | 150 | 0.41 |
| 6 | 115 | 0.70 |
| 4 | 115 | 0.12 |

The simulations of the orthogonal turning process of Ti-6Al-4V titanium alloy taking into account the influence of coefficient of friction were held in the DEFORM 2D/3D software. The material was selected from the DEFORM database: Ti6Al4V-machiningSFTC. Material constitutive model was changed to Johnson-Cook model [39, 40], expressed by the following expression of the equivalent stress:

$$\bar{\sigma}_{JC} = A + B(\bar{\varepsilon})^n] \cdot [1 + C\ln(\dot{\bar{\varepsilon}}/\dot{\bar{\varepsilon}}_0)] \cdot \left[1-\left(\frac{T_W-T_0}{T_m-T_0}\right)^m\right] \quad (3)$$

where: $\bar{\sigma}_{JC}$ – Johnson-Cook plastic equivalent stress [MPa], $A$ – initial yield stress [MPa], B – hardening modulus [MPa], $C$ – strain rate dependency coefficient [MPa], m – thermal softening coefficient, $n$ – work-hardening exponent, $T_w$ – workpiece computed temperature [°C], $T_m$ – melting temperature [°C], $T_0$ – room temperature [°C], $\bar{\varepsilon}$ – plastic strain, $\dot{\bar{\varepsilon}}$ – equivalent plastic strain rate [$s^{-1}$], $\dot{\bar{\varepsilon}}_0$ – reference plastic strain rate [$s^{-1}$].

The above model provides a satisfactory description of the behavior of metals and alloys since it considers large strains, high strain rates, and temperature dependent visco-plasticity [39]. The values of coefficients A, B, n, C, m for the Ti-6Al-4V titanium alloy are presented in Table 4 at the base of [40].

Table 4. Johnson-Cook model coefficients for Ti-6Al-4V

| Material | A [MPa] | B [MPa] | n | C | m |
|---|---|---|---|---|---|
| Ti-6Al-4V | 1098 | 1092 | 0.93 | 0.014 | 1.1 |

### Experimental results and discussion

Table 5 shows the mean values of cutting force (X load) and thrust force (Y load) obtained as the result of simulations. In order to access validity of the results of simulations the results of experimental research are shown in Table 6. The experiment was conducted with use of CCMT 120408–MM 1105 cutting insert and following cutting parameters were indicated: $v_c$ = 80 m/min, $f$ = 0.1 mm/rev and $a_p$ = 1 mm. The experiment was conducted in flood cooling conditions.

Table 5. List of cutting force and feed force values obtained on the basis of simulations in the DEFORM 2D/3D software

| Standard Run | Cutting speed $v_c$ [m/min] | Coefficient of friction $\mu$ | X load $F_c$ [N] | Y load $F_T$ [N] |
|---|---|---|---|---|
| 5 | 115 | 0.41 | 176.35 | 135.73 |
| 7 | 150 | 0.12 | 134.88 | 111.59 |
| 9 | 150 | 0.70 | 174.81 | 133.60 |
| 1 | 80 | 0.12 | 190.49 | 140.65 |
| 3 | 80 | 0.70 | 217.53 | 111.18 |
| 2 | 80 | 0.41 | 194.04 | 129.41 |
| 8 | 150 | 0.41 | 159.95 | 137.44 |
| 6 | 115 | 0.70 | 193.96 | 123.49 |
| 4 | 115 | 0.12 | 168.69 | 141.32 |

Table 6. Cutting force and thrust force values obtained in experimental research

| Cutting speed $v_c$ [m/min] | Feed $f$ [mm/rev] | Depth of cut $a_p$ [mm] | Cutting force $F_c$ [N] | Thrust force $F_T$ [N] |
|---|---|---|---|---|
| 80 | 0.1 | 1 | 249.15 | 171.52 |

