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Optimisation of machining parameters during ball end milling of hardened steel with various surface inclinations

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Abstract

This paper proposes a method for the reduction of forces and the improvement of efficiency during finish ball end milling of hardened 55NiCrMoV6 steel. The primary objective of this work concentrates on the optimal selection of milling parameters (cutting speed – v_c, surface inclination angle α), which enables the simultaneous minimisation of cutting force values and increased process efficiency. The research includes the measurement of cutting forces (F_x, F_y, F_z) during milling tests with variable input parameters and calculation of process efficiency accounting for cutting parameters and surface inclination. The paper then focuses on the multi-criteria optimisation of the ball end milling process in terms of cutting forces and efficiency. This procedure is carried out with the application of the response surface method, based on the minimisation of a total utility function. The work shows that surface inclination angle has a significant influence on the cutting force values. Minimal cutting forces and relative high efficiency can be achieved with cutting speed v_c = 375 m/min and surface inclination angle α = 15°.

Keywords: inclined surfaces; ball end milling; cutting forces; efficiency; optimisation

1. Introduction

The ball end milling process is used mainly for the production of drop forging dies and casting mould made of hardened steel [1], or in the aerospace industry in manufacturing wing parts made from aluminium alloys and composites [2]. The fundamental challenges of curvilinear surface milling are related primarily to the machined surface quality [3], process efficiency, and tool life [4].

The key factor which influences the machining process' technological and economic effects is cutting force and its components. Excessive cutting force values are undesirable because they induce tool deflections, which in turn form dimensional errors or high levels of surface roughness [5]. High cutting force values can also result in chipping of the tool and thus significantly reduce tool life [6]. During milling, process kinematics determine variations of cross sectional area of cut, and thus cutting forces [7]. Therefore it is important to be able to reliably simulate the physical and technological effects of the milling process.

The literature shows that the problem of cutting force estimation during the machining processes has been investigated by the many researchers. Their work can be divided into two distinct approaches:

the analytical and mechanistic. According to Fontaine et al. [8] the analytical models focus mainly on the physical mechanisms of chip formation, as slip stress and strain. In contrast, the mechanistic models estimate cutting forces based on the assumption that their values are proportional to the sectional area of cut and specific cutting force coefficients [9]. These models can be used to estimate the cutting forces for a selected combination of cutting parameters and tool geometry. However, from a practical point of view, the selection of cutting parameters which enable minimisation of cutting forces and simultaneous improvement of process efficiency is of great importance. In order to achieve this objective, machining process optimisation can be applied.

From the literature it can be seen that the most widely considered optimisation objectives include maximisation of tool life [10] and minimisation of tool wear [11], machining vibrations [12], surface roughness [13], and cutting forces [14]. López de Lacalle et al. [15] optimised the toolpath during ball end milling on the basis of the predicted cutting forces, in order to minimize dimensional errors. A similar approach was proposed by Lazoglu et al. [16], who selected tool paths optimised to minimise cutting force. The results showed that the optimum path can achieve almost a 60% reduction in mean force. Gok et al. [17] optimised the cutting force and tool deflection during ball end milling of X40CrMoV5-1 tool steel considering variable cutting parameters and tool path strategies. The results obtained revealed that the most significant parameter was pick feed (step over) in the machining of inclined surfaces using three different coated cutting tools. Masmiati and Sarhan [18] applied Taguchi optimisation and signal-to-noise ratio (S/N) response analysis of the surface integrity after ball end milling of S50C steel. Through the analysis, it was found that surface inclination angle had a significant influence on microhardness and residual stress in the feed direction. Furthermore, as Vakondios et al. [19] found during ball end milling trials on Al7075-T6 alloy, the selection of surface inclination angle can affect also the surface roughness. Their results showed that the surface roughness parameter (*Rz*) was significantly affected by the surface inclination angle and milling kinematics. Kuram and Ozcelik [20] investigated the effects of spindle speed, feed per tooth and depth of cut on tool wear, force components and surface roughness during micro-milling of aluminium Al 7075, with the application of Taguchi experimental design method. It was found that the minimum tool wear, cutting forces and surface roughness were achieved by milling with the lowest investigated cutting speed, feed per tooth and depth of cut values.

The review of the literature above has shown that ball end milling process optimisation procedures focus mainly on cutting forces, milling strategies, surface quality and tool life. However process efficiency is not usually considered. It should be emphasized that during ball end milling, cutting speed is dependent on the spindle speed and the tool's effective diameter, which in turn is a function of tool diameter, axial depth of cut and surface inclination angle. Consequently, these factors have a direct influence on material removal rate and machining time. According to Rybicki [21], an increase in surface inclination angle from 10° up to 60°, during ball end milling with constant cutting speed mode, resulted in an approximately 55% increase in cutting time. In addition, Chen et al. [22] have shown that surface inclination angle has a significant influence on the cutting forces, due to variations in edge force values along the length of the cutting edge. Therefore, reliable optimisation of the ball end milling with variable surface inclinations should focus both on cutting forces and process efficiency.

