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Original scientific paper

Energy Efficiency in Alloyed Steel Milling Process with Nano-Fluid Based Cooling and Lubrication

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Abstract: In this study, the energy efficiency of the workpiece material removal process in the cutting zone during end milling, was analysed. End mill cutter with exchangeable coated inserts was used. Hard-to-machine and high-alloyed tool steel X210CrVMo2-1 was used as the workpiece material. The experimental research and analysing included two cases of cutting zone cooling and lubrication: first with a standard emulsion (water and oil), and second with nano-fluid. The nano-fluid is made as a dispersion of molybdenum disulphide nanoparticles in a standard emulsion. Nano-fluid, as a cooling and lubricating agent, was dosed by flooding technique. A standard system on the tool machine was used there. Feed per tooth, cutting speed, and depth of cut are selected as controlled cutting process parameters. For the experimental research, Taguchi's experimental plan L9 was used, which is given nine combinations of input cutting process parameters values. The same set of cutting process parameter combinations was used for both cooling and lubrication case. Based on the measured cutting forces, the cutting power and cutting energy values were recalculated and analysed. As an indicator of the process productivity, material removal rate is also included in the analysis, and consequently, specific cutting energy was analysed as an additional indicator of energy efficiency. Statistical analysis by ANOVA, development of adequate energy efficiency indicators models, and process parameters optimisation were also performed. Based on developed model, optimal values of the input cutting process parameters, f_z = 0.172 mm/tooth, v_c = 109 m/min, and a_p = 10 mm were obtained.

Keywords: cooling; energy efficiency; lubrication; milling; nano-fluid

1 INTRODUCTION

In the contemporary mechanical industry, optimisation of product quality, production time, manufacturing costs, and reaching of sustainable production processes, and minimal environment impact, are essential aspirations. Constant aspiration has led to the development of many directions such as green production, sustainable production, etc. On the other hand, the development of the information-communication technologies gives the possibility for development of more robust and comprehensive production process monitoring and control. It is clear that modern mechanical industry relies on basic concepts and elements of Industry 4.0. Anyway, all mentioned industrial concepts involve the development and using of advanced production methods, which are based on reaching high process efficiency, economy, productivity and flexibility [1-5]. Advanced production processes are based on high efficient processes, optimized technological parameters, raw material flows and number of processes, minimum energy consumption and maximum utilization of production equipment capacity. Also, there are requirements for minimal use of additional or dangerous resources, maximum waste reducing, use of renewable resources, etc. These requirements and goals are often in conflict, and must be researched and coordinated.

In a wide spectrum of contemporary production processes and methods, advanced machining processes hold particular significance due to their widespread use in shaping raw workpiece materials into intricate mechanical components. Methods based on cutting processes have a relatively low productivity rate, but it is possible to achieve high quality and accuracy of mechanical components due to their kinematics and machining system properties. In the case of machining high alloyed tool steels, which have extremely low machinability, in general, there are most difficulties in reaching the appropriate cutting process performance. During mechanical tool wedge penetrating in the workpiece materials and deforming them, it causes complex material flow and chip separation. In the chip separation zone, there are very complex thermo-mechanical and chemical processes and phenomena [1]. There are high cutting forces, intensive friction between cutting tool body and workpiece material flow, vibrations during processing, large amount of generated heat, intensive abrasive wear mechanisms, etc. High and variable cutting forces values cause elastic deforming of cutting tool and workpiece, which leads to low dimensional accuracy [1, 6]. Intensive influence of generated heat, wear mechanisms between cutting tool body and workpiece material plastic flow and vibrations, cause poor cutting tool life, high workpiece machined surface roughness, etc.

Based on the mentioned processes and consequences, it is possible to determine the negatives that affect the process economy and productivity, and energy efficiency too [6]. Standard cutting method includes cooling and lubrication process, regard to extend tool life, decreasing of cutting tool values, and achieving low machined surface roughness. These methods can cause the need for using a large amount of cooling and lubrication fluid (abbreviated CLF). There are problems in its efficiency to friction decreasing and generated heat taking away from cutting zone. Also, there are problems with maintaining environmental awareness in the production process [7].

1.1 Researches on Nano-Fluid Based Cooling and Lubrication

In the last few years, during the wide development of nanotechnologies, there are intensive researches into the application of nano-fluids in cooling and lubrication in cutting processes [8]. Nano-fluid is almost a standard fluid which consists of nanoparticles which are mixed in it. Based on different mechanisms of interaction in the zone between two bodies, nanoparticles significantly change the properties of the base fluid (Fig. 1). It causes more efficiently separating of body surfaces in relative motion, base fluid viscosity increasing, lower friction, sliding into rolling friction change, base fluid thermal conductivity increasing, oxidation reducing, and so on.

In a previous research on machining performance improvement and eco-friendly processes, Čep et al. investigated cutting tool material influence on tool wear during machining of hard-to-machine steel [9]. Cutting parameters optimization due to minimizing energy consumption and productivity was investigated in [10].

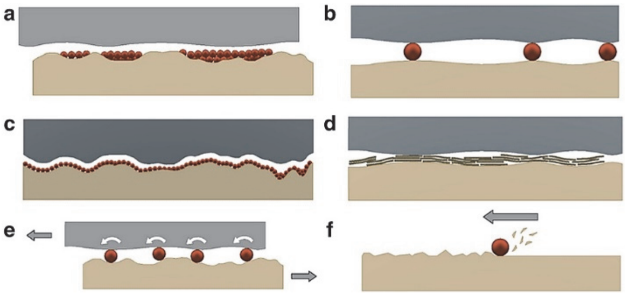

Figure 1 Mechanisms of nanoparticles between two moved bodies [8]

