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Analysis of Power Grid Parameters Depending on the Variable Concentration and Size of Copper Nanoparticles and Aerosol Formation Parameters in the Minimum Quantity Lubrication Method during Turning of Ti6Al4V Titanium Alloy

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ABSTRACT

Titanium alloys belong to the group of difficult-to-cut materials, machining of which leads to a number of challenges including large thermal loads on the cutting inserts and difficulties in obtaining a high quality machined surface. Great cutting forces, in turn, result in increased energy consumption. Therefore, it becomes important to attempt to reduce the amount of power consumed during machining, which can be achieved, among other things, by reducing the value of the coefficient of friction in the cutting zone. This paper presents a study on the influence of the size as well as the Cu nanoparticle concentration added to cutting fluid in MQL method on the power grid parameters while turning of Ti6Al4V titanium alloy. In this research, nanoparticles of 22 nm and 65 nm at concentrations of 0.5 wt% and 0.75 wt% were used. Turning process was carried out with constant cutting parameters and variable aerosol formation parameters, i.e. mass flow rate of nanofluid and volumetric flow rate of air. Based on the study, the use of 22 nm nanoparticles at 0.5 wt% concentration is recommended to achieve the smallest monitored values of the power grid parameters. The statistical analysis revealed that, out of the aerosol formation parameters considered, both the air flow rate and nanofluid flow rate do not significantly affect the values of the analysed power network parameters. However, the most significant factor is the variable nanoparticle size.

Keywords: copper nanoparticles, MQL, nanofluids, active power, apparent power.

INTRODUCTION

Over the last few years, there has been an increase in public environmental awareness, extending not only to the aspects of everyday life, but also to industry. The industrial sector is responsible for the consumption of approximately 31% of total energy in the USA, with 60% of this energy related to manufacturing [1]. Increased energy consumption, on the other hand, is associated with greater carbon dioxide emissions, reaching up to 36% for industry [2], so reducing this phenomenon is an extremely important issue in terms of minimising global warming and climate change [3]. As metalworking is a major consumer of energy, the choice of cutting fluid as well as cutting parameters has a huge impact on the potential for energy savings [4,5]. The machining of titanium alloys, which are widely used in the biomedical [6–8] and aerospace [9–11] industries, is challenging not only in terms of cutting tool wear, but also due to the high temperatures generated in the cutting zone [12]. Therefore, abandoning the use of cutting fluids is not a good option for difficult-to-cut materials. As a result, wet machining is used, which effectively reduces the temperature during machining, but at the same time poses health and environmental risks, especially when mineral oils are used as coolants [13, 14]. Shokrani et al. [15] also point out that this method of cooling is associated with an increase of 40% in energy consumption compared to dry machining, which is closely related to the operation of the pump feeding the machining fluid. The authors mention that this is also a result of hardening of the workpiece, leading to an increase in cutting forces and, consequently, the amount of energy used to machine the Ti6Al4V alloy. While this phenomenon is not very significant when machining steel, it is crucial when cutting titanium alloys, the machining of which involves high temperatures. The study indicates that the use of wet machining is not a good solution in economic terms.

As a consequence, different ways of cooling the cutting zone are being researched that would maintain the benefits of using cutting fluids, while reducing the negative environmental impact. For this reason, researchers have focused, among other things, on the minimum quantity lubrication (MQL) method, in which an aerosol based on compressed air and cutting fluid is supplied to the cutting zone. This method of cooling can provide an alternative to wet machining and is also much more environmentally friendly [16]. While in most cases it can reduce friction and temperature in the cutting zone, sometimes it does not provide a high level of effectiveness in this area [17].