In this paper the analysis of forces and process efficiency during finishing ball end milling of hardened 55NiCrMoV6 steel is presented. The primary objective of this work concentrates on the optimal selection of cutting speed and surface inclination angle, which enables the simultaneous minimisation of cutting force values and growth of the process' efficiency. A multi-criteria optimisation process, based on minimisation of a total utility function is carried out. The application of the obtained results can be used to improve the technological and economic effects of the process by enhancing machined surface quality and reducing cutting time and tool wear.

2. Experimental details

2.1. Work and tool materials

The work material used in the research was alloy steel 55NiCrMoV6 with hardness approximately 58 HRC. The sample had a rectangular prism shape with dimensions: 125 mm x 230 mm x 160 mm. The elemental composition of the material is given in Table 1. The milling tests were carried out with a monolithic ball end mill made of fine-grained tungsten carbide (WC) with an anti-wear TiAlN coating. The milling tool had the following geometry: diameter D=16 mm, number of teeth z=2, orthogonal rake angle γ_o = -15°, helix angle λ_s = 30°, cutting edge radius r_n = 5 µm, orthogonal flank angle α_o = 6°, orthogonal wedge angle β_o = 99°. During the experiments, the critical flank wear, VB_{B_cr}, was no more than 0.05 mm in order to exclude its influence on the recorded cutting force signals.

Table 1. Chemical composition of the alloy steel 55NiCrMoV6.

C	Si	Mn	Cr	Mo	Ni	V
0.5 – 0.6%	0.1 – 0.4%	0.65 – 0.95%	0.6 – 0.8%	0.25 – 0.35%	1.5 – 1.8%	0.07 – 0.12%

2.2. Ball end milling tests

The milling tests were carried out on a 5-axes CNC milling workstation (DMU 60monoBLOCK), in upward ramping and slot milling conditions (see – Fig. 1). During all experiments, the width of the machined groove B was lower than the value of pick feed b_r, in order to exclude the effect of the b_r parameter from the investigation (Fig. 1c).