A study on minimizing energy consumption and productivity was investigated by Chen et al [10]. It was concluded that optimized cutting parameters based on mathematical modeling. Similar procedure was performed in [11], and it was concluded that optimal cutting parameters based on genetic algorithm. Wang et al. [12] employed evolutionary strategy based optimization approach to identify optimal cutting conditions due to energy consumption in machining. Conclusions were made about the parameter domains that provide minimal values of energy consumption. In [13] authors analyzed and optimized a balance between maximum energy efficiency and maximum machining efficiency. A comprehensive analysis of machining energy consumption and economy was done by Nguyen [14]. In this study, optimal solutions were determined in regard to low specific cutting energy, by experimentation and using of special genetic algorithm. In research [15], authors performed optimization of MoS_2 nanolubrication parameters in aluminum milling, to achieve the lowest cutting force. They analyzed the influence of concentration, nozzle orientation, and air pressure by Taguchi experimental plan. Uysal et al. [16] analysed different cooling and lubrication conditions, based on MoS_2 nanoparticles, in the milling of hardened steel. There it is concluded that minimum tool wear and surface roughness values were obtained in nano MQL cooling and lubrication with 40 ml/h flow rate. Mechanism and phenomena of film formation on cutting tool were analysed by Behera [17]. In this study a special mix of nanopowders was used. Bai [18] used different types of nano-fluids that were selected and mixed with base oil, due to investigating their influence on cutting forces. They analysed nanofluid viscosity and concluded the advance of using the spherical nanoparticles. In study [19] was done investigation of cutting force in the milling of steel, where Al_2O_3 nanoparticles were used as a lubricant. Effect of nano-fluid based MQL technique on cutting force was investigated by Subbiah [20]. In the analysis it was noted that cutting force, tool temperature and surface roughness decreased with increasing percentage of used nanoparticles. Reducing of cutting force, tool wear and surface roughness during end milling is noted in the study [21]. There were used different nanoparticles, which were mixed in MQL oil. Influence of cutting parameters and lubrication types and techniques on power consumption in milling was investigated by Zerooğlu [22]. In this study it is noted that nano-fluid led to machining improvements. Investigation of the influence of varying nanoparticles proportions for milling of AISI 4340 steel was performed in [23]. In this study, a positive effect of using nanoparticles was enhanced on milling performance also. By analysis of previous research, a certain number of studies on the used nano-fluids types can be observed. There is a certain number of studies related to the analysis of nano-fluid delivery parameters. A relatively smaller number of researches are focused on fluid dosing techniques comparison.

2 EXPERIMENTATION

For experimental investigation the Emco Concept Mill 450 machining centre was used. Its nominal power is 11 kW, and maximum number of main spindle revolutions is 12000 min^{-1}. For side end milling experimental runs, the end milling tool with indexable cutting insert was used. The used tool holder was Sandvik R390-020B20-11L, and the coated cutting inserts were Sandvik R390-11 T3 08M, with quality grade mark GC1130. Tool diameter is $d_c = 20$ mm, number of cutting inserts is $z_N = 2$, and cutting edge length of $l_c = 20$ mm. Cutting insert material is carbide in base, coated with TiAlN layer.

High-alloyed tool steel X210CrVMo2-1 was used as workpiece material. This is chromium-molybdenum steel (Tab. 1). It is usually used in die and mould industry for production of punching tool and plates, dies and moulds for cold deforming. It is used for very responsible mechanical parts and assembling elements in moveable machines and mechanisms. This high-alloyed tool steel has extremely low material machinability. High workpiece material tensile strength intense heat generation. The very hard crystalline phases in the workpiece material are formed by chromium and molybdenum. It causes very intensive cutting tool wear. Based on it, it is necessary to select adequate lubrication and cooling of cutting tool and workpiece.

Table 1 Chemical composition of workpiece material X155CrVMo12-1

C	Mn	Mo	V	Cr	P	S
1.55%	0.30%	0.70%	1.00%	12.00%	< 0.03%	< 0.03%

Base fluid for nano-fluid was standard cooling and lubrication emulsion, which was mixed in descaled and deionized technical water with synthetic oil Castrol Hysol T15, in concentration of 5%. As nanoparticles, molybdenum-disulphide (MoS_2) in powder state was used. The used molybdenum-disulphide has three-atomic plate shaped crystal, which forms a hexagonal structure, with one atom layer thick. In all experimental runs, the nanoparticles' concentration of 1.5 grams per litre of emulsion was used. The concentrate emulsion mixture with nanoparticles was prepared using the adjustable electrical mixing devices (Fig. 2). During experimental runs, nano-fluid was supplied as flooding technique on external side of cutting tool. Standard equipment on the tool machine was used. It is an advantage, because no special equipment is required. The nano-fluid homogeneity is ensured by the cutting tool rotation. In the tank, nano-fluids were constantly mixed to avoid nanoparticles subsidence.

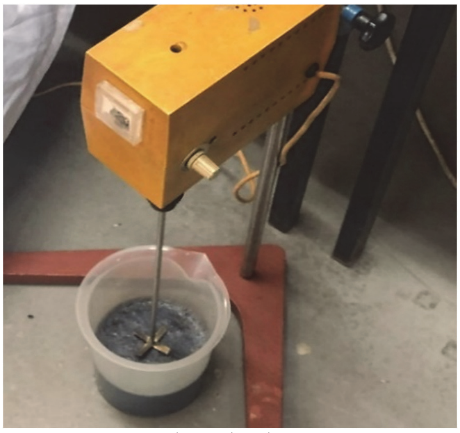

Figure 2 Preparation of nano-fluid for cooling and lubrication

Experimental setup on machining centre is shown in Fig. 3. Measuring cutting forces components device was performed by Kistler three component dynamometer 9259A. It was connected with PC over signal amplifier Kistler 5001 and integrated A/D card HP3567A for signal acquisition and transformation. In this case, three component dynamometer was set and used to measure the cutting forces components in three perpendicular directions noted as F_x (N), F_y (N), and F_z (N). The mentioned measuring directions correspond to the directions of the machine centre transversal axis. The device Kistler for cutting forces component measuring was mounted on the standard hydro-pneumatic clamp device on machine tool table. On dynamometer upper plate was set and fixed a tub to prevent nano-fluid spilling in machine centre work space and other systems of machine centre. In the fixed tub the workpiece was clamped by two screws, through the body, directly to the upper plate of measuring device. The workpiece shape was prepared for down-milling, which was used in all experimental runs.

