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INFLUENCE OF AL2O3 NANOPARTICLE MASS CONCENTRATION AND AEROSOL FORMATION PARAMETERS ON TOOL VIBRATION DURING TURNING OF Ti6Al4V TITANIUM ALLOY

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Machining difficult-to-cut materials involves challenging machining conditions, including higher temperatures in the cutting zone, cutting forces and friction. Another important phenomenon is vibration, which is undesirable when manufacturing high quality workpieces. One way to reduce vibration in the cutting zone is to use cooling methods. Due to its environmentally friendly nature, the minimum quantity lubrication (MQL) method has already been widely used in metalworking. However, when combined with nanofluids, it improves the ability of the aerosol to dissipate more heat and increase lubrication in the cutting zone. This paper presents the effect of a polyol ester-based Al2O3 nanofluid due to the varying mass concentration of nanoparticles on the vibration during turning of Ti6Al4V alloy and compares the results with dry cutting and the MQL method without nanoparticles. Four concentrations (*0.25−1 wt%*), variable nanofluid flow rate *E=0.388−1.182 g/min* and air flow rate *P=10−40 l/min* were considered. According to the statistical analysis, the most important factor influencing tool vibration was the mass concentration of nanoparticles in the cutting fluid. By combining the MQL method with *0.5 wt%* Al2O3, the vibration acceleration RMS values were found to be the lowest. When compared to the MQL method without nanoparticles, the RMS values for dry cutting ranged from *17.8%* to *24.9%*, and for wet cutting they were reduced by about *10.9-18.5%*.

Key words: Al2O3 nanoparticles, nanofluids, MQL, vibrations, variable air flow rate, variable nanofluid flow rate.

1. Introduction

Modern materials like titanium alloys find extensive application in the aircraft sector [1]. They are characterised by high hardness as well as high corrosion and high temperature resistance [2, 3]. Due to their applications, manufactured components should meet certain requirements in terms of the condition of the surface layer, as the stability of their operation and safety depend on it [4]. The state of the surface layer is affected by numerous things. Some of these factors are vibration, tool wear, cutting fluid type, workpiece material mechanical qualities, and cutting conditions [5, 6]. In contrast, vibrations are influenced by, for example, cutting forces and friction in the cutting zone [7, 8]. The occurrence of vibration during machining leads to tool displacement, which negatively affects the roughness and waviness of the machined surface [4, 9]. According to Huang *et al.,* [10], a $34.2-40.5\%$ increase in the machined surface roughness was observed when vibrations were present during the milling process of Ti6Al4V alloy. This negative factor can also lead to catastrophic tool wear [11].

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Recent studies have increasingly employed cooling techniques to mitigate friction and vibrations during machining operations [12]. Among these methods, Minimum Quantity Lubrication (MQL) is commonly utilized to diminish temperature and friction at the primary cutting zone [13]. Notably, MQL involves the application of a minimal amount of coolant, rendering it an environmentally friendly process compared to flood cooling approaches [14]. Lubricating and cooling the cutting zone is especially crucial when cutting hard-to-machine materials, as it reduces vibration. [15].

Carou *et al.* [16] focussed on the vibration analysis while machining magnesium alloys under MQL conditions. The authors claim that the MQL method allows a significant reduction in vibration as compared to dry machining. The authors explain that this is due to the lubricating effect of the additives contained in the aerosol. Özbek and Saruhan [17] also performed the machining experiments on AISI D2 steel under MQL cooling conditions. The authors studied the effect of vibrations and cutting temperature on surface roughnes values. Consequently, it has been demonstrated that the application of aerosol to the cutting zone lowers friction and temperature, which in turn increases tool life through effective lubrication. The MQL process reduces vibration values in comparison to dry machining. Another study confirming the effectiveness of the MQL method in decreasing tool vibration was conducted by Swain *et al.* [18]. In this case, Ti6Al4V alloy was turned in the presence of aerosol and under dry machining conditions. It has been observed that as the cutting time increased, the vibration amplitude increased more rapidly with dry cutting than with the MQL method, where the amplitude increased steadily and slowly. Finally, after $95\,minutes$ of the test corresponding to the end of tool life, it was found that the MQL method resulted in a reduction in vibration of approximately 19% compared to dry cutting. Sahoo *et al.* [19] carried out a study involving turning of Ti6Al4V alloy under dry machining, MQL and compressed air cooling methods. The researchers revealed that the use of the latter two methods of cutting zone cooling reduced the vibration amplitude by 50.39% and 41.14%, respectively, compared to dry machining. The most effective performance of the aerosol in reducing the vibration amplitude was explained by its greater ability to dissipate heat, which in turn decreased tool wear. Research on the influence of the cooling method on vibration was also conducted by Zhong *et al.* [20]. During the experiment, peripheral milling of 7050-T7451 aluminium alloy was carried out under dry machining conditions and a variation of the minimum quantity lubrication method, described by the researchers as MQL and characterised by a cutting fluid flow rate of $50-300\,ml/min$. As a result, it was found that the use of cutting fluid in the MQL method allows for accelerated damping of the vibrations generated during machining. It was also observed that at higher cutting speeds, a cutting fluid flow rate of $150\,ml/min$ resulted in a lower RMS vibration value than at the flow rate of $300\,ml/min$. Such results were explained by increased cutting temperature, which resulted from the higher cutting speed and led to softening of the material. Cooling the cutting zone at a higher rate ($300\,ml/min$) leads to a more effective decrease in temperature than at $150\,ml/min$, which leads to limited softening of the workpiece material and generation of higher vibration RMS values. In addition to the conventional MQL method, the use of an aerosol containing nanoparticles is also being considered during studies. In their simplest form, nanofluids consist of a base fluid (usually oil) and the addition of solid particles (metals, oxides, carbides, etc.) ranging in size from 1 to $100\,nm$ [21, 22]. This composition allows more efficient heat removal from the cutting zone compared to conventional cutting fluids used in the minimum quantity lubrication method [23]. The performance of nanoparticles is based on four basic mechanisms: formation of tribofilm, mending effect, ball bearing mechanism, and polishing effect, which influence the lubrication efficiency in the cutting zone, increase tool life and the quality of the machined surface [24, 25]. Korkmaz *et al.* [26] indicate that the use of a MQL method leads to improved material cutting due to the lubricating effect. The frictional resistance is eliminated and thus the vibration of the tool is reduced, which promotes an enhancement of the machined surface quality. Maruda *et al.* [27] used copper nanoparticles of varying sizes and concentrations when turning 316L steel under MQL cooling conditions. Variable nanoparticle-related parameters were proven to have a significant effect on the RMS values of vibration accelerations, as minimum values in all three directions (main, feed and thrust) were observed when $22\,nm$ nanoparticles at a concentration of $0.5\,wt\%$ were used. Therefore, this indicates that the analysed parameters related to the composition of the nanofluid need to be correctly selected. At the same time, it was highlighted that particle size had a greater influence on vibrations than particle concentration. Yi *et al.* [28] discussed the effect of graphene oxide nanoparticles contained in a semi-synthetic cutting fluid at the concentrations of: $0.1\,wt\%$, $0.3\,wt\%$ and $0.5\,wt\%$ during turning of Ti6Al4V alloy. Based on machined surface roughness, the researchers found that the nanofluid at $0.5\,wt\%$ lubricated the cutting zone better than the conventional machining fluid, reducing turning vibrations and this enhanced machining quality. The observed phenomenon of the ability of graphene oxide nanoparticles to reduce vibrations is confirmed by a subsequent study by Yi *et al.* [29]. The same concentration values were used, thus demonstrating that vibrations during turning of Ti6Al4V alloy at a cutting fluid pressure of $0.1\,MPa$ and a feed rate of $0.05\,mm\,/\,rev$ were positively affected by the use of $0.3\,wt\%$ graphene oxide. The amplitude of vibration decreased by up to 76% compared to the base fluid. This time, a concentration of $0.5\,wt\%$ did not provide the greatest vibration reduction capability, which was justified by the deterioration of the lubricating properties of the nanofluid due to agglomeration of the nanoparticles.