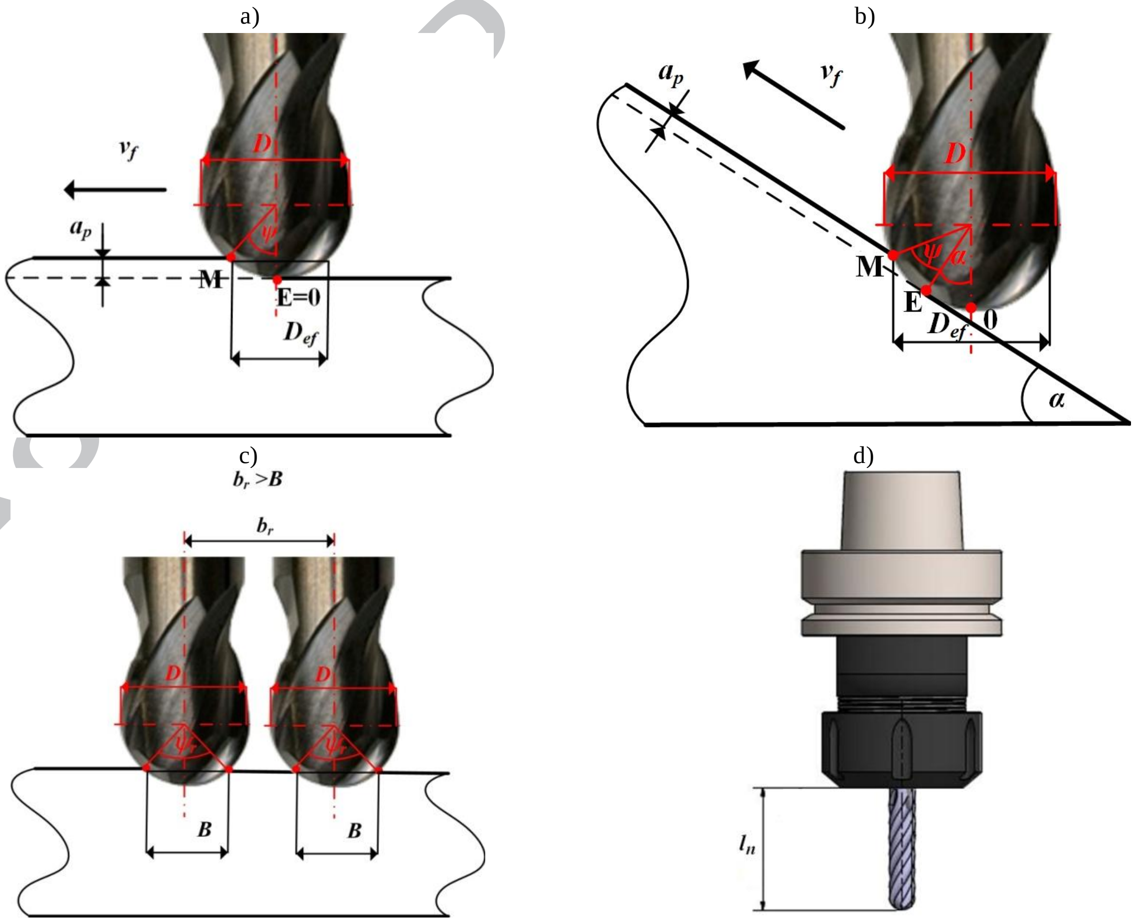


Fig. 1. Cutting modes of ball end milling: a) slot milling with α = 0°; b) upward ramping with α > 0°; c) selection of pick feed b_r; d) the designation of tool overhang

The investigations carried out were divided into the two parts. In the first stage, the influence of cutting parameters on cutting forces in the machine tool coordinate system were investigated. Cutting parameters applied in this experimental stage are presented in the Table 2. The range of specified variables includes the values typically used for finish milling of hardened steels with carbide end mills.

Table 2. Cutting parameters applied in the research.

α [°]	f_z [mm]	a_p [mm]	v_c [m/min]	l_n [mm]	b_r [mm]
0–60 interval 15	0.02-0.1 interval 0.02	0.2	100 – 400 interval 100	60	3.49-3.55

The second part of the research was focused on the multi-criteria optimisation of the milling process. The detailed experimental program of this part is described in section 2.5.

2.3. The measurement of cutting forces

Cutting forces (F_x, F_y, F_z), were measured using a piezoelectric force dynamometer connected through charge amplifiers and band-pass filters to a data acquisition computer (see – Fig. 2).

The force components were defined in the machine tool's coordinate system as: X – feed normal force F_x [N], Y – feed force F_y [N], Z – thrust force F_z [N]. The acquisition of the force signal was made with the aid of **ANALIZATOR** software [7]. This software was also used to calculate the signal's statistical measures and filtration carried out with a low-pass filter with a steepness of 90 dB/oct, and cut off frequency described by the dependency: $f_c \approx 2f_{zo}+10\%$, where f_{zo} is tooth passing frequency.

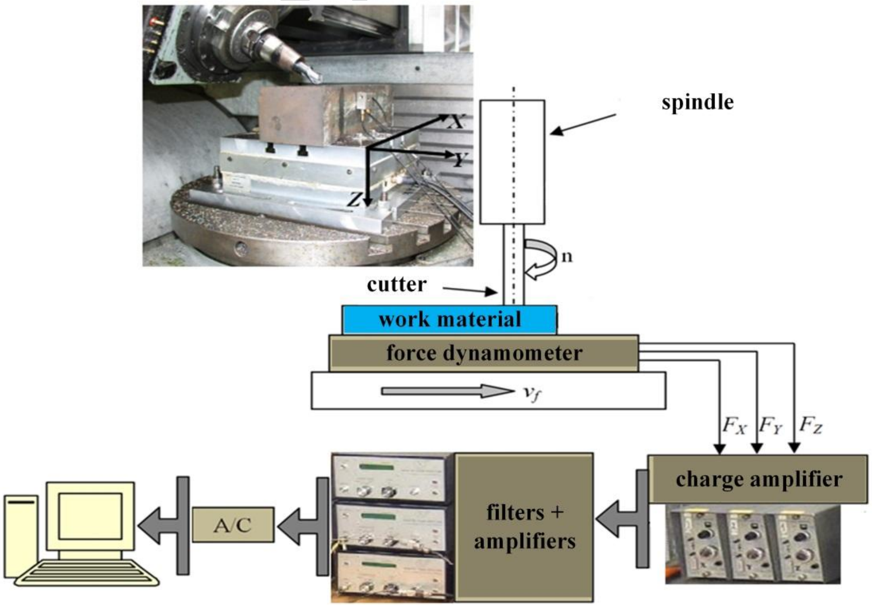


Fig. 2. Schematic diagram of experimental arrangement

The acquired and filtered force signals enabled the calculation of the maximum and minimum forces per tooth (F_{x_max}, F_{y_min}, F_{z_max} – see Fig. 3). It can be seen in this diagram that each of the two teeth on the tool generates a different peak cutting force. The analysis carried out here focuses on these peak force values because of their influence on the machining process' physical phenomena (e.g.: tool deflections, tool wear) and technological effects (e.g. machined surface's dimensional errors, surface roughness, tool life). The analysis was facilitated by calculating average values of F_{x_max}, F_{y_min}, F_{z_max}