According to Obikawa et al. [18], when grooving with an uncoated P25 carbide tool, the MQL method provided a lower chip temperature of 300 K, but compared to wet machining, the temperature was 100 K higher. The authors emphasise that the ability to cool the cutting zone during aerosol application is directly related to the tool material. Therefore, solutions are being sought to improve both the lubricating and cooling properties of the aerosol used in the MQL method, with one of them being the addition of nanoparticles to cutting fluids [16, 19]. Such a solution can significantly affect the thermal properties of coolants, since it is known that liquids have a much lower thermal conductivity than solids [20]. In addition, particles with the size less than 100 nm added to the cutting fluid often contribute to the formation of a layer of lubricating film between the tool and the workpiece, leading to an improvement in the lubricating properties of the coolant [21]. The action of nanoparticles is based on four basic mechanisms, such as tribofilm formation [22–24], polishing effect [25–27], mending effect [28–30] and ball-bearing effect, also known as rolling effect [31–33]. Songmei et al. [34] proved that the use of nanoparticles during MQL cooling can improve machining conditions when milling Ti6Al4V alloy. However, the authors pointed out that the best results in terms of cutting force reduction were obtained when copper nanoparticles were used, while the best results in terms of surface roughness were obtained after the use of graphite nanoparticles. The nanofluid containing copper provided an 8.84% reduction in cutting force compared to the aerosol without the addition of nanoparticles. This is particularly important from the point of view of decreasing energy consumption during machining, as the values of the main cutting force Fz are closely related to power and specific energy consumption [35,36].

The effect of the MQL method with nanoparticles on the cutting force values is also confirmed by the study of Usluer et al. [37]. Four cooling methods were used when turning S235JR steel: dry cutting, MQL, MQL with Multi-Walled Carbon Nanotubes (MWCNTs) at a concentration of 0.2%, MQL with MWCNTs and MoS_2 at concentrations of 0.1%. The authors demonstrated that by using the MQL method with an aerosol containing only MWCNTs, the lowest cutting force and thrust force values were obtained compared to the other cooling methods. In addition, a reduction in machining costs of 61%, 73% and 76% was also reported when compared to the MQL method with MWCNTs and MoS_2, the MQL method and dry machining due to reduced energy consumption and increased tool life. Thakur et al. [38] used SiC nanoparticles with concentrations of 0.5 wt%, 1 wt% and 1.5 wt% and carried out turning of EN-24 steel under MQL cooling conditions. Compared to an aerosol containing no nanoparticles, the use of a nanofluid with a concentration of 1.5 wt% resulted in the lowest main cutting force values. The authors pointed out that SiC nanoparticles are responsible for this, as they created a layer of tribofilm between the tool and the workpiece, and its thickness increased with nanoparticle concentration. It reduced the friction coefficient, which, by lowering the frictional force, led to a reduction in cutting force. Padhan et al. [39]analysed the effect of the MQL method with nanoparticles on energy consumption when turning AISI D3 steel. The nanofluid was prepared by adding 2.5 mg of graphene nanoparticles to 500 ml of base fluid. Its performance was compared with dry machining, which showed that the minimum quantity lubrication method with nanofluid had a significant impact on lowering the energy consumed during machining, due to the effective cooling and lubrication of the cutting zone. In contrast, dry machining resulted in the generation of high temperatures. When grinding the Ti6Al4V alloy, Ahmed and González [40] demonstrated a significant effect of graphene nanofluids on energy consumption. As a result of using nanofluid at a concentration of 0.1 wt%, specific cutting energy was reduced by up to 93% and 91%, respectively, compared to dry machining and MQL cooling conditions. In addition, a reduction in cutting forces was also observed. Makhesana et al. [14] conducted a study during turning of Inconel 690 alloy, which also confirms the positive effect of nanofluids on decreasing the amount of energy consumed. The authors used 1 wt% MoS_2 nanoparticles in the cutting fluid and compared such a modified MQL method with dry machining, wet machining and an MQL method without nanoparticles. It was found that the MQL method with nanoparticles resulted in a 56%, 39% and 12% reduction in energy consumption compared to the dry, wet and minimum quantity lubrication methods. The authors explained that this was a result of effective heat removal from the cutting zone, as well as lowered friction due to the MoS_2 nanoparticle penetration of the cutting tool–workpiece material interface. Increased lubricating properties of the nanofluid, corresponding to a reduction in cutting forces and leading to a decrease in energy consumption, were also pointed out.