It has been noticed from the abovementioned literature that, the integration of Al_2O_3 nanoparticles into machining processes, particularly in the turning of titanium alloy Ti6Al4V, presents a novel approach to enhance machining performance. Despite the abundance of literature on the topic, further investigation into the effects of the MQL method and nanofluids on vibrations in metal machining is necessary. This is because the cutting fluid's nanoparticle concentration and the MQL method's aerosol formation parameters can vary greatly. Any changes in nanoparticle-related parameters could lead to improved or worsened lubricating conditions leading to higher friction and vibration values, which could have an even greater effect when combined with properly selected aerosol formation parameters. However, there is a lack of studies from recent years that simultaneously consider all these factors and additionally compare them with MQL without nanoparticles and dry cutting. Therefore, the authors carried out a study to determine which of the aforementioned parameters has the biggest influence on the reduction of tool vibration during machining of the difficult-to-cut Ti6Al4V alloy. In addition, vibration values measured in three directions when applying the nanofluid were compared with the MQL method without nanoparticles and cutting without any coolant.

2. Experimental procedure

2.1. Nanofluid preparation

The nanofluid was prepared with $15\,nm$ Al_2O_3 nanoparticles and polyolester base fluid. To acquire mass concentrations of 0.25, 0.5, 0.75, and $1\,wt\%$, nanoparticles were weighed using an Ohaus Adventurer AX324M analytical balance. The nanoparticles were subsequently dispersed using a Hielscher UP200St ultrasonic homogeniser with base fluid. For MQL, nanofluid was deposited in a Lubrimat L60 aerosol producing device and administered to the cutting zone. Table 1 shows the exact values of the cutting fluid flow rate E and air flow rate P, which were adjusted using the Parameter Space Investigation approach during the testing.

Table 1. Parameters used for aerosol formation

Test point according to PSI	Volumetric flow rate of air $P, l/min$	Mass flow rate of cutting fluid $E, g/min$
1	25	0.752
2	35	0.46
3	15	1.06
4	30	1.182
5	10	0.606
6	20	0.89
7	40	0.388

2.2. Ti6Al4V turning and vibration measurements

The turning process was carried out on a CNC CKE6136i lathe. The chemical composition of the Ti6Al4V workpiece material was: $Fe_{max} = 0.16\%$, $O_{max} = 0.16\%$, $Al = 6.05\%$, $H_{max} < 0.0006\%$, $C_{max} = 0.012\%$, $N_{max} = 0.010\%$, $Ti \approx 89.36\%$, $V = 4.16\%$. A turning tool was used with a SVLBR2020K16 toolholder and a VBMT160404-F1 insert. The insert had an AlTiN coating applied using the PVD method, and its thickness was $3 \mu m$. However its core was made of P25 carbide. The insert had the following geometry: major cutting edge angle $\kappa_r = 95°$, major cutting edge inclination angle $\lambda_s = 5°$, corner radius $r_\varepsilon = 0.4\,mm$, minor cutting edge angle $\kappa_r' = 50°$, corner angle $\varepsilon = 35°$. The cutting parameters during turning were chosen according to the tool manufacturer's recommendations: $v_c = 70\,m/min$, $f = 0.065\,mm/rev$, $a_p = 0.6\,mm$, and the cooling methods applied included: MQL method with Al_2O_3 nanoparticles, MQL method without nanoparticles, dry cutting.

Measurements of the vibration acceleration of the turning tool-tool post system were made using a Brüel and Kjær type 4321 three-component piezoelectric accelerometer, mounted on the tool post of a dynamometer. The signal measured by the meter was sent to a Brüel & Kjaer Nexus 2692/OS4 charge amplifier and then to an analogue-to-digital converter and computer, where it was recorded using signal analysis software. The entire experimental set-up, including the measurement apparatus, is shown in Fig.1.