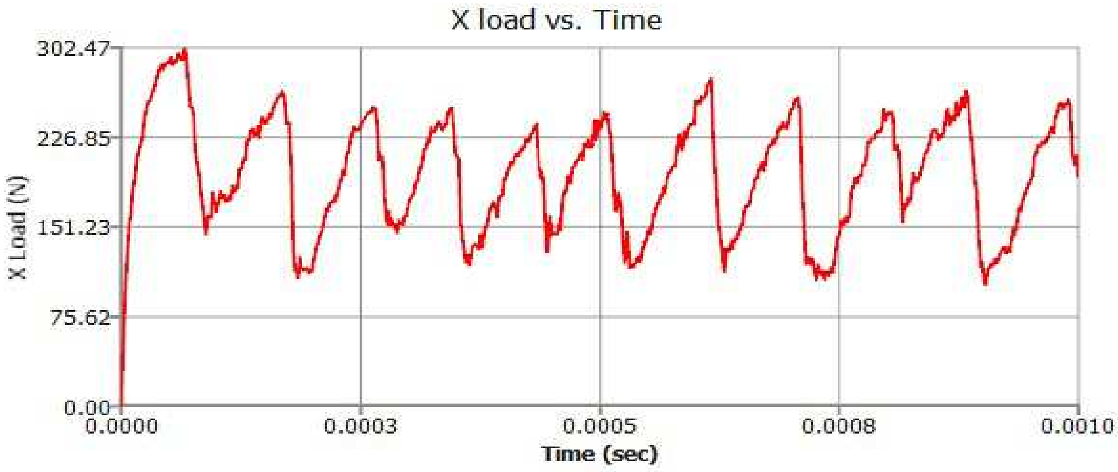

Figure 2. X load (cutting force) versus time graph ($v_c$ = 80 m/min, $\mu$= 0.41)

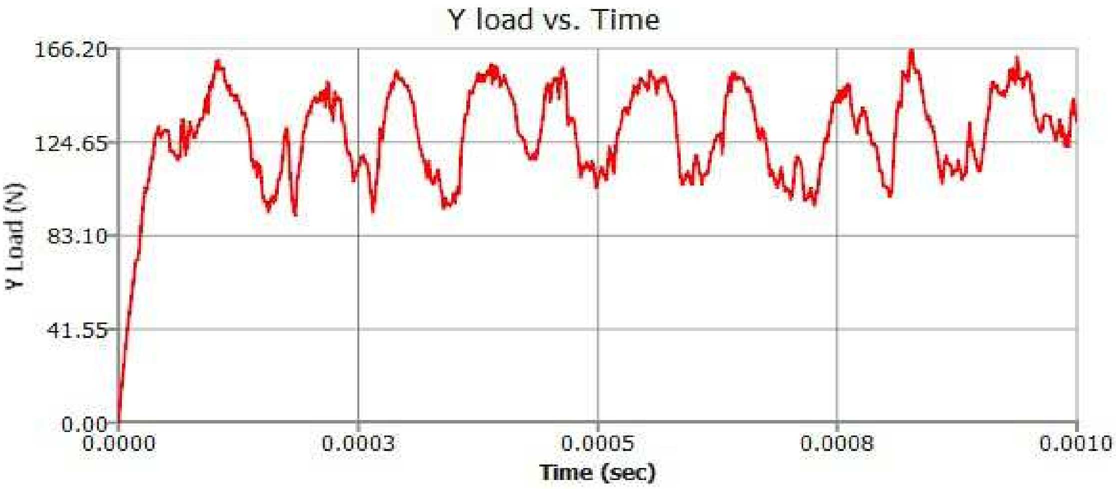

Figure 3. Y load (thrust force) versus time graph ($v_c$ = 80 m/min, $\mu$= 0.41)

Figure 2 and Figure 3 show the sample graphs of cutting force and thrust force versus time for cutting speed 80 m/min and coefficient of friction of 0.41 generated in DERORM 2D/3D software. It can be seen that the cutting force is periodic due to a segmented chip formation.

It can be seen that the difference between the experimental and simulation results of the cutting force value is about 22 % for $v_c$ = 80 m/min and coefficient of friction $\mu$ = 0.41. For the thrust force this difference is about 25 %.

The friction coefficient had a significant influence on the cutting force and thrust force regardless of the cutting speed value (Figure 4 and Figure 5). With increase of the coefficient of friction the cutting force increased and the thrust force decreased. This dependence is confirmed by Amrita et. al. [1], who studied the influence of the addition of nanographite to the soluble oil on the coefficient of friction and cutting forces for AISI 1040 steel. It was confirmed that for fluid with nanoparticles the coefficient of friction and cutting forces were decreased in comparison to conventional soluble oil. Talib and Rahim [32] examined the coefficient of friction of crude jatropha oil, synthetic ester and modified jatropha oils at various molar ratios of jatropha methyl ester. It was shown that the coefficient of friction was minimized for modified jatropha oil with the highest molar ratio of jatropha methyl ester (MJO5) and the highest value of coefficient of friction was obtained for the synthetic ester. Turning of AISI 1045 steel tests generally confirm the dependency of increase in cutting forces with increase of coefficient of friction with exception of machining with synthetic ester.

Moreover, it can be seen that increasing cutting speed increased cutting force. The same dependence was observed by Khan and Maity [19] during finish turning of CP-Ti grade 2 under different cooling conditions.