Despite numerous studies on the influence of the nanoparticles used in the MQL method on energy consumption, there is a lack of research discussing these issues in relation to the aerosol formation parameters, that affect its ability to penetrate the cutting zone. This paper presents the important aspects of the proper selection and effect of the nanoparticle concentration and their size, when introduced into the cutting fluid, on selected values of power network parameters. For this purpose, an experiment was carried out in which variable values of both the volumetric flow rate of air and mass flow rate of nanofluid, as well as variable values of both the Cu nanoparticle concentration and size were used during the MQL turning of Ti6Al4V alloy.

MATERIALS AND METHODS

Aerosol preparation

To prepare the nanofluid used in the aerosol of the MQL method, copper nanoparticles of sizes: 22 nm and 65 nm at concentrations of 0.5 wt% and 0.75 wt% were used. A polyol ester based cutting fluid with the properties shown in Table 1 was used as the base fluid. Dispersion of the copper nanoparticles in the base fluid was carried out for one hour using a Hielscher UP200St ultrasonic homogeniser. Prepared nanofluid was then placed in a Steidle Lubrimat L60 apparatus, which is a two-channel device with adjustable air and cutting fluid flow rates. The nozzles spraying the aerosol were directed at the flank and rake surfaces of the tool at a distance of 0.05 m [41]. During the tests, variable aerosol formation parameters (volumetric flow rate of air Q_A and mass flow rate of nanofluid E) were used, the values of which, in relation to the test points defined by the Parameter Space Investigation (PSI) method [41], are shown in Table 2.

Turning process

Turning was carried out on a DMTG CKE6136i CNC lathe using a VBMT160404-F1 cutting insert and a SVLBR2020K16 toolholder. The workpiece material was Ti6Al4V titanium alloy, which is widely used for biomedical implants, airframes of jet engines or turbine blades due to its corrosion resistance and ability to operate at high temperatures [42,43]. Machining was performed with constant cutting parameters: v_c = 70 m/min, f = 0.065 mm/rev, a_p = 0.6 mm, selected according to the recommendations of the cutting insert manufacturer.

Table 1. Properties of cutting fluid based on polyol ester provided by Carl Bechem GmbH

Kinematic viscosity (at 40°C), mm^2/s	Density (at 15°C), g/cm^3	Solidification point, °C	Flash point, °C
0.915−0.930	41.4−50.6	≤ -40	≥ 290

Table 2. Aerosol formation parameters

Aerosol formation parameter	Test point number (according to PSI)						
	1	2	3	4	5	6	7
Q_A, l/min	25	35	15	30	10	20	40
E, g/min	0.752	0.46	1.06	1.182	0.606	0.89	0.388

Power and voltage measurements

For power and voltage measurements, a Lumel ND30loT 1-phase and 3-phase network parameter meter was used, enabling the measurement of 54 harmonic and energy parameters of current and voltage. By using this meter, the values of active power P, apparent power S and voltage U were monitored during turning with variable aerosol formation parameters and variable sizes and concentrations of copper nanoparticles. Three repetitions were performed for each test. The network parameter meter, the cutting insert geometry and CNC lathe used for the experiment are shown in Figure 1.