based of equations:

$$F_{x\_max} = \frac{\sum_{j=1}^{J} F_{xj\_max}}{J} [\mathrm{N}], \quad F_{y\_min} = \frac{\sum_{j=1}^{J} F_{yj\_min}}{J} [\mathrm{N}], \quad F_{z\_max} = \frac{\sum_{j=1}^{J} F_{zj\_max}}{J} [\mathrm{N}] \tag{1}$$

where: F_{xj_max}, F_{zj_max} are maximum measured forces per j-th tooth, in the feed normal and thrust directions,

F_{yj_min} is minimum measured force per j-th tooth, in feed direction,

J is number of cutting teeth in the measurement range.

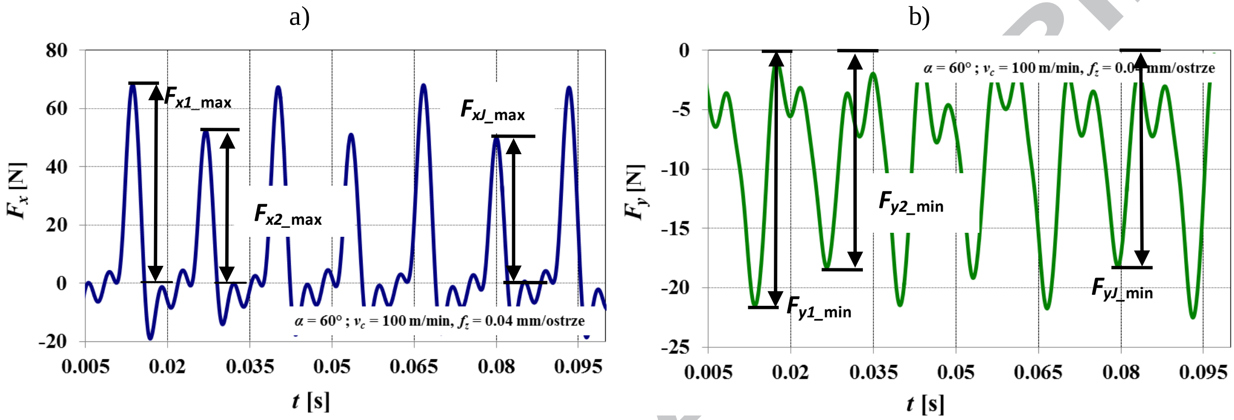


Fig. 3. The designation of F_{xj_max}, F_{yj_min} forces on the experimental time course for: a) F_x, b) F_y

2.4. The determination of material removal rate

Material removal rate Q_V is an important machining process efficiency indicator. During machining with constant sectional areas of cut, Q_V is inversely proportional to cutting time. The material removal rate Q_V for the ball end milling process can be calculated from the following expressions:

$$Q_V = a_p \cdot b_r \cdot f_z \cdot z \cdot n \quad [\mathrm{mm^3/min}], \qquad \text{when } b_r < B \tag{2}$$

$$Q_V = \frac{1}{8} D^2 (\psi_r - \sin\psi_r) f_z \cdot z \cdot n \quad [\mathrm{mm^3/min}], \qquad \text{when } b_r \geq B \tag{3}$$

where: n is rotational speed [rev/min]; ψ_r is tool working angle [rad].

The tool immersion angle ψ_r contained in equation (3) is defined in a reference plane, which is collinear to the tool's axis and perpendicular to the feed motion vector (Fig. 1c). Its value can be calculated from the equation:

$$\psi_r = 2\arcsin\left(\frac{B}{D}\right) \quad [\mathrm{rad}] \tag{4}$$

The width of the machined groove B, during the ball end milling process can be calculated from the following equations:

$$B = 2\sqrt{a_p (D - a_p)} \quad [\mathrm{mm}] \qquad \text{when } \alpha = 0 \tag{5}$$

$$B = 2\sqrt{\left(\frac{D}{2}\cdot\sin\alpha\right)^2 - \left(\frac{D}{2}\cdot\sin\alpha - \frac{a_p}{\sin\alpha}\right)^2} \quad [\mathrm{mm}] \qquad \text{when } \alpha > 0. \tag{6}$$

where: α is surface inclination angle [rad].