In the tests, the signal sampling frequency was $f_{pr} \approx 16\,384\,Hz$. The tangential direction (main) – tangential vibration acceleration (main) A_c, feed direction – feed vibration acceleration A_f, and thrust direction – thrust vibration acceleration A_p were measured. For each process input parameter combination, measurements were taken three times to analyze them. A time interval without cutting tool input or output was used to calculate vibration acceleration. To analyze the stabilized signal, the cutting layer cross-section variability in input and output time intervals and dynamic interactions between machine-tool-holder-workpiece system elements during tool penetration were ignored.

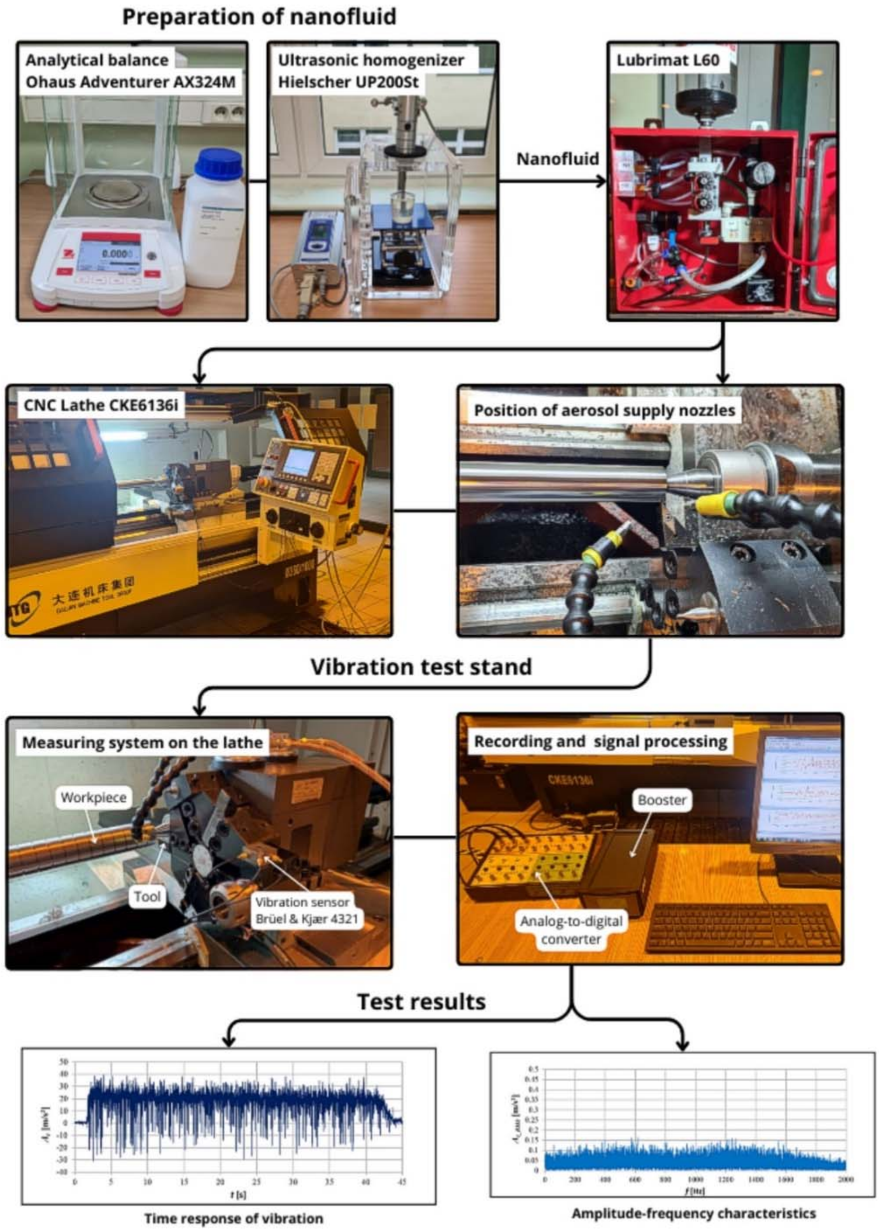

Fig.1. Experimental set-up for conducted studies.

3. Results and discussion

In the first step of the analysis of the vibrations recorded during the longitudinal turning process of titanium alloy Ti6Al4V, their time courses were evaluated in terms of variable cooling/lubrication methods. Accordingly, Figure 2 presents examples of the vibration time courses for dry cutting, turning while using the MQL method without nanoparticles and under the conditions of the MQL+Al_2O_3 $0.5\,wt\%15\,nm$.

In a longitudinal turning process with constant cutting parameters, the nominal cross-sectional area of the machined layer is constant over time. Therefore, the force and vibration signals recorded during the process should be characterised by relative constancy in the time domain. Some short-term variations in the signals of physical phenomena occurring during longitudinal turning are caused by the penetration and exit of the tool from the workpiece material.