RESULTS AND DISCUSSION

Based on the results acquired when MQL turning of Ti6Al4V alloy with copper nanoparticles, a statistical analysis was performed using Statistica 13 software. The significance of the influence of the input values: volumetric flow rate of air Q_A, mass flow rate of nanofluid E, copper nanoparticle size s and concentration C, on the output values: active power P, apparent power S and voltage U, was determined by means of Pareto plots (Fig. 2–4). Analysis of the obtained results (Fig. 2) revealed that, out of the four input parameters considered, only the parameters regarding variable nanoparticle mass concentration and size have a significant influence on the active power P values. Such a high importance of the proper selection of these two variable parameters may be due to the fact that copper nanoparticles cause a reduction in friction in the tool-workpiece material contact zone, and are also responsible for the ball bearing effect between the chip and the tool [44]. This results in a lower cutting force in contrast to the minimum quantity lubrication without any nanoparticles, and thus lower energy consumption during machining. The ability to choose the right nanoparticle concentration and size when introducing them into the cutting fluid was also emphasised in a study by Maruda et al. [19], when investigating machined surface topography and tool vibration. From a statistical point of view, the size of the nanoparticles has the greatest influence on the active power P, followed by the mass concentration. This means that, in order to obtain the lowest possible value of the active power P used when turning of Ti6Al4V under minimum quantity lubrication cooling method, it

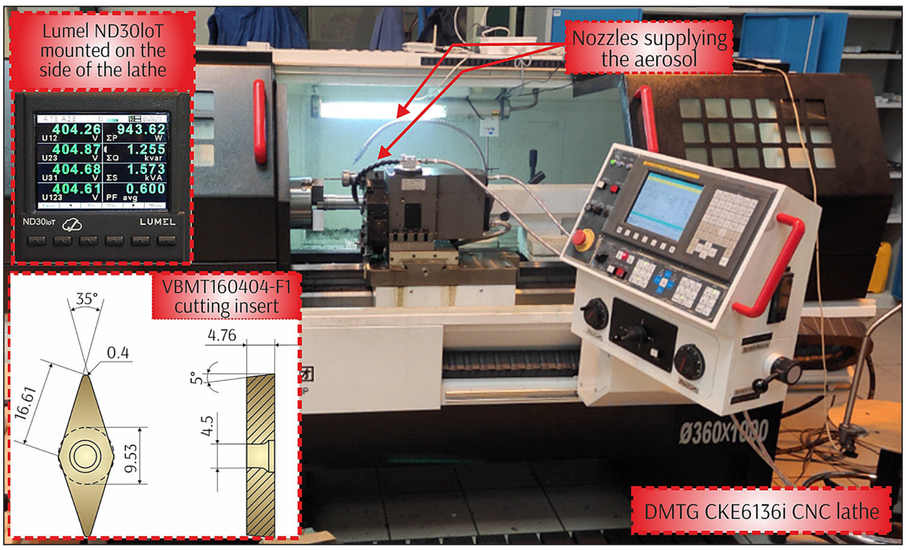

Fig. 1. Equipment used for the experimental studies

is essential to focus on the proper selection of nanoparticle concentration and size when contained in a nanofluid. Similarly to the active power P (Fig. 2), a parameter related to the nanoparticle size shows a significant influence on the apparent power value S (Fig. 3). Furthermore, there was no noticeable effect of the aerosol formation parameters on the analysed power S and P according to the values selected by the PSI method. In the case of voltage U (Fig. 4), no significant effect was observed for any of the considered input parameters.

Based on the evaluation of the significant influence of the individual parameters obtained from the Pareto charts analysis, surface charts were prepared (Fig. 5–7), showing the selection of the values of the variables so as to acquire the