Free-form surface machining with a ball end mill is usually conducted with a constant rotational speed n and variable surface inclination angle α (see – Fig 4a). Thus, the cutting speed v_c, defined as the linear speed of the active cutting edge through the work material, varies with angle α. The maximum cutting speed value (located at point M of the cutting edge – see Fig. 1) can be calculated as:

$$v_c = \frac{\pi \cdot D_{ef} \cdot n}{1000} \quad \text{[m/min]} \tag{7}$$

Where D_{ef} denotes the ball end mill's effective diameter at point M on the cutting edge (Fig. 1). This can be determined from:

$$D_{ef} = D \cdot \sin\psi \quad \text{[mm]} \qquad \text{when } \alpha = 0, \tag{8}$$

$$D_{ef} = D \cdot \sin(\psi + \alpha) \quad \text{[mm]} \qquad \text{when } \alpha > 0. \tag{9}$$

Where ψ denotes ball end mill's working angle, defined in the plane collinear to the tool's axis and feed motion vector (Fig. 1b). Its value can be calculated from:

$$\psi = \arccos\left(1 - \frac{2 \cdot a_p}{D}\right) \quad \text{[rad]} \tag{10}$$

Equations (7 – 10) show that cutting speed during ball end milling is a function of tool diameter, rotational speed, axial depth of cut, and surface inclination angle: v_c = f(D, n, a_p, α). In addition, cutting speed v_c is variable along the active length of the cutting edge (Fig. 4a).

Using a variable cutting speed along the tool-path can unfavourably affect the process' technological effects (e.g. surface quality, tool life). Therefore a constant cutting speed along the tool-path should be applied. This cutting mode can be achieved by maintaining the surface inclination angle at a constant level, independent of the surface shape (Fig. 4b). Nevertheless, it should be emphasized that in this milling mode, the cutting speed is constant only in a one specified – during the calculations – point of the active cutting edge (e.g. points M, E in Fig. 1b). On the remaining length of the active cutting edge, cutting speed value is variable and proportional to the corresponding ball end mill's effective diameter. Figure 5 depicts the variations of cutting speed values, corresponding to active lengths of cutting edge in function of tool's effective diameter and surface inclination angle.

The limiting values of cutting speed (denoted by points E and M) during ball end milling are depended on working ψ and surface inclination α angles. It can be seen from the figure 5 that in case of a slot milling (α =0), the minimal cutting speed in E point is equal to zero. However, the growth of surface inclinations leads to the growth of the minimal cutting speed values and the decrease of differences between the minimal and maximal cutting speeds. This finding seems to be important in terms of thermo-mechanical interactions between the tool and workpiece during machining.

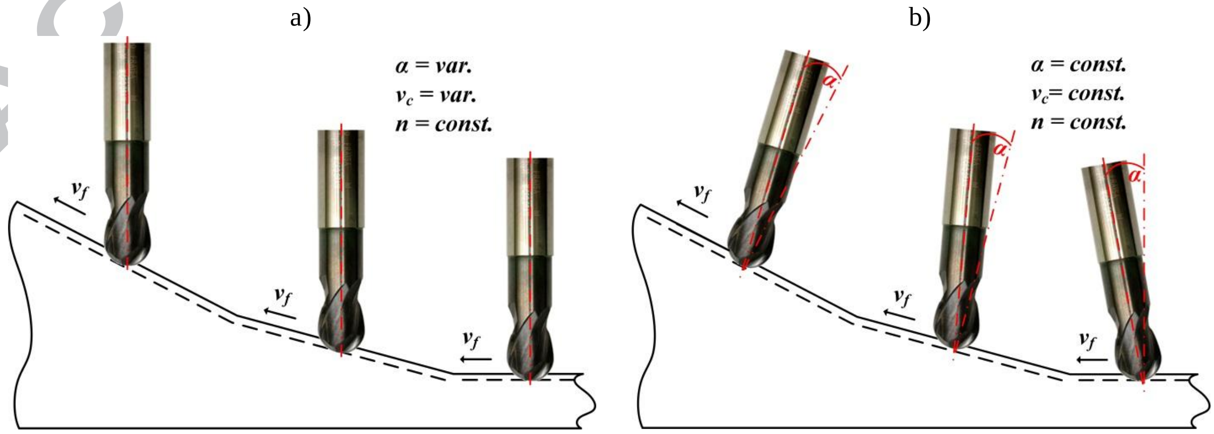


Fig. 4. Ball end milling strategies: a) with variable cutting speed and surface inclination angle along the toolpath; b) with constant cutting speed and surface inclination angle along the toolpath