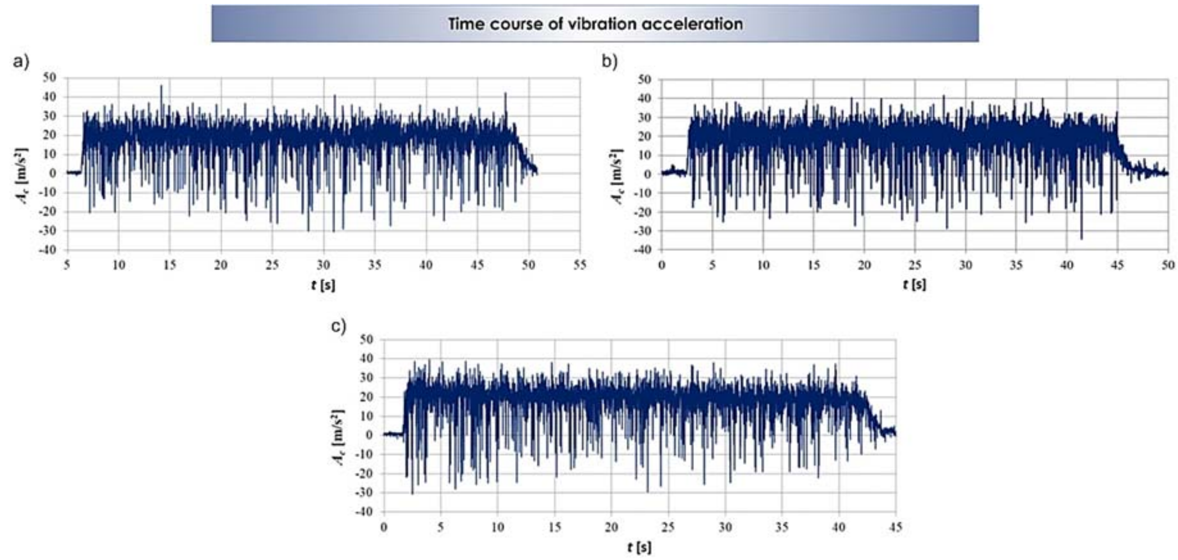

Fig.2. Time domain signals at: a) dry cutting, b) MQL without nanoparticles ($E=0.752\,g/min$; $P=25\,l/min$), c) MQL + Al_2O_3 $15\,nm\,0.5\,wt\%$ ($E=0.752\,g/min$; $P=25\,l/min$).

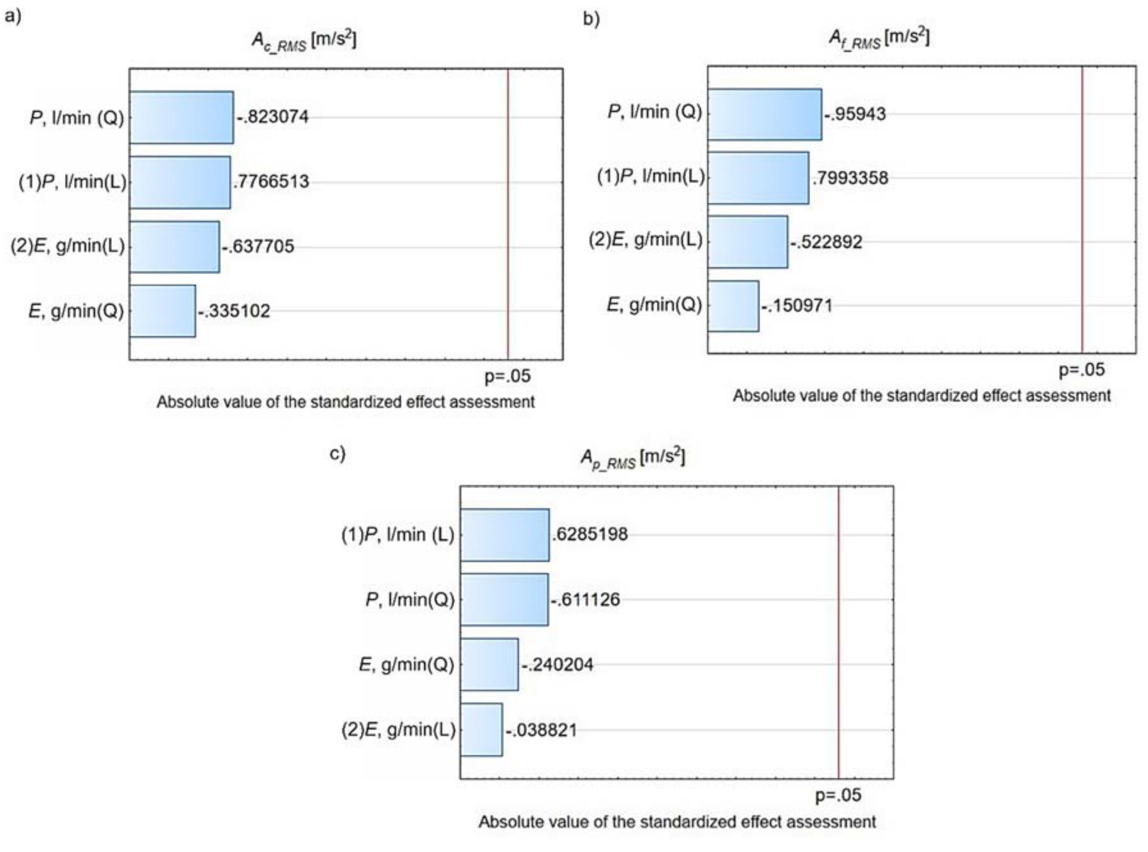

Fig.3. Pareto plot showing standardized effects for active medium formation parameters P and E and vibration acceleration signal components: a) A_{c_RMS} , b) A_{f_RMS} ,, c) A_{p_RMS} ,. Machining under MQL conditions without nanoparticles.

According to Fig.2, it can be observed that, regardless of the cooling/lubrication method and the type of cutting fluid, the longitudinal turning process is uniform, with no significant oscillations of the vibration acceleration signals. The recorded variations in vibration signals only correspond to the periods of input and output of the tool from the workpiece material. This suggests that no unfavourable self-excited or resonant vibrations were generated during the turning process and, in addition, the machining was carried out with relatively constant values of the actual cutting parameters (depth and feed).

The next stage of the analysis involved establishing a statistical measure – the root mean square (RMS) value – of vibration acceleration for various process input parameters, as well as determining the statistical significance of the effect of selected aforementioned parameters on RMS values of vibration acceleration. Regression models in the form of quadratic equations of two and three variables were adopted to include non-monotonic influence of process input parameters on RMS values of vibration acceleration. Then, with reference to the defined RMS values of vibration acceleration (for the process input quantities studied) and the regression equations generated in Statistica 13 software (RMS measures of vibration acceleration), an ANOVA analysis of variance was performed. As a result of the analysis, Pareto plots of standardised effects were generated (Figs 3-4), comparing the absolute values of the standardised effect assessment for the studied input quantities, relating them to a linear L and quadratic Q relationship.