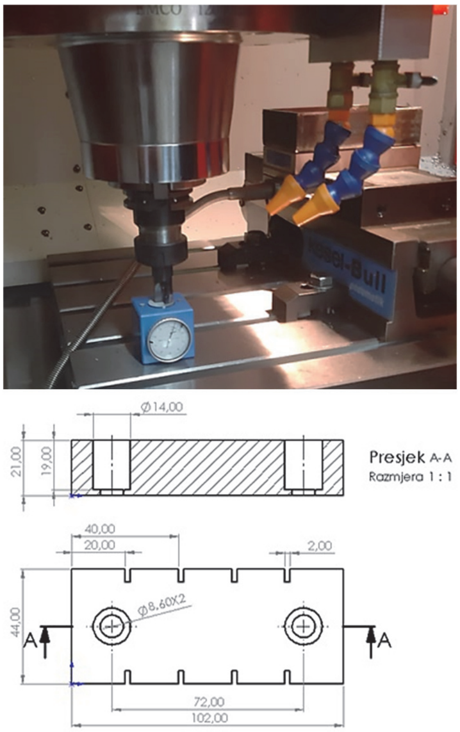

Figure 3 Experimental setup and workpiece geometry

The Taguchi plan L9 was used as experimental plan, with nine experimental runs. There were combined three cutting process parameters, on three value levels. Controlled parameters were: feed per tooth f_z = 0.100, 0.150, and 0.200 mm/tooth, cutting speeds v_c = 100, 150, and 200 m/min, and depths of cut a_p = 4, 7, and 10 mm. Cutting width was set to constant value of a_e = 2 mm. Experiment plan was used for two stages, with regard to cooling and lubrication condition: nine runs without nanoparticles base fluid, and nine runs with nanoparticles in base fluid. This combination resulted with summary of 18 experimental runs.

2.1 Milling Process Productivity and Energy Efficiency

For milling process productivity analysis, the values of material removal rate (*MRR*) were used. According to literature sources, based on end milling process geometry and kinematic, for each experimental run material removal rate *MRR* (mm³/min) was calculated as:

$$MRR = a_p \cdot a_e \cdot v_f \tag{1}$$

there are a_p (mm) depth of cut, a_e (mm) milling width, and v_f (mm/min) auxiliary movement speed, or feed rate calculated as:

$$v_f = f_z \cdot z_N \cdot n = \frac{1000 \cdot v_c \cdot f_z \cdot z_N}{d_c \cdot \pi} \tag{2}$$

where z_n is number of cutting teeth, n (min^{-1}) is main spindle revolutions, v_c is cutting speed (m/min), d_c (mm) is cutting tool diameter, and f_z (mm/tooth) is feed per tooth.

Total energy refers to the energy spent on tool machine functioning and energy spent on cutting process [1]. The tool machine functioning refers to the operation of main systems (main spindle, auxiliary movements), control system, and auxiliary systems (cooling and lubrication, tool change, etc.). For basically estimating the energy consumption and efficiency of cutting process as a process of mechanical chip separation, the cutting power and cutting energy of milling process can be employed. Taking into account simplifications, based on the fact that cutting speed is much greater than the speed of auxiliary movement $v_c >> v_f$, the cutting power P_c (W) can be calculated by [1]:

$$P_c = \frac{F_t \cdot v_c}{60} \tag{3}$$

where F_t (N) is tangential cutting force. Cutting energy E_c (W·s) was calculated as:

$$E_c = \int_0^{t_c} P_c \cdot \mathrm{d}t = P_c \cdot t_c = P_c \cdot \frac{L_c}{v_f} \tag{4}$$

where t_c (s) is cutting time, and L_c (mm) is machining length.

In end milling process, tangential cutting force corresponds to average value of chip thickness h_m (mm), and chip width b (mm), as geometric parameters of cross section of undeformed chip (Fig. 4). Down-milling process was used in all experiment runs, as a recommended strategy in milling. In this milling strategy, during cutter rotation the tooth first engages the largest undeformed chip cross-section. It can be recalculated from resultant cutting force in *xy*-plane F_{XY} (N), and average engagement angle φ_m (°). Resultant cutting forces in *xy*-plane F_{XY} are the resultant cutting forces F_x (N) and F_y (N), measured by dynamometer. Tangential cutting force was calculated based on mechanistic cutting force model on cutting wedge, which was based on average undeformed chip cross section [1]. The model is based on the value of resultant cutting force in *xy*-plane F_{XY}. This force is equal to the resultant of the tangential cutting force (F_t) and radial cutting force (F_r). In using the milling width value and milling tool engagement angle, there is established direct mathematical formulation between the measurable quantities (F_x, F_y, F_z), and the quantities used in further calculations (F_t, F_r, F_a).

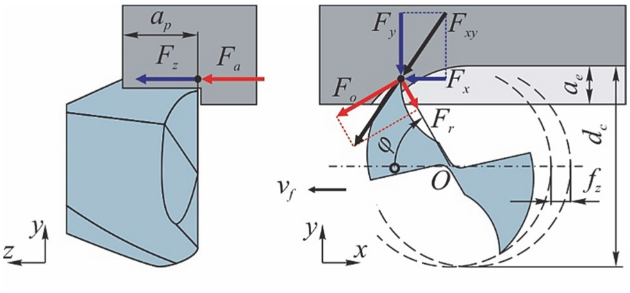

Figure 4 Model of cutting forces

In the analysis of cutting process energy efficiency, specific cutting energy *SCE* (J/mm³) can be employed. This is the amount of energy that needs to be spent to remove the observed workpiece material volume. Also, specific cutting energy in machining can be defined as the ratio between the necessary power consumption and the observed material removal rate in milling. Formulation is:

$$SCE = \frac{E_c}{MRV} = \frac{P_c \cdot t_c}{MRR \cdot t_c} = \frac{F_t \cdot v_c}{a_p \cdot a_e \cdot v_f} \tag{5}$$

where is *MRV* (mm³) the workpiece material removed volume.

3 RESULTS AND DISCUSSION

In Fig. 5 is shown a diagram of cutting force values for nine experimental combinations of input cutting process parameters. The diagram shows the values of the resultant cutting force in the *xy*-plane, and the recalculated tangential cutting force. For each combination of cutting process parameter values, the relationship between cutting force component values is shown for two cases: without using nanoparticles in emulsion, and with using MoS_2 nanoparticles in emulsions. Based on the diagram, it can be noticed that the values of the resultant cutting force in *xy*-plane and tangential cutting force are lower when using nano-fluid, for all experimental cutting process parameter combinations. A significant difference between the value of F_{XY} and the value of F_t is stated. It suggests that the radial cutting force component (F_r), which is acting towards the tool centre, has significant value. Radial cutting force component causes tool deflection and dimension errors, but it is not considered in this analyses.