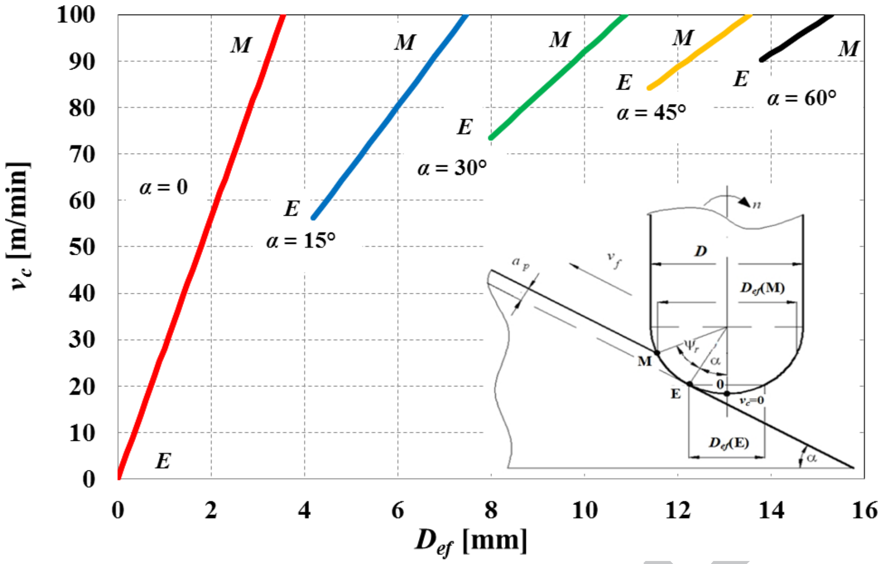


Fig. 5. Relations between the cutting speed and effective diameter during ball end milling mode with the constant cutting speed at the point M of the tool. Tool diameter D = 16 mm, depth of cut a_p = 0.2 mm, maximal cutting speed $v_c(M)$ = 100 m/min, rotational speed n = 2082÷8953 rev/min

In order to improve process efficiency during ball end milling in constant cutting speed mode, an appropriate value of surface inclination angle should be selected. Figure 6 shows the relationship between material removal rate, surface inclination angle and cutting speed (constant in M point), as defined by equation (3).

This analysis indicates that the highest process efficiency can be reached during milling with surface inclination α=0, which results from the relatively low tool's effective diameter D_{ef} in point M and thus high rotational speed n required to the maintaining the cutting speed at the specified level. In turn, the growth of rotational speed causes the reduction of cutting time and simultaneously an increase of the material removal rate. However, in this cutting mode, cutting forces are usually higher than those obtained during milling with α>0 [22, 7] and hence the quality of the machined surface is reduced. Thus, the surface inclination angle during ball end milling of free form surfaces should be optimized to minimise cutting forces and maximise material removal rate.

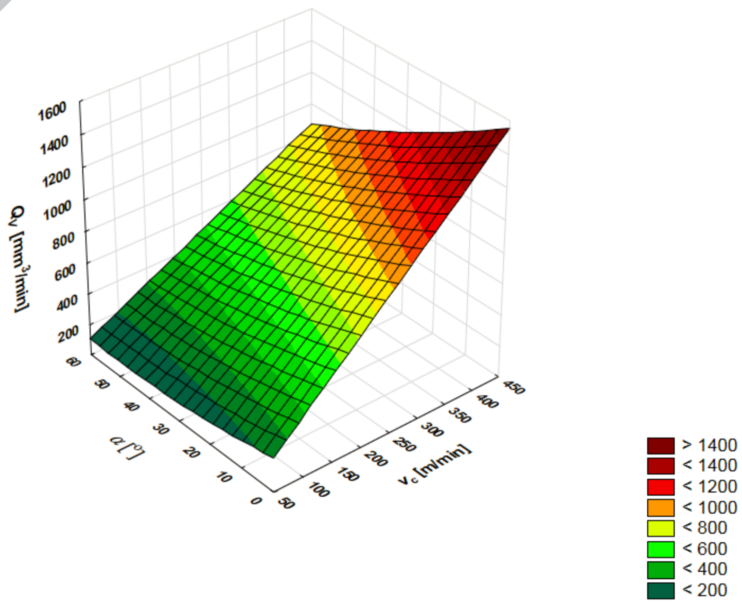


Fig. 6. The influence of the cutting speed and surface inclination angle on the material removal rate. D=16 mm, f_z=0.1 mm/tooth, a_p=0.2 mm, z=2.

2.5. Multi-criteria optimisation of the ball end milling process

A multi-criteria optimisation procedure, based on utility function minimisation, was applied in this research. This optimisation was based on combining multiple outputs into a single utility function $U(\alpha, v_c)$. Thus, the problem of simultaneous optimization of many output factors was simplified to the minimisation of a single total response utility.

The optimisation was based on the following optimisation criteria:

- maximum values of normal F_n and feed normal F_x forces,
- material removal rate Q_V.

The primary objective of the optimisation was the minimisation of the F_n and F_x forces and simultaneous maximisation of the material removal rate Q_V.