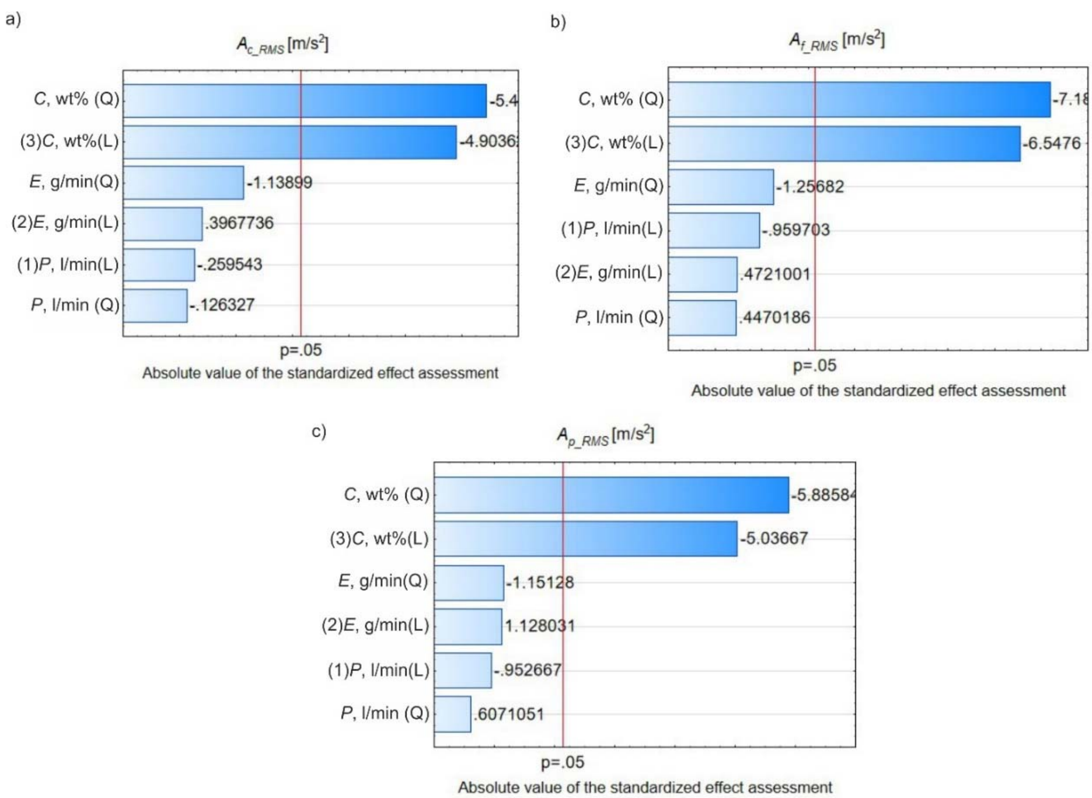

Fig.4. Pareto plot showing standardized effects for active medium formation parameters P and E and vibration acceleration signal components: a) A_{c_RMS}, b) A_{f_RMS}, c) A_{p_RMS}. Machining under MQL + Al_2O_3.

Figure 3 presents Pareto plots of standardised effects for the RMS values of vibration accelerations generated during turning using the MQL method (without nanoparticles), with the active medium formation parameters P and E as input quantities. The active medium formation parameters P and E do not have a statistically significant effect on the RMS values of vibration accelerations in the examined directions during the turning process using the MQL method in the investigated range of input quantities, when considering both their quadratic and linear effects on vibrations. Turning under MQL settings with Al_2O_3 nanoparticles highlighted the impact of cutting fluid flow parameters P and E and nanoparticle mass concentration in nanofluid C (Fig.4). From the analysis of standardised effect Pareto plots (Fig.4), it was found that, regardless of the vibration acceleration component (A_{c_RMS}, A_{f_RMS}, A_{p_RMS}), only the value of the nanoparticle mass concentration in the nanofluid C had a statistically significant influence on the vibration RMS values. The analysis carried out contributed to the selection of input quantities having a statistical effect on the RMS values of vibrations generated during turning under MQL + Al_2O_3 conditions.

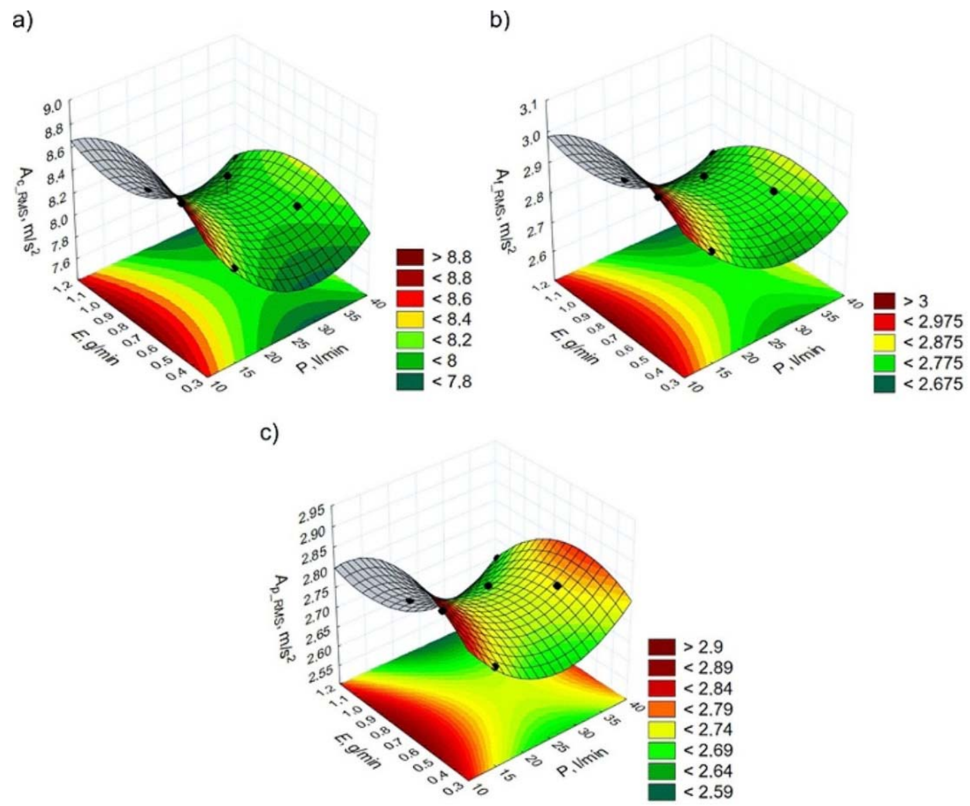

Fig.5. RMS values of vibration acceleration as a function of active medium formation parameters E and P (without nano particles): a) main direction (A_{c_RMS}); b) feed direction (A_{f_RMS}); c) thrust direction (A_{p_RMS}).