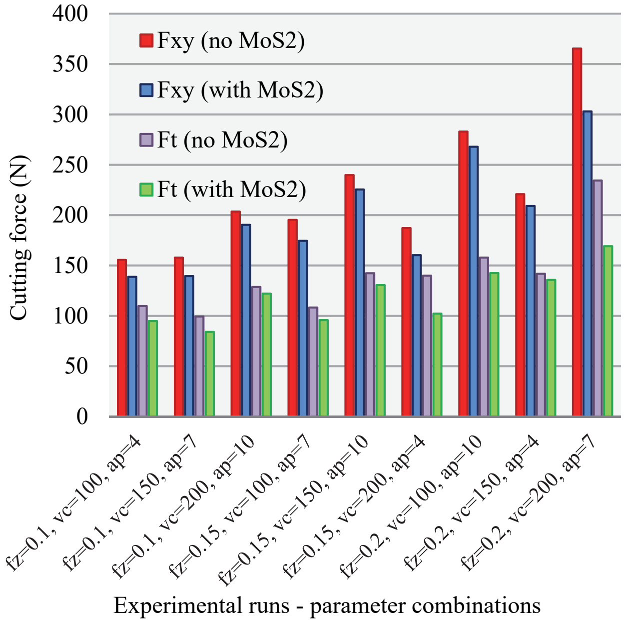

Figure 5 Cutting force component values for experimental runs

The calculated values of material removal rate (*MRR*), cutting power (P_c), and cutting energy (E_c), are given in Tab. 2. The calculation was performed using the previously given equations, measured cutting force component values, and values of cutting process parameter.

Table 2 Results of experimentation and data recalculation

Exp. run	f_z / mm/ tooth	v_c / m/ min	a_p / mm	*MRR* / mm³/ min	Without MoS_2		With MoS_2	
					P_c / W	E_c / Ws	P_c / W	E_c / Ws
1	0.100	100	4.0	2547	183	689	158	596
2	0.100	150	7.0	6685	248	624	210	529
3	0.100	200	10.0	12733	429	809	407	767
4	0.150	100	7.0	6685	180	453	160	401
5	0.150	150	10.0	14324	356	596	327	547
6	0.150	200	4.0	7640	466	585	340	428
7	0.200	100	10.0	12733	263	496	238	448
8	0.200	150	4.0	7640	354	445	339	426
9	0.200	200	7.0	17826	781	736	564	531

According to the values shown in the previous table, and the diagram of the cutting power (Fig. 4), it can be concluded that the cutting power increases with increasing of depth of cut and the feed per tooth. The highest cutting power value, for the case of milling without using of nano-fluid based cooling and lubrication (only emulsion), was obtained when the values of the cutting process parameters were used f_z = 0.200 mm/tooth, v_c = 200 m/min, and a_p = 7 mm. Also, the highest cutting power, for the case of nano-fluid based cooling and lubrication, was obtained for the same cutting parameter values combination. The lowest cutting power value, for the case of milling without the use of nano-fluid based cooling and lubrication, was obtained when used f_z = 0.150 mm/tooth, v_c = 100 m/min, and a_p = 7 mm. In the other hand, the lowest cutting power value in the case of nano-fluid based cooling and lubrication, is obtained when minimal value levels of cutting parameters used are: f_z = 0.150 mm/tooth, v_c = 100 m/min, and a_p = 4 mm.

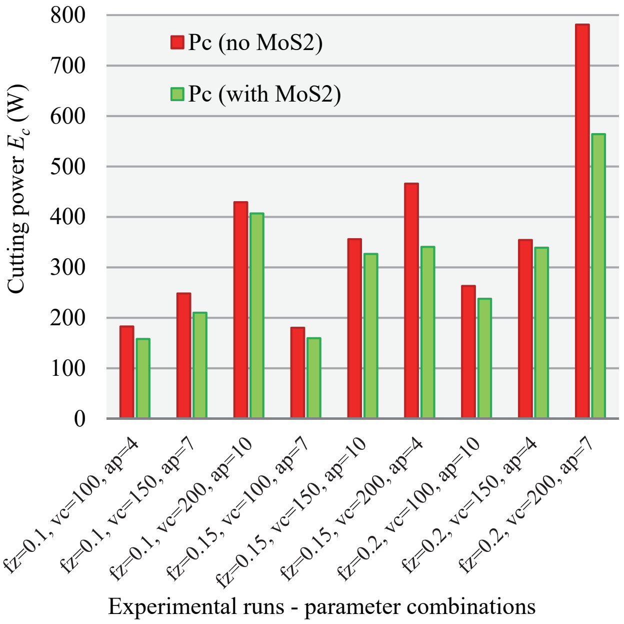

Figure 6 Cutting power for different experimental runs

According to the previous data, the cutting power increases with the increase of the cutting process parameters. The cutting speed is directly involved in the cutting power, and increasing of the cutting speed directly leads to the highest cutting power. If the influence of the cutting speed is omitted, cutting power increase is accompanied by an increase of tangential cutting force value. Tangential cutting force is directly proportional to the cross-section area of the undeformed chip. It is clear that the cross-section area of undeformed chip is defined by product of depth of cut and undeformed chip thickness, or feed per tooth at least. On the other hand, when using cutting parameters that obtain a small cross-section area of the undeformed chip, additional plastic deformation, unfavourable material flows, and plugging of workpiece material can occur in front of the cutting tool wedge and rake wedge side. This is an unfavourable phenomenon in the cutting zone, which may slightly increase the expected cutting force component value. The reason for the increase of cutting force is most often reflected in the increase in deformation hardening of the material. However, the greatest saving of the necessary cutting power for milling is obtained with the use of maximum value levels of feed per tooth and cutting speed, and middle value of depth of cut, as follows: f_z = 0.200 mm/tooth, v_c = 200 m/min, and a_p = 7 mm. The mentioned divergence in cutting power value, obtained when using nano-fluid based cooling and lubrication is 217 W.