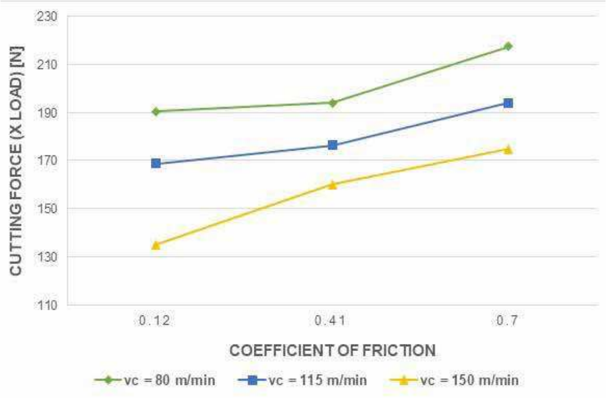

Fig. 4. Influence of coefficient of friction and cutting speed on the cutting force

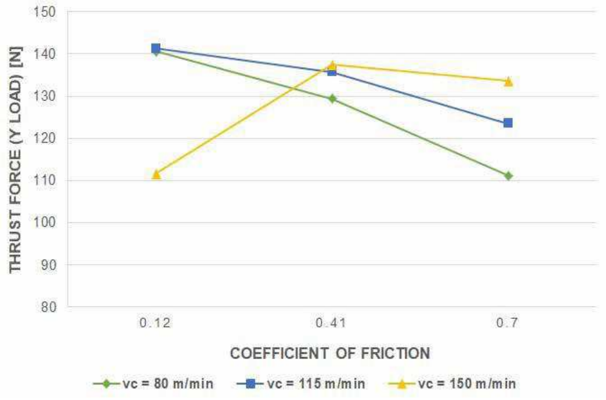

Fig. 5. Influence of coefficient of friction and cutting speed on the thrust force

Figure 6 shows the influence of coefficient of friction on the chip formation process. The segmented chips were obtained in the entire range of tested parameters. Segmented chip formation is a two stage process in which workpiece material is plastically deformed ahead of the tool causing it to bulge. Catastrophic failure occurs and a shear band is formed extending from the tool tip to the workpiece surface when a critical strain level is reached. The resulting chips consist of moderately deformed chip segments separated by narrow bands of intensely sheared material [9].