Figure 5 illustrates the influence of aerosol generation parameters on the root mean square (RMS) values of vibration acceleration in all three directions during turning in the Minimum Quantity Lubrication (MQL) method without the presence of nanoparticles. The RMS values of vibration accelerations in the main direction (Fig.5a) showed that turning with higher air flows ($P=25-40 l/min$) and in the range of maximum and minimum cutting fluid flow rates E had the lowest A_{c_RMS} values. Smaller droplets and higher air vector velocities may help droplets penetrate the workpiece-tool contact area [30]. The RMS values of vibration acceleration in feed (Fig.5b) and thrust (Fig.5c) followed a similar pattern to the main direction. The study investigates the impact of Al_2O_3 nanoparticle mass concentration (C) in the cutting fluid on the root mean square (RMS) values of vibration acceleration in three examined directions during turning, as illustrated in

Fig.6. Notably, the parameter concerning the mass flow rate of the cutting fluid (E) was excluded from the analysis due to its statistically insignificant influence.

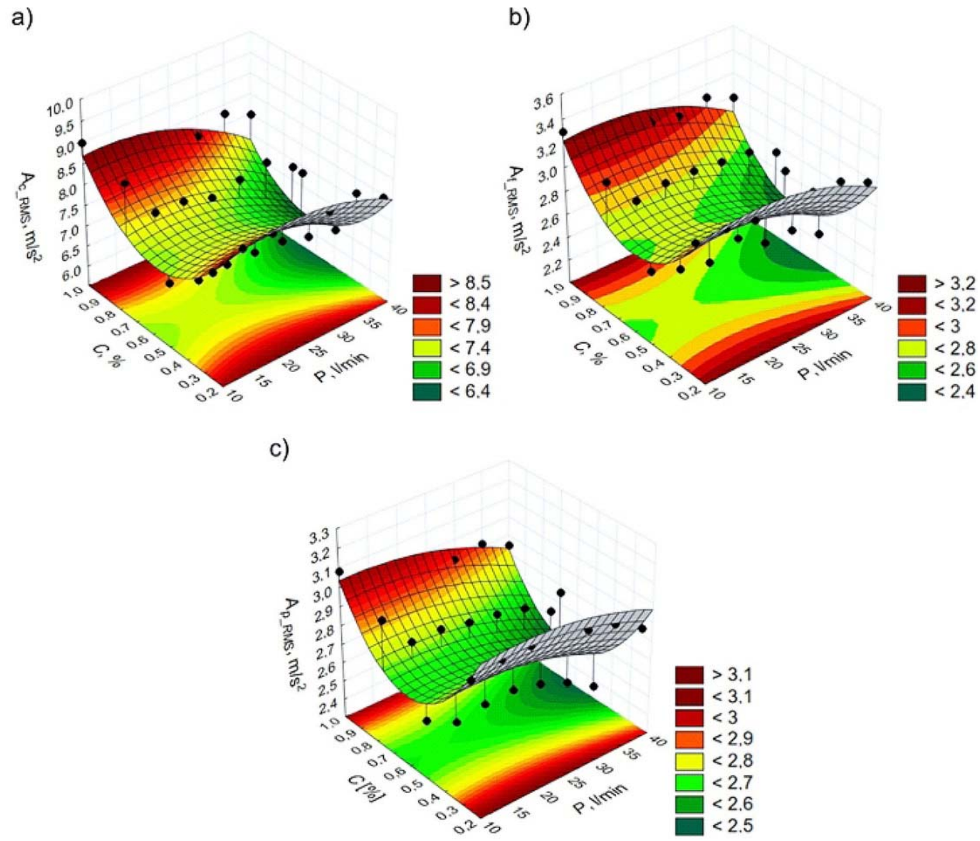

Fig.6. RMS values of vibration accelerations under conditions of MQL + Al_2O_3, as a function of C and P parameters: a) main direction (A_{c_RMS}); b) feed direction (A_{f_RMS}); c) thrust direction (A_{p_RMS}).

As shown in Fig.7, the RMS value of vibration acceleration for the three directions during the turning of Ti6Al4V titanium alloy is affected by the mass concentration of Al_2O_3 nanoparticles added into the cutting fluid using the MQL method.

Turning with nanofluid containing $0.5\,wt\%$ Al_2O_3 nanoparticles in minimum quantity lubrication had the lowest RMS vibration acceleration (Fig.7). Vibrations in the three measured directions were reduced from 10.1 to $17.4\,wt\%$ utilizing nanofluid with such nanoparticle concentration compared to $0.75\,wt\%$. Comparing vibration values obtained during turning with the minimum and highest mass concentration C of Al_2O_3 nanoparticles in the cutting fluid showed a 16.7% to 24.3% difference. Research indicates that using $0.5\,wt\%$ aluminium (III) oxide nanofluids in the $0.25-1\,wt\%$ concentration range enhances cutting fluid penetration into the tool-chip contact area by enhancing thermal properties and rolling friction between the tool and chip [31]. For high air flow rate P, vibration acceleration RMS in all three directions was minimal. According to Maruda *et al.* [32], P values above $20\,l/min$ cause aerosol droplets with small diameters, increased spray angle, and air velocities, which help droplets penetrate the cutting zone and increase aerosol lubrication. This could explain the aerosol's capacity to lower RMS vibration acceleration at $P=30-35\,l/min$.