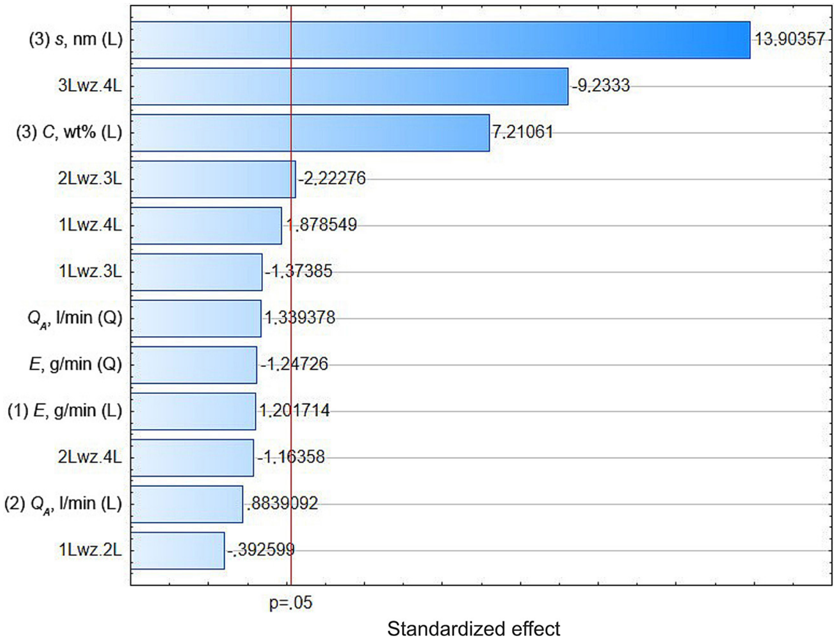

Fig. 2. Pareto chart of standardised effects for aerosol formation parameters Q_A and E, nanoparticle size s, nanoparticle concentration C and active power P when turning of Ti6Al4V with MQL method

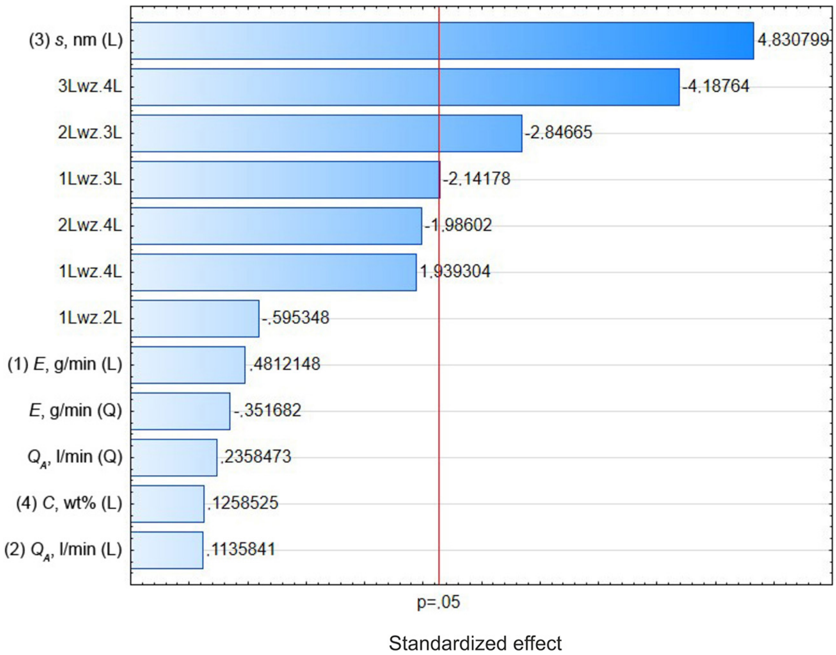

Fig. 3. Pareto chart of standardised effects for aerosol formation parameters Q_A and E, nanoparticle size s, nanoparticle concentration C and apparent power S when turning of Ti6Al4V with MQL method