In Fig. 7. is shown a diagram of cutting energy value, as the most significant indicator of energy consumption in the cutting process. It can be observed that the cutting energy value changes with the changing of cutting process parameters. The highest cutting energy value, for both cases of cooling and lubrication, without and with nanoparticles in emulsion, was obtained for milling with f_z = 0.100 mm/tooth, v_c = 200 m/min, and a_p = 10 mm. In any case, it is clearly observed that the cutting energy is lower in the case of using nano-fluid based cooling and lubrication, for all experimental combinations. The lowest cutting energy value, for the case of milling without the use of nano-fluid based cooling and lubrication, was obtained when using f_z = 0.200 mm/tooth, v_c = 150 m/min, and a_p = 4 mm. But, in case of nano-fluid based cooling and lubrication, the lowest value of cutting energy was obtained for cutting process parameters f_z = 0.150 mm/tooth, v_c = 100 m/min, and a_p = 7 mm.

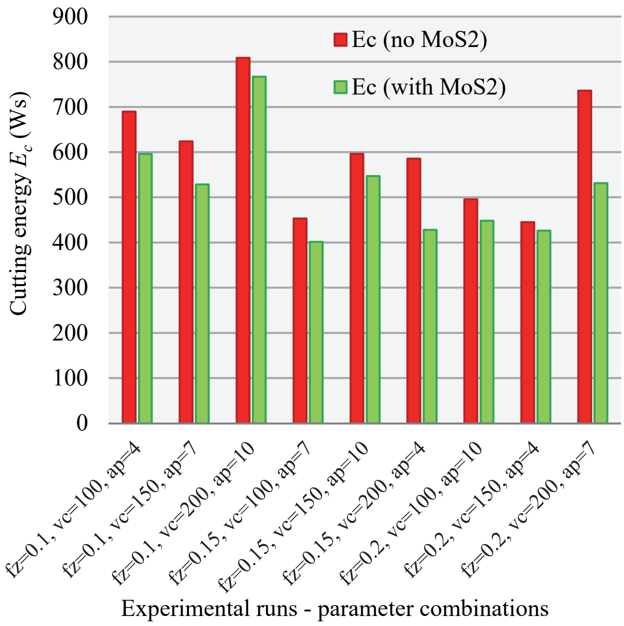

Figure 7 Cutting energy for different experimental runs

Percentage reduction of cutting energy, for the case of using nano-fluid based cooling and lubrication, is shown in the diagram from Fig. 8. It can be concluded that the highest percentage of reduction in cutting process energy consumption of 28%, was obtained in the ninth experimental run, with maximum value of feed per tooth (f_z = 0.200 mm/tooth), maximum value of cutting speed (v_c = 200 m/min), and middle value of depth of cut (a_p = 7 mm). In that case, cutting energy was reduced from 736 at 531 Ws. A minimal cutting energy reduction of 4% was obtained in the eighth experimental run, for the milling with cutting process parameters: f_z = 0.200 mm/tooth, v_c = 150 m/min, and a_p = 4 mm. If all percentages of energy reduction are taken into account, the cutting energy reduction average value of 14% is reached.

For nano-fluid based cooling and lubrication, significantly high cutting energy percentage reduction occurs with regard to lower cutting force component. According to the equations given earlier, the cutting energy value is also dependent on the auxiliary movement speed. By increasing the auxiliary movement speed, the duration of the cutting process (observed experimental run) is reduced and thus the energy consumption as well. The used nanoparticles in CLF reduce the sliding friction between the workpiece material plastic flow and the rake side of the cutting tool wedge. In some cases, when spherical nanoparticles are used, a partial transformation of sliding friction into rolling friction can occur. If nanoparticles are dragging into the mentioned contact zone, a more even contact pressure distribution and generated heat is obtained. Lower contact pressure leads to a reduction in cutting forces.

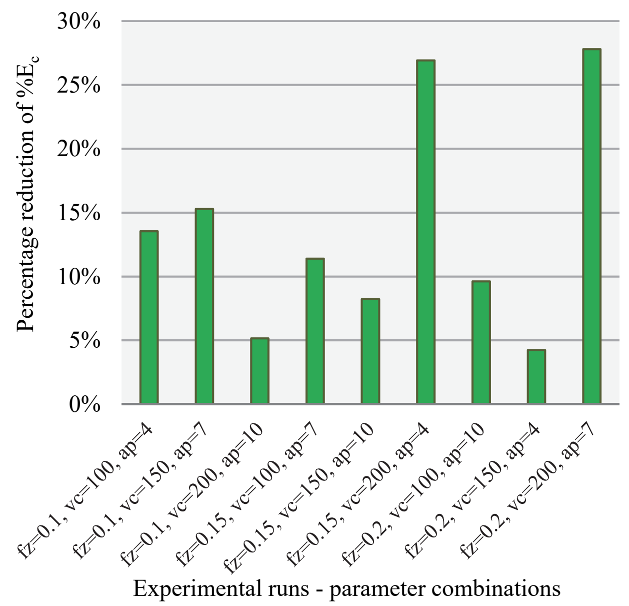

Figure 8 Cutting energy reduction in case use of nano-fluid

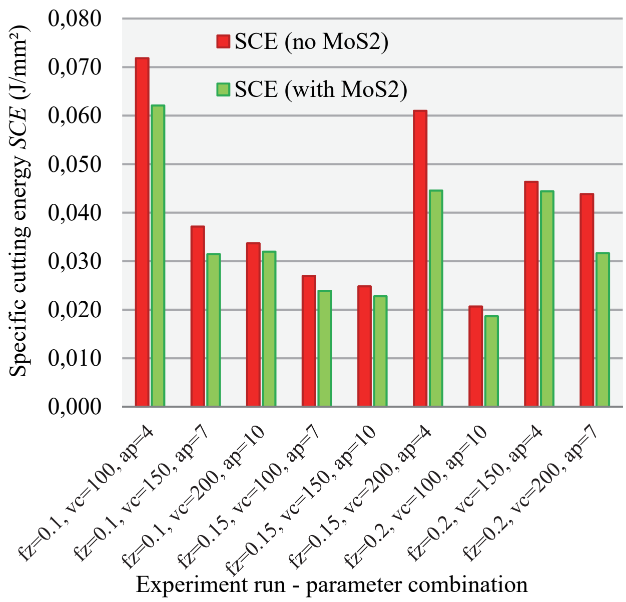

Figure 9 Specific cutting energy for different experimental runs

Also, a more even distribution of the generated heat and local temperature rising, leads to the appearance of a more even workpiece material softening, and thus the cutting forces. Friction force on rake side is a significant component in the resultant cutting force, and it is clear that the reduction of the tangent cutting force will be less. Based on the analysis of the diagram from the previous figure, it can be concluded that the percentage reduction of cutting energy is greater in cases where a larger cross-sectional area of the undeformed chip and higher values of the cutting speed are used.