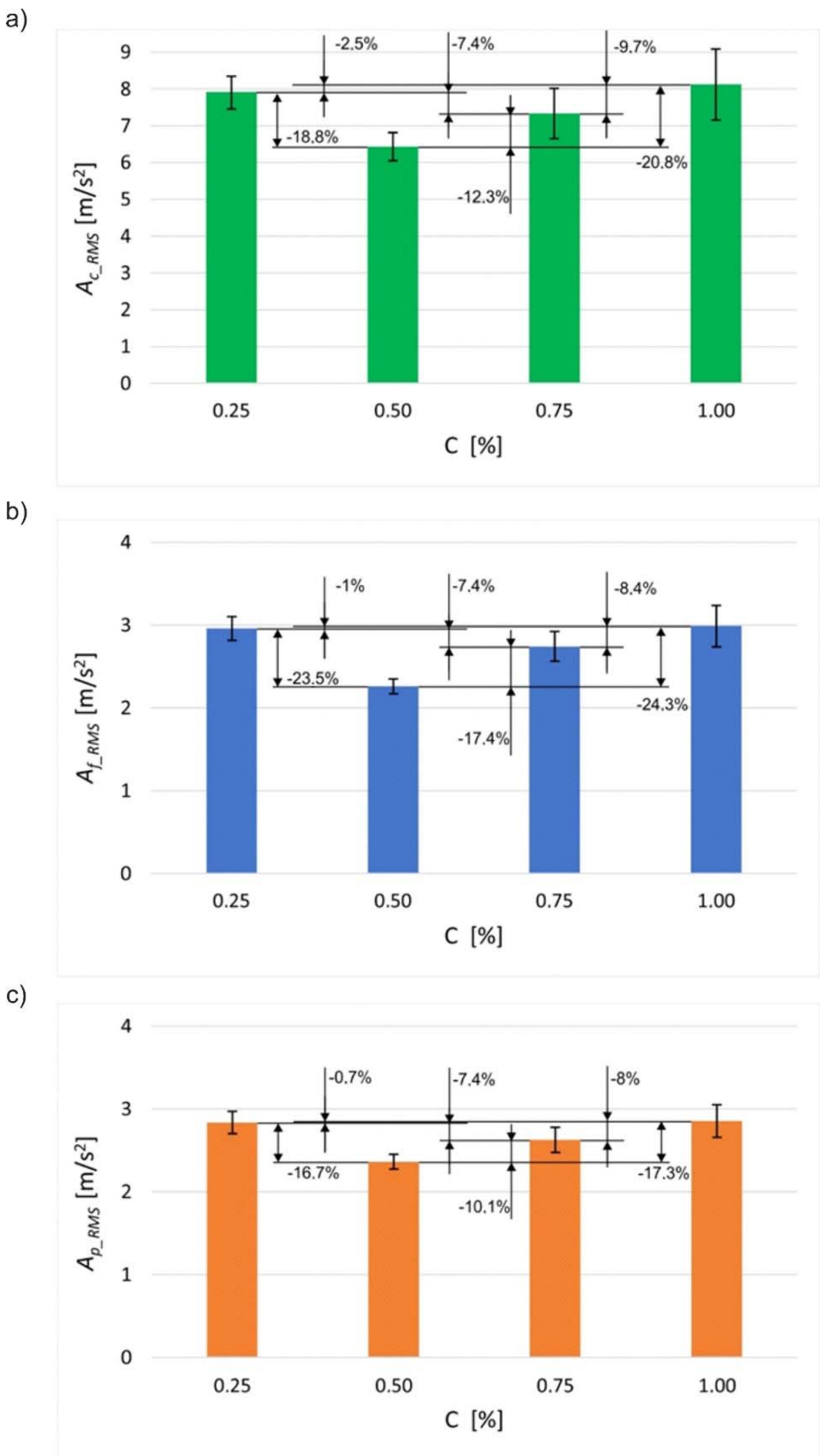

Fig.7. RMS values of vibration acceleration with varying Al_2O_3 nanoparticles mass concentration at a) main, b) feed, c) thrust direction.

In the final step of tool vibration analysis during turning, the RMS vibration acceleration values for the cooling/lubrication strategies were compared (Fig.8). Therefore, the lowest RMS vibration acceleration values in proportion to nanoparticle mass concentration in the MQL method were selected and compared with dry cutting and the MQL method without nanoparticles at PSI point 7: $E=0.388\,g\,/\,min$ and $P=40l\,/\,min$.