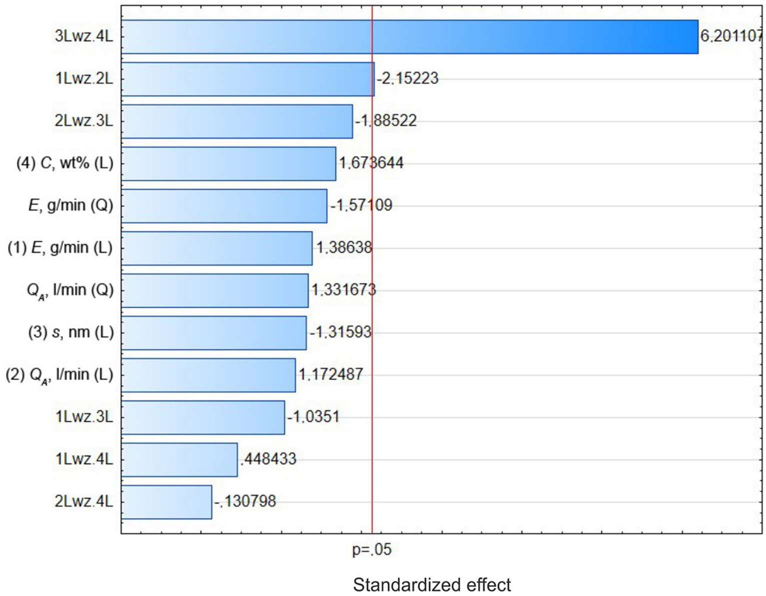

Fig. 4. Pareto chart of standardised effects for aerosol formation parameters Q_A and E, nanoparticle size s, nanoparticle concentration C and voltage U when turning of Ti6Al4V with MQL method

smallest values of the output parameters, i.e. active power *P,* apparent power *S* and voltage *U*. The parameters that, according to the Pareto plots, showed the greatest significance on the value of the selected power network parameter, were displayed on the X and Y axes in Fig. 5−7. When analysing the active power values (Fig. 5), it was observed that the lowest *P* values were obtained when using a 22 nm nanoparticles at 0.5 wt%. In contrast, maximum active power values were found for *C* = 0.75 wt% and *s* = 65 nm. Ali et al. [45] indicate that increasing the nanoparticle concentration from 0.5 wt% to 0.8 wt% can lead to a formation of nanoparticle agglomerations, resulting in an increase in friction coefficient and cutting force. Ultimately, this causes an increase in energy consumption during machining. Thus, this may explain the maximum value of active power *P* obtained at a mass concentration of Cu nanoparticles above 0.75 wt%.

From the relation illustrating the effect of nanoparticle size *s* and nanofluid mass flow rate *E* on the apparent power values (Fig. 6), it can be concluded that, as in the case of active power *P* (Fig. 5), minimum *S* values are achieved when using nanoparticles of the smallest size. The lowest apparent power values with regard to nanofluid flow rate were observed in the range of E = 0.3−0.6 g/min. According to the relation showing the influence of the nanoparticle concentration and nanofluid mass flow rate on the voltage values (Fig. 7), favourable results are obtained for the entire considered range of concentration *C* and *E* ranging from 0.3 to 0.45 g/min. The minimum voltage value *U* was observed for *E* ranging from 0.3 up to 0.35 g/min. However, the maximum voltage values were observed when the flow rate of the nanofluid was in the range of 0.7−1 g/min. An analysis of the results shown in Fig. 8 revealed that the minimum values of active power *P* were obtained using 22 nm nanoparticles at 0.5 wt%. This is because smaller nanoparticles are able to penetrate the cutting zone more effectively

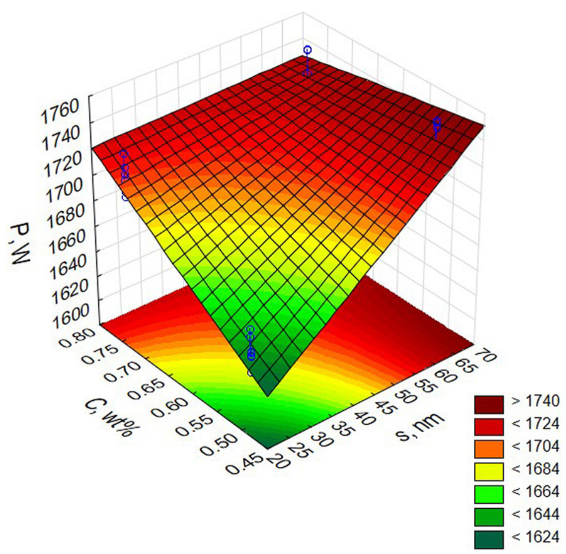

Fig. 5. Influence of the nanoparticle concentration *C* and size *s* in the MQL method on active power values *P* during turning of Ti6Al4V alloy