A comparison of specific cutting energy values for different combinations and different CLF types is given in Fig. 9. Specific cutting energy is a significant indicator of the cutting process energy efficiency, because it directly indicates how much energy is needed to remove the same volume of workpiece material. From the diagram, it can be noted that the specific cutting energy is lower in the case of using nano-fluid based cooling and lubrication, for any cutting process parameter. The largest absolute difference for different CLF was obtained for cutting process parameters f_z = 0.150 mm/tooth, v_c = 200 m/min, and a_p = 4 mm. In accordance with earlier theoretical analyses, the largest percentage difference was obtained for cutting process parameters f_z = 0.2 mm/tooth, v_c = 200 m/min, and a_p = 7 mm.

According to experimentally determined values and previous analysis, the smallest amount of specific cutting energy for removing the same volume of workpiece material is consumed in the case of using higher values of cutting process parameters. The reason is that the removing of the observed volume of workpiece material is carried out faster in processing time, even though the required power is greater. There can be concluded that the roughing milling, which uses higher cutting process parameter values, is a relatively more energy efficient. Further, it can be assumed that by efficient cutting process management, in given cutting process parameter domain and cooling and lubrication framework, adequate process data can be found for the execution of the maximum possible energy efficient cutting process.

3.1 Energy Efficiency Indicators Modelling and Optimisation

In order to create adequate basis for managing and controlling the milling process in the frame of energy efficiency, the cutting process parameters were optimized. For the purpose of optimization, adequate models of the cutting process energy efficiency indicators were developed. It is important to note that material removal rate is defined according to Eq. (1), as an analytical theoretical formulation. It is clear that this process productivity is not affected by the cooling and lubrication conditions. Models of other indicators, cutting energy and cutting power, are formed as empirical models. The experimentally obtained data and assumed mathematical formulations of the model were subjected to a statistical analysis. Statistical analysis was performed using the analysis of variance (ANOVA) method. By conducting the analysis, considering the signification level of the input parameters, sufficiently accurate and adequate models with interaction between inputs were formed.

For cutting power, in case of milling without nanoparticles in CLF, model is (noted with WO):

$$P_c(WO) = 825.4 - 4715.3 \cdot f_z - 2.433 \cdot v_c - 136.7 \cdot a_p + \\ + 23.28 \cdot f_z \cdot v_c + 530.1 \cdot f_z \cdot a_p + 0.462 \cdot v_c \cdot a_p \quad (6)$$

and for cutting power for milling with nano-fluid based cooling and lubrication, model is (noted with MoS_2):

$$P_c(MoS_2) = 420.9 - 429.2 \cdot f_z - 1.426 \cdot v_c - 107.8 \cdot a_p + \\ + 4.337 \cdot f_z \cdot v_c + 254.9 \cdot f_z \cdot a_p + 0.525 \cdot v_c \cdot a_p \quad (7)$$

The results of the analysis of variance for the previously given models are given as follows, for cutting power in Tab. 3, and for cutting energy in Tab. 4. It can be observed that certain sources, as individual input factors or input factors combinations, are retained in the model, regardless of the *p* value. This was done in order to increase the accuracy of the models. From the statistical analysis, it can be concluded that cutting speed is the most influential factor. It is followed by the feed per tooth influence, in both cooling and lubrication cases.

Table 3 Results of ANOVA for cutting power (no nanoparticles in CLF)

Source	Sum of squares	*DoF*	Mean square	*F* value	*p* value
Model	274895.6	6	45815.9	23.02	0.0422
$A\text{-}f_z$	40595.2	1	40595.2	20.39	0.0457
$B\text{-}v_c$	121040	1	121040	60.82	0.0160
$C\text{-}a_p$	3510.0	1	3510.0	1.764	0.3155
AB	3951.90	1	3951.90	1.986	0.2942
AC	7375.23	1	7375.23	3.706	0.1941
BC	5610.05	1	5610.05	2.819	0.2352
Resid.	3980.49	2	1990.25		
Total	278876.11	8			

Table 4 Results of ANOVA for cutting power (nano-fluid as CLF)

Source	Sum of squares	*DoF*	Mean square	*F* value	*p* value
Model	136413.3	6	22735.5	502.2	0.0020
$A\text{-}f_z$	26415.3	1	26415.3	583.5	0.0017
$B\text{-}v_c$	55257.7	1	55257.7	1220.7	0.0008
$C\text{-}a_p$	2006.1	1	2006.1	44.32	0.0218
AB	137.14	1	137.14	3.03	0.2239
AC	1706.8	1	1706.8	37.7	0.0255
BC	7243.1	1	7243.1	160.0	0.0062
Resid.	90.537	2	45.269		
Total	136503.8	8			

For the model of cutting power of milling without nanoparticles in CLF, standard deviation is SD = 44.6, mean value is $\bar{x}$ = 362.26, and signal-to-noise ratio is S/N = 15.56. Correlation coefficient is R^2 = 0.987, and mean value of absolute percentage error values is 5.74%. For the model of cutting energy in case of milling with nano-fluid based cooling and lubrication, mean value is $\bar{x}$ = 304.75, standard deviation SD = 6.73, correlation coefficient is R^2 = 0.987, signal-to-noise ratio is S/N = 67.65, and mean value of absolute percentage error values is 0.84%.

Fig. 10 and Fig. 11 show the responses of previously developed models of cutting power, for different types of CLF. An increase of cutting power can be observed with an increase in cutting speed and feed per tooth, in both cases. In any case, good matching between experimental recalculated data and developed model responses can be noted.