The normal F_n and feed normal F_x components are the forces defined in the machine-workpiece system (Fig. 7). The F_x component is perpendicular to the plane defined by the feed motion vector and tool's rotational axis. However, the F_n component is tangent to the plane defined by the feed motion vector and tool's rotational axis. Thus, the normal F_n and feed normal F_x force vectors are perpendicular to each other. These forces were selected as optimisation criteria as they generate tool deflections during machining [24, 25] which in turn impacts on the quality of the machined surface [5].

With reference to Figure 7, the instantaneous value of normal force F_n is given as [25]:

$$F_n(t) = F_z(t) \cdot \sin\alpha + F_y(t) \cdot \cos\alpha \text{ [N]} \tag{11}$$

The optimisation research included milling tests, which were conducted on the basis of a 4 level, 2 factor, full factorial experiment with variable cutting speed and surface inclination. This experiment included also the measurement of F_x, F_y, F_z forces. The whole experiment included the 16 trials conducted with the milling parameters set on the different levels (see – Tab. 3). Moreover the each trial has been repeated 3 times in order to carry out the statistical analysis. This analysis was conducted in Matlab Mathworks software and involved the use of response surface method (RSM), as well as the analysis of variance (ANOVA). In order to identify the outliers from the conducted measurements, the Chauvenet's criterion has been applied. This method involved the calculation of the k determinant for the values of measured forces in the each experiment, according to equation:

$$k = \frac{\left|F_{i\_ave} - F_{susp}\right|}{\sigma} \tag{12}$$

where: F_{i_ave} is the mean arithmetic value of measured forces in the each experiment, F_{susp} is the value of suspected outlier, σ is the standard deviation of measured forces in the each experiment.

In the next step, the normal distribution function was applied for the determination of probability $P(k)$ corresponding to k value. In case, when the $P(k) < 0.5$, then the outlier has been excluded from the analysis.

During these tests, the maximum recommended feed per tooth values were selected, in order to increase the material removal rate. In addition, the milling tests excluded cases with a surface inclination angle $\alpha = 0$, since this would resulted in an intense ploughing action and hence deterioration of the generated surface's quality [3].

The results obtained from the milling tests were used to form response surfaces determined on the basis of least squares fit to the experimental data. Having established the response surfaces for F_n and F_x it was possible to investigate the full design space defined by the two cutting parameters α and v_c.

In order to optimise these cutting parameters a utility function was defined:

$$U(\alpha, v_c) = \frac{1}{3}\left\{\frac{(F_n - F_{n,min})}{(F_{n,max} - F_{n,min})} + \frac{(F_x - F_{x,min})}{(F_{x,max} - F_{x,min})} + \left(1 - \frac{(Q_v - Q_{v,min})}{(Q_{v,max} - Q_{v,min})}\right)\right\} \tag{13}$$

Where: $F_{n,min}$, $F_{x,min}$, $Q_{v,min}$ are the minimum values of the three cutting criteria over the range of cutting parameters,

$F_{n,max}$, $F_{x,max}$, $Q_{v,max}$ are the maximum values of the three cutting criteria over the range of cutting parameters.

Table 3. The 4 level, 2 factor, full factorial experiment applied in the research.

Experimental no.	α [°]	v_c [m/min]	f_z [mm/tooth]	a_p [mm]	b_r [mm]	l_n [mm]
1	15	100	0.1	0.2	3.23	60
2	15	200	0.1	0.2	3.23	60
3	15	300	0.1	0.2	3.23	60
4	15	400	0.1	0.2	3.23	60
5	30	100	0.1	0.2	3.49	60
6	30	200	0.1	0.2	3.49	60
7	30	300	0.1	0.2	3.49	60
8	30	400	0.1	0.2	3.49	60
9	45	100	0.1	0.2	3.53	60
10	45	200	0.1	0.2	3.53	60
11	45	300	0.1	0.2	3.53	60
12	45	400	0.1	0.2	3.53	60
13	60	100	0.1	0.2	3.55	60
14	60	200	0.1	0.2	3.55	60
15	60	300	0.1	0.2	3.55	60
16	60	400	0.1	0.2	3.55	60

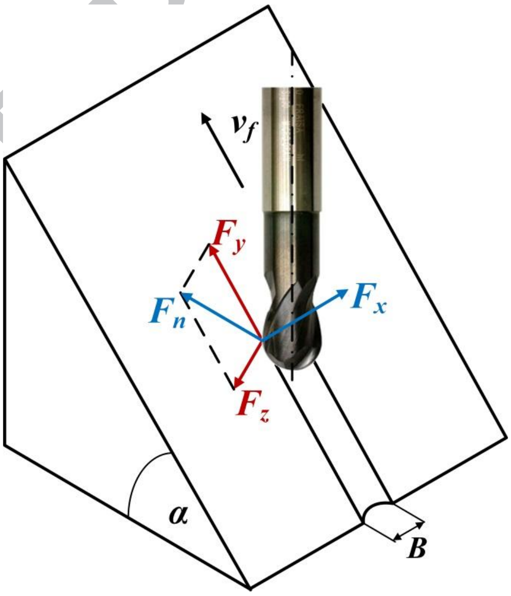


Fig. 7. Cutting force distribution in machine tool's coordinate system during ball end milling of inclined surface