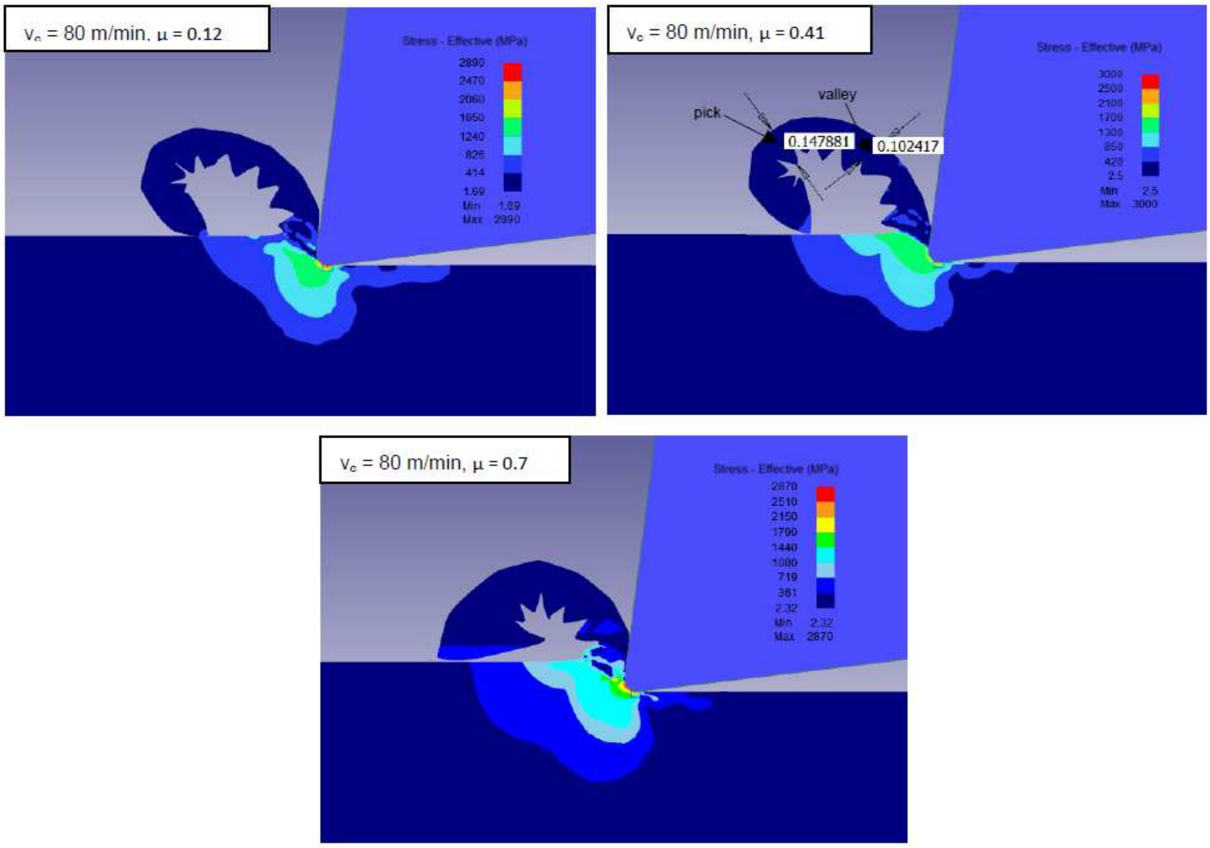

Fig. 6. The influence of coefficient of friction on chip formation process

The chip compression ratio $\lambda_h$ also increased with increase of coefficient of friction. Table 7 shows values of the deformed chip thickness and the chip compression ratio. The chip compression ratio was calculated as [8]:

$$\lambda_h = \frac{h_c}{h} \tag{4}$$

The deformed chip thickness hc was calculated as the average value of five picks' heights and five valley heights (Figure 6) and the undeformed chip thickness $h$ was equal to the value of feed (h = 0.1 mm). Moreover it can be seen that the chip compression ratio decreased with increase of cutting speed value (Figure 7).

Table 7. List of deformed chip thicknesses and chip compression ratios calculated on the basis of simulations in the DEFORM 2D/3D program

| **Standard Run** | **Cutting speed $v_c$ [m/min]** | **Coefficient of friction $\mu$** | **Deformed chip thickness $h_c$ [mm]** | **Chip compression ratio $\lambda_h$** |
|---|---|---|---|---|
| 5 | 115 | 0.41 | 0.1120 | 1.1195 |
| 7 | 150 | 0.12 | 0.1003 | 1.0028 |
| 9 | 150 | 0.7 | 0.1102 | 1.1016 |
| 1 | 80 | 0.12 | 0.1061 | 1.1916 |
| 3 | 80 | 0.7 | 0.1416 | 1.4160 |
| 2 | 80 | 0.41 | 0.1221 | 1.2209 |
| 8 | 150 | 0.41 | 0.1010 | 1.0096 |
| 6 | 115 | 0.7 | 0.1197 | 1.1975 |
| 4 | 115 | 0.12 | 0.1152 | 1.1520 |

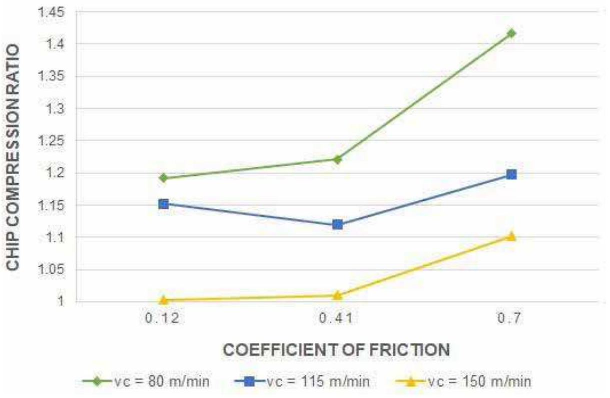

Fig. 7. The influence of coefficient of friction and cutting speed on the chip compression ratio

## Conclusions

Based on the results of the simulations presented above, it can be concluded that the coefficient of friction plays a significant role during Ti-6Al-4V titanium alloy machining. With the increase of friction coefficient, the cutting force and the thrust force increase significantly.

Irrespectively of the cutting parameters, the segmented chip was produced; however the coefficient of friction and cutting speed value influenced the chip compression ratio.

Based on the discussed research it is worth noting that the coefficient of friction is important factor in Ti-6Al-4V alloy machining. On the other hand it is worth pointing out that the different tabulations of friction data list different values even for the same sliding materials with the same lubricant. This leads to the conclusion that much attention should be paid to the determination of coefficient of friction for the specific cooling and lubricating methods. Knowledge of the specific values of coefficient of friction for the specific conditions will allow simulating the process closer to a real one.

On the basis of the experimental results and literature overview it can be concluded that the results of simulations can be a reliable starting point for further experimental research.

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