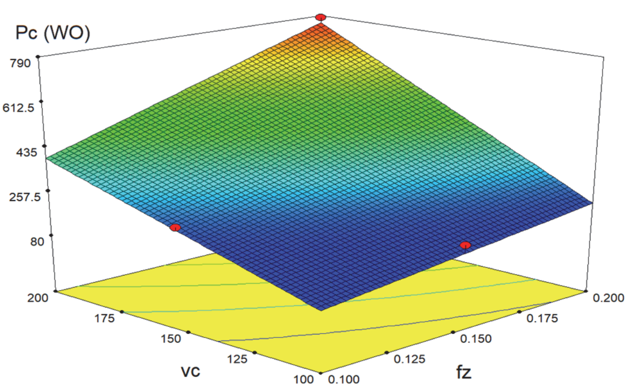

Figure 10 Cutting power model response - no nanoparticles in CLF

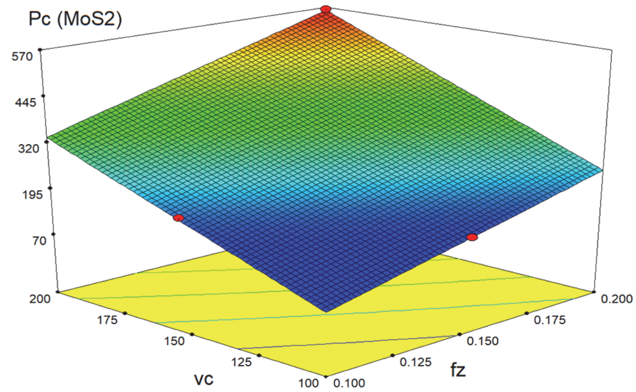

Figure 11 Cutting power model response - nano-based fluid as CLF

For cutting energy, in case of milling without nanoparticles in CLF, model is (noted with WO):

$$E_c(WO) = 1857.9 - 4780.1 \cdot f_z - 1.929 \cdot v_c - 284.8 \cdot a_p - \\ - 12.51 \cdot f_z \cdot v_c + 949.3 \cdot f_z \cdot a_p + 0.981 \cdot v_c \cdot a_p \quad (8)$$

and for cutting energy for milling with nano-fluid based cooling and lubrication, model is (noted with MoS_2):

$$E_c(MoS_2) = 1326.4 - 245.7 \cdot f_z - 1.3 \cdot v_c - 253.6 \cdot a_p - \\ - 30.35 \cdot f_z \cdot v_c + 620.1 \cdot f_z \cdot a_p + 1.102 \cdot v_c \cdot a_p \quad (9)$$

In Tab. 4 and Tab. 5 are given the results of analysis of variance for the previously given cutting energy models and experimental data. There are data in case of milling without nanoparticles in CLF, and case of nano-fluid based cooling and lubrication, respectively. It can be observed that certain sources, as individual input factors or input factors combinations, are retained in the model, regardless of the p value. This was done in order to increase the accuracy of the models. Based on statistical analysis, it can be concluded that cutting speed is the most influential factor, for both cooling and lubrication cases (without and with nanoparticles). For the case of CLF without nanoparticles, the next most influential factor is multiplication of depth of cut and cutting speed. For CLF with nanoparticles, the next most influential factor is the multiplication of cutting speed and depth of cut, also.

Table 5 Results of ANOVA for cutting energy (no nanoparticles in CLF)

Source	Sum of squares	*DoF*	Mean square	*F* value	*p* value
Model	126075.9	6	21012.6	36.447	0.0269
$A\text{-}f_z$	0.845947	1	0.84595	0.00146	0.9729
$B\text{-}v_c$	61616.49	1	61616.5	106.88	0.0092
$C\text{-}a_p$	547.6532	1	547.65	0.9499	0.4325
AB	1140.738	1	1140.74	1.9786	0.2948
AC	23654.57	1	23654.6	41.029	0.0235
BC	25284.88	1	25284.9	43.857	0.0220
Resid.	1153.054	2	576.53		
Total	127228.9	8			

For the model of cutting energy in milling without nanoparticles in CLF, mean value is $\bar{x}$ = 603.71, standard deviation is SD = 24.01, and signal-to-noise ratio is S/N = 17.08, correlation coefficient is R^2 = 0.99, and mean value of absolute percentage error values is 1.41%. For the model of cutting energy in milling with nano-fluid based cooling and lubrication, mean value is $\bar{x} = 519.27$, standard deviation is $SD = 24.48$, and signal-to-noise ratio is $S/N = 16.64$. Correlation coefficient is $R^2 = 0.98$, and mean value of absolute percentage error values is 4.34%.

Table 6 Results of ANOVA for cutting energy (nano-fluid as CLF)

Source	Sum of squares	DoF	Mean square	F value	p value
Model	103043.8	6	17173.9	28.655	0.0341
A-f_z	7.1961	1	7.1961	0.01201	0.9227
B-v_c	22852.03	1	22852.0	38.1294	0.0252
C-a_p	518.17	1	518.169	0.8646	0.4506
AB	6717.24	1	6717.24	11.208	0.0788
AC	10091.34	1	10091.3	16.838	0.0546
BC	31855.1	1	31855.1	53.1518	0.0183
Resid.	1198.66	2	599.33		
Total	104242.5	8			

Responses of developed cutting energy models, for milling with different CL fluid, are shown in Fig. 12 and Fig. 13. As in the previous, a good matching of experimental values and modelled data can be noted. Cutting power increase can be explained with an increase of cutting speed and feed per tooth. For cutting power, it can be noted adequate match between experimental data and developed model response.