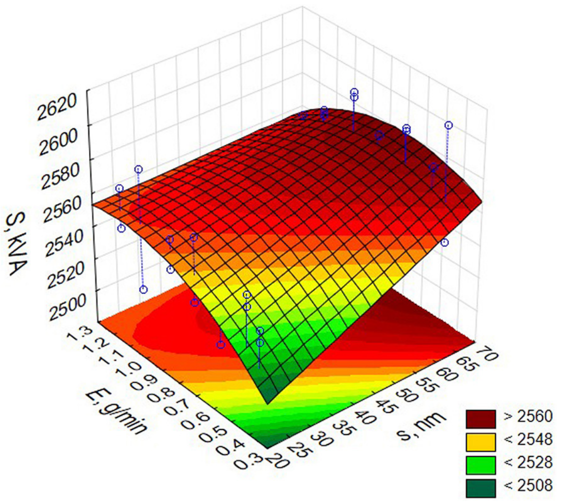

Fig. 6. Influence of the nanoparticle size *s* and nanofluid mass flow rate *E* on apparent power values *S* when turning of Ti6Al4V

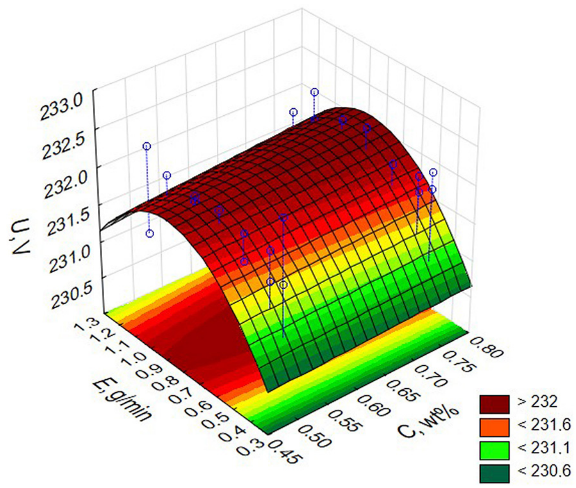

Fig. 7. Influence of the nanoparticle concentration *C* and nanofluid mass flow rate *E* on voltage values *U* when turning of Ti6Al4V