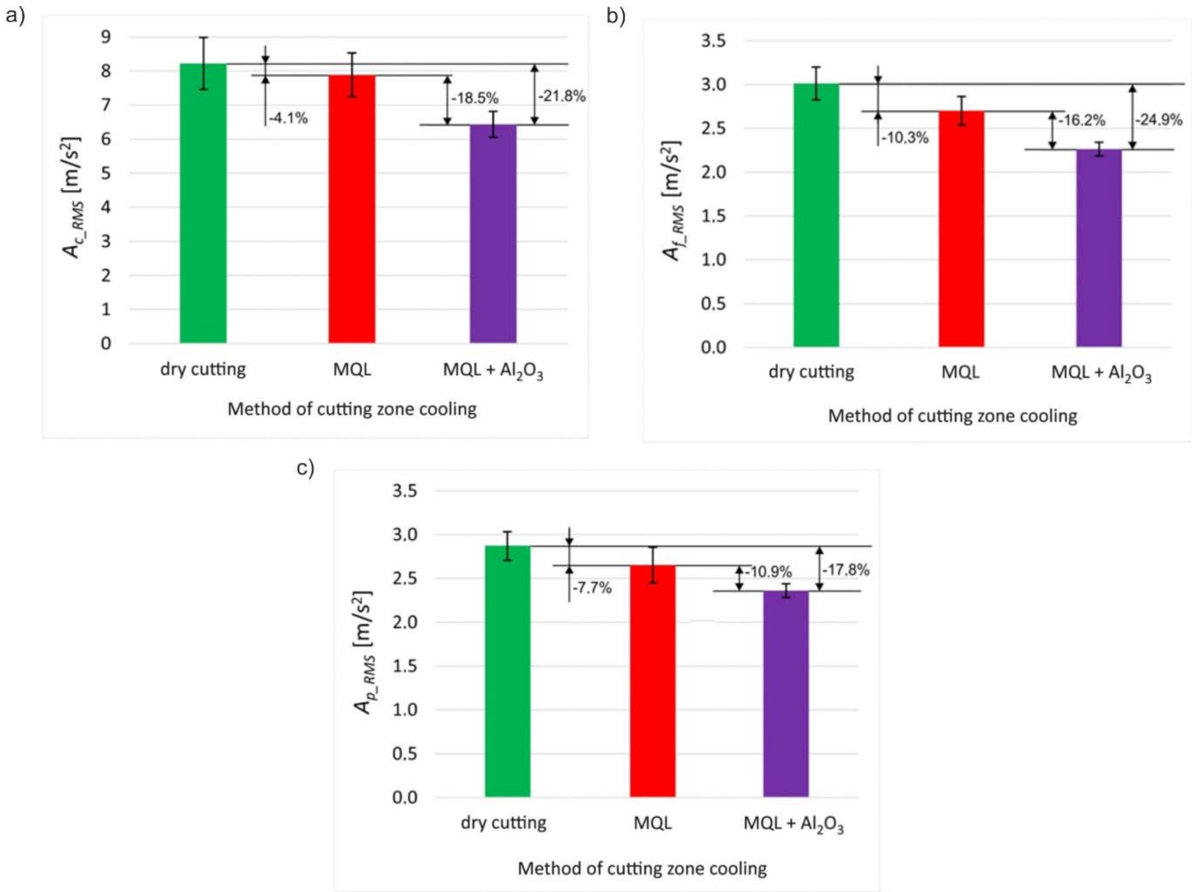

Fig.8. Overall results of RMS values under different conditions a) main direction, b) feed direction, c) thrust direction.

It was found that for most of the cutting zone cooling methods studied, the RMS values of vibration accelerations generated during turning as a function of the variation in the aerosol formation parameters were comparable, regardless of the direction of vibration interaction. When considering the lowest vibration values for the individual cooling methods (Fig.8), it was observed that the minimum RMS values of vibration accelerations in all three direction were obtained during turning under MQL conditions with $0.5\,wt\%$ Al_2O_3 nanoparticles. In this case, the vibration acceleration values are significantly smaller than the corresponding RMS values of vibration generated during turning using the other cutting zone cooling methods. This relationship suggests that from the point of view of minimizing vibration accelerations in the longitudinal turning process of titanium alloy, the MQL method with the addition of Al_2O_3 nanoparticles at a concentration of $0.5\,wt\%$ should be applied. Compared to the minimum quantity lubrication method without nanoparticles and dry machining, Al_2O_3 nanoparticles caused a decrease in vibration in the main direction by 18.5% and 21.8%, in the feed direction by 16.2% and 24.9%, and in the thrust direction by 10.9% and 17.8%. As presented by Tiwari and Amarnath [33], higher RMS values of vibration during dry cutting could be explained by the lack of cutting fluid, which led to an elevated friction coefficient in the tool-workpiece contact area.

The MQL method provided an aerosol that could easily penetrate the cutting zone therefore improving the lubrication in the tool-workpiece interface and lowering tool vibrations. However, the MQL without the nanoparticles could not provide a formation of tribofilm layer which could further lower the RMS values, which explaines the lowest values obtained for MQL with Al_2O_3. Overall, in the case of dry cutting and turning with the MQL method, the differences in the generated vibration values are insignificant and may only be a result of some random phenomena occurring in the machining process.

4. Conclusions

The research showed that Al_2O_3 nanoparticles, their concentration, and MQL aerosol production parameters affect vibration acceleration values during turning the difficult-to-cut Ti6Al4V alloy. The analyses drawn the following conclusions:

- After establishing the statistical significance of the effect of input parameters (mass flow rate of cutting fluid E, volumetric flow rate of air P, and mass concentration of Al_2O_3 nanoparticles C in nanofluids) on vibration acceleration RMS values, the concentration of nanoparticles showed the greatest effect. Parameters P and E do not significantly affect vibration acceleration RMS values.
- RMS vibration acceleration measurements for machining in MQL without and with Al_2O_3 nanoparticles show that air flow above $20 l/min$ lowers the parameter in both directions. Droplet sizes are smaller, air vector velocities are higher, and machining fluid penetrates the cutting zone better. Nanofluids are affected by nanoparticle mass concentration. Thus, larger P values and $0.5 wt\%$ nanoparticle concentration produce the lowest RMS vibration acceleration. The nanofluid's enhanced thermal characteristics and nanoparticle-induced rolling friction may increase tool-workpiece material-chip contact area penetration.
- Nanofluids with a concentration of $0.5 wt\%$ Al_2O_3 nanoparticles were determined to have the greatest efficacy in lowering the RMS value of vibration acceleration when compared to the MQL method and dry cutting. Reducing the considered parameter from 10.9% to 18.5% compared to the MQL method and from $17.8\% A_f$ to 24.9% compared to dry cutting are the outcomes of the MQL + Al_2O_3 approach.

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Nomenclature

A_c – tangential (main) vibration acceleration
– acceleration of the vibration in the feed direction
A_p – acceleration of the vibration in the thrust direction
a_p – depth of cut
C – nanoparticles concentration of Al_2O_3 nanoparticles
E – mass flow rate of cutting fluid air flow rate
f – feed rate
L – linear relationship used in the standardised effect assessment for the input quantities
P – volumetric flow rate of air

Q – quadratic relationship used in the standardised effect assessment for the input quantities

r_ε – corner radius

t – time

v_c – cutting speed

ε – corner angle

κ_r – major cutting edge angle

κ_r' – minor cutting edge angle

λ_s – major cutting edge inclination angle

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