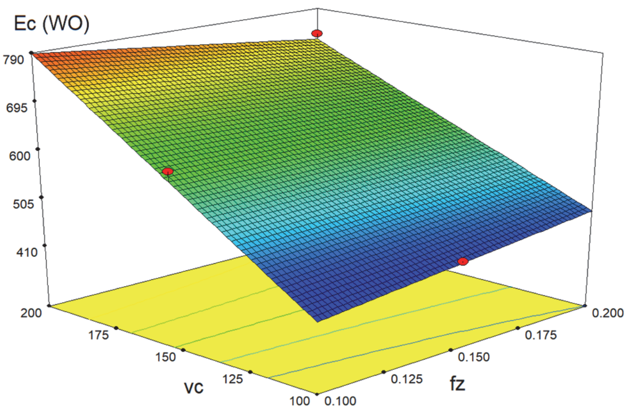

Figure 12 Cutting energy model response - no nanoparticles in CLF

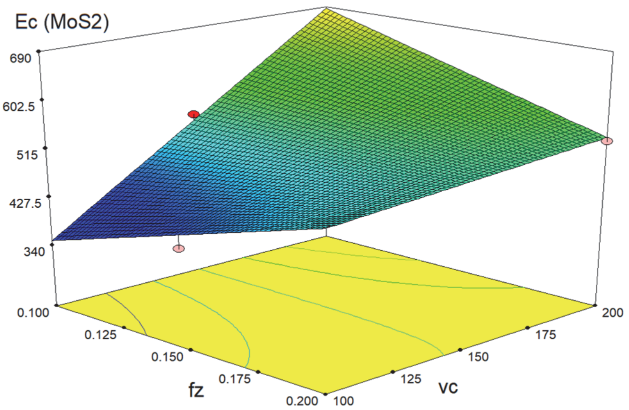

Figure 13 Cutting energy model response - nano-based fluid as CLF

The results of the previous statistical and regression analysis showed that the given cutting energy efficiency indicator models are sufficiently accurate and adequate. This indicates that developed models can be used in the input parameters optimization procedure. The optimization was performed with the aim of process productivity increasing, and energy consumption reducing. Accordingly, the optimization framework is shown in Tab. 7. The optimization procedure was carried out for milling with two types of cooling and lubrication, with and without nanoparticles in CLF.

In mathematical optimization framework, material removal rates have equal value, for both cooling and lubrication cases. Also, it is clear that the developed models of cutting energy are different. Accordingly, in optimisation procedure cutting energy model is taken according to the cooling and lubrication with or without nanoparticles. The limits of input parameter value are taken from Tab. 2. According to the cooling and lubrication case, adequate mathematical model of cutting energy is used. There is used Eq. (8) for milling with using of CLF without nanoparticles, and Eq. (9) for milling with using of CLF with nanoparticles. In the case of milling without the use of nanoparticles in CLF, the cutting energy limits were 445.06 and 808.65 J/mm³. In the case of milling with nano-fluid based cooling and lubrication, the cutting energy limits were 401.35 and 766.93 J/mm³.

Table 7 Input and output parameter optimisation framework

Parameter	Goal	Limit		Weight	
		Lower	Upper	Lower	Upper
f_z	In range	0.100	0.200	1	1
v_c	In range	100	200	1	1
a_p	In range	4.0	10.0	1	1
MRR	Maximize	2547	17826	1	1
E_c	Minimize	By case	By case	1	1

The optimization solutions searched procedure was carried out based on the gradient method. For milling with the use of CLF without nanoparticles, as the optimal values of the input cutting process parameters $f_z = 0.172$ mm/tooth, $v_c = 109$ m/min, and $a_p = 10$ mm were obtained. Desirability of this optimal solution is 79.4%. In this cooling and lubrication case, the optimization results show that it is recommended to use lower values of cutting speeds and higher values of depth of cuts. Input cutting process parameters, $f_z = 0.200$ mm/tooth, $v_c = 200$ m/min, and $a_p = 5.5$ mm, were obtained as the optimal values. The desirability of the obtained optimization result is 88.9%. In case of cooling and lubrication with nano-based CLF, optimisation shows that the higher cutting speed values and feed per tooth are better. Generally, it can be concluded that it is more appropriate to use nano-fluid based cooling and lubrication, if a more energy efficient and productive milling process is desired.

4 CONCLUSIONS

In this study, based on the Taguchi experimental plan, the influence of using nanoparticles mixed in cooling and lubrication fluid in end milling process energy efficiency performance is investigated. For the purpose of analysis there are compared the results obtained when using a standard emulsion with water and oil, and nano-based fluid formed by standard emulsion with mixed molybdenum disulphide nanoparticles. Throughout the study, the data obtained by measuring the cutting forces was used, for the purpose of recalculating cutting power and cutting energy. Also, based on cutting parameters, the process productivity was calculated, and then the specific cutting, as a very significant indicator of the process energy efficiency.

Experimental analysis has shown that in all cases of milling runs with different combinations of cutting process parameters, a lower value of the indicator was obtained when using nano-based fluid for cooling and lubrication of cutting zone. Also, in some cases the saving in energy consumption is over 20%, when nano-based fluid is used. The greatest savings were obtained when using higher values of feed per tooth, cutting speed and depth of cut. On the basis of experimentally obtained data, empirical modelling of cutting energy and cutting power was performed, while material removal rate formulation was taken from the previous research. Models of mentioned indicators with input parameters and their mutual interaction are proposed. Statistical analysis method ANOVA was used for determination of cutting process parameters signification. The proposed models are defined as sufficiently accurate and adequate, because the biggest mean value of absolute percentage error was found in the model of cutting power in milling without nanoparticles in cooling and lubrication fluid, which was 5.74%. Finally, the input parameters were optimized, based on the minimization of energy consumption and the maximization of productivity. In case of cooling and lubrication without nanoparticles, optimal parameters are: feed per tooth of 0.172 mm/tooth, cutting speed of 109 m/min, and depth of cut of 10 mm. In case of cooling and lubrication with mixed nanoparticles, optimal parameters are: feed per tooth of 0.200 mm/tooth, cutting speed of 200 m/min, and depth of cut of 5.5 mm.

Based on analysis results it can be concluded that the use of nano-based cooling and lubrication fluids gives a significantly better result in terms of cutting process performance. Also, it is shown in this study that using nanoparticles in cooling and lubrication fluid can significantly reduce cutting power, cutting energy, and specific cutting energy, which contribute to greater energy efficiency of the process. Future research will include analysing the influence of different CLF dosing techniques, as well as influence of different mixed nanoparticles types. Also, cutting process performance investigation will be performed for machining other contemporary engineering materials, such are: titanium alloy, nickel alloy, etc.

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