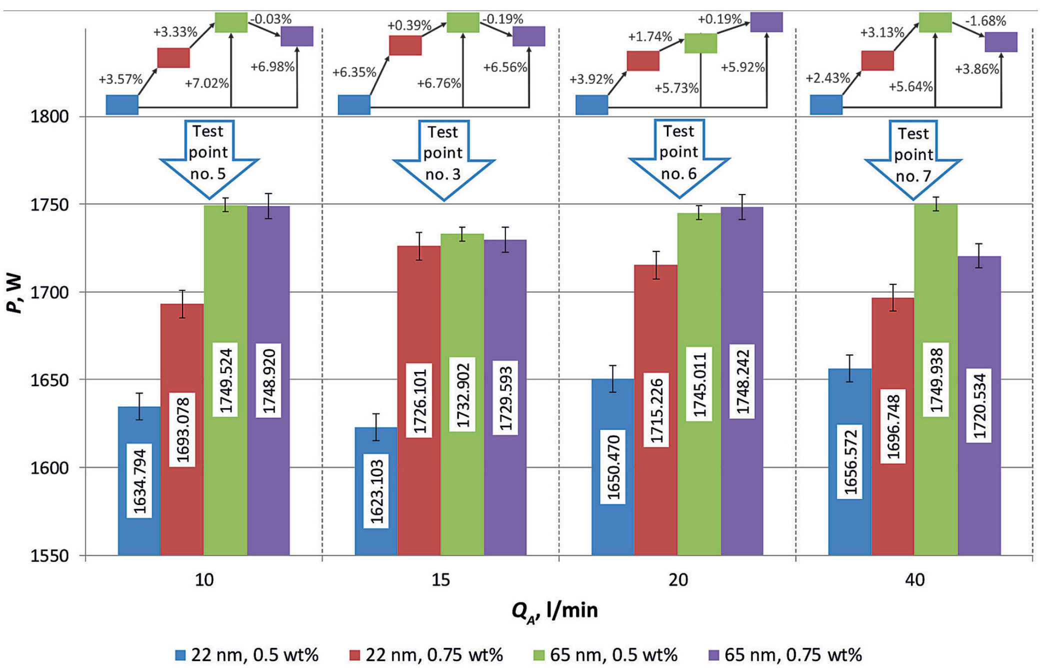

Fig. 8. The effect of volumetric flow rate of air Q_A on the active power values *P* during turning of Ti6Al4V depending on the concentration *C* and size *s* of nanoparticles according to selected points of the PSI method

and, by functioning on the ball-bearing principle, increase the tribological properties of the aerosol [46]. Such a phenomenon could lead to a reduction in cutting forces and, consequently, have a positive effect on energy consumption and active power values during turning. Raising the copper nanoparticle size to $s = 65$ nm resulted in a significant increase in the value of the analysed parameter, with the greatest difference observed at the fifth test point, where a rise in active power values reached more than 7%. For this nanoparticle size, large *P* values were found to occur at each test point analysed, both at concentrations of 0.5 wt% and 0.75 wt%. In the case of 22 nm Cu nanoparticles, a particular effect of concentration on the active power values was observed for each point considered, with the maximum difference noted at point three and the minimum at point seven. An increase in concentration to $C = 0.75$ wt% then resulted in a 6.35% and 2.43% rise in active power values, respectively. When applying nanoparticles with a diameter of 65 nm, the effect of nanoparticle concentration is negligible and does not significantly affect the active power values, which vary from 0.03% to 0.19%. The exception is the test carried out for the 7th PSI point, where a 1.68% decrease in active power values was observed as the concentration increased from 0.5 wt% to 0.75 wt%. In addition, there was no clear effect of variable flow rate of air Q_A on the active power values *P*. This is consistent with the result of the Pareto chart analysis for the active power (Fig. 2), according to which the nanoparticle concentration and size have the most significant impact on the *P* values.

CONCLUSIONS

The conducted study allowed to determine the influence of the active medium formation parameters, as well as the copper nanoparticle concentration and size applied in the MQL technique, on the power network parameters during the turning of Ti6Al4V alloy. Based on the analysis of the results obtained, the following conclusions were drawn. Out of all analysed input parameters, only the concentration and size of the copper nanoparticles show a significant influence on the active and apparent power during the processing of the Ti6Al4V alloy. The aerosol formation parameters, i.e. volumetric flow rate of air and mass flow rate of nanofluid, have no relevant effect on the values of the examined power network parameters. In the case of voltage, no significant effect was found for any of the parameters considered. Increasing the size of the copper nanoparticles from 22 nm to 65 nm results in a greater values of the energy network parameters. Smaller nanoparticles reach the tool–workpiece material contact zone more effectively and are therefore able to reduce cutting forces due to their ball-bearing effect and, consequently, reduce active power, apparent power and voltage values. Increasing the 0.5 wt% concentration of copper nanoparticles to 0.75 wt% causes a rise in the *P* value for 22 nm copper nanoparticles. The increase in the *P* value with nanoparticle concentration can be related to the formation of nanoparticle agglomeration, which causes an increase in the coefficient of friction and cutting force. In contrast, for 65 nm nanoparticles, there is no clear effect of the concentration on the active power values. As a result of this study, it was found that in order to obtain the most favourable values of power network parameters, it is necessary to pay special attention to selection of the proper nanoparticle size, concentration and the flow rate of the nanofluid. In order to significantly reduce the active power, apparent power and voltage values during the turning of the Ti6Al4V alloy, it is recommended to use 22 nm nanoparticles at 0.5 wt% and nanofluid mass flow rate of 0.3 to a maximum of 0.45 g/min.

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