Within the utility function the individual criteria values have been normalised over the full range of cutting parameters before being summed and equal weighting has been given to each criterion. Minimisation of the utility function will minimise the two cutting forces whilst maximising the material removal rate. Consequently it will allow the optimal input parameters (v_{c_opt}, $\alpha_{\_opt}$) to be obtained.

3. Results and discussion

The Figure 8 depicts the influence of α angle on the cutting forces: F_{x_max}, F_{y_min}, F_{z_max}. It was observed that cutting forces: F_{x_max}, F_{y_min}, F_{z_max} reach the highest absolute values during slot milling with $\alpha = 0$, independently of the selected feed per tooth f_z value (Fig. 8a, b, c). In this case, the cutting speed near the tool's rotational axis is very low (for point 0 of cutting tool the $v_{cmin} = 0$). Consequently, the large volume of the material which flows toward the cutter is not transformed into a chip. Instead, large elastic-plastic deformations press the material under the tool's flank face. This phenomenon is accompanied by the generation of high ploughing force values acting on the tool's flank face [23]. On the other hand, the growth of surface inclination angle leads to the growth of the minimum cutting speed (located at the point E of tool). This relation affects the reduction of ploughing mechanism and thereby the decreasing trend of forces with the increase of surface inclination angle. Moreover, the increase of minimum cutting speed at the point E can lead also to the growth of cutting temperature in the vicinity of point E, simultaneously contributing to the softening of hardened steel and further reduction of forces [26].

The highest influence of α angle on the cutting forces' F_{x_max}, F_{y_min}, F_{z_max} values can be found in the range: $0 \leq \alpha \leq 15°$. However, in the interval: $15° < \alpha \leq 60°$, the influence of the surface inclination angle on forces is low, which can simultaneously constitute the effective application range of the ball end mills during machining of hardened steel. Figure 8 reveals that increasing feed per tooth, f_z, induces an increase in cutting force absolute values, which is a typical relation found during metal cutting. However, for the F_{y_min} force, in the range $\alpha > 0$, the influence of feed per tooth f_z is insignificant.

Figure 9 presents the influence of the cutting speed v_c on F_{x_max}, F_{y_min}, F_{z_max}, F_{n_max} forces during milling with the selected surface inclinations. The feed normal force component (F_{x_max} – Fig. 9a) tends to decrease as cutting speed increases. Nevertheless, in case of the feed F_{y_min} (Fig. 9b), the thrust F_{z_max} (Fig. 9c) and the normal F_{n_max} components (Fig. 9d), a growing trend of force absolute values together with the growth of cutting speed is observed. This ambiguous effect of cutting speed on force components can be correlated with the occurrence of the opposing phenomena during milling at the higher cutting speeds. Among these phenomena, the softening effect of hardened steel can be distinguished, as well as the intensification of dynamical interactions in the milling system, correlated with the stability loss, the growth of vibrations level, and centrifugal force values [27, 28].

The results of the cutting trials undertaken to provide the data needed to generate the response surfaces are shown in Table 4.

In this table the normal force has been calculated using equation (11) and the material removal rate using equation (3). The experimental data for the feed normal force, F_x, and the normal force, F_n, is shown in figure 10. It is evident from this figure that the feed normal force has a more complex relationship with the cutting angle and speed than the normal force. Response surfaces have been estimated using this data by assuming incomplete quadratic and cubic polynomials for F_n and F_x respectively. These polynomials are defined as:

$$F_{n\_max} = a_1 + a_2\alpha + a_3 v_c + a_4 \alpha v_c + a_5 \alpha^2 + a_6 v_c^2 + a_7 \alpha^2 v_c + a_8 \alpha v_c^2 \tag{14}$$

$$F_{x\_max} = b_1 + b_2\alpha + b_3 v_c + b_4 \alpha v_c + b_5 \alpha^2 + b_6 v_c^2 + b_7 \alpha^2 v_c + b_8 \alpha v_c^2 + b_9 \alpha^3 + b_{10} v_c^3 \tag{15}$$

The terms $a_1 \cdots a_8$ and $b_1 \cdots b_{12}$ have been determined to give a least squares fit to the experimental data. Their values are presented in the table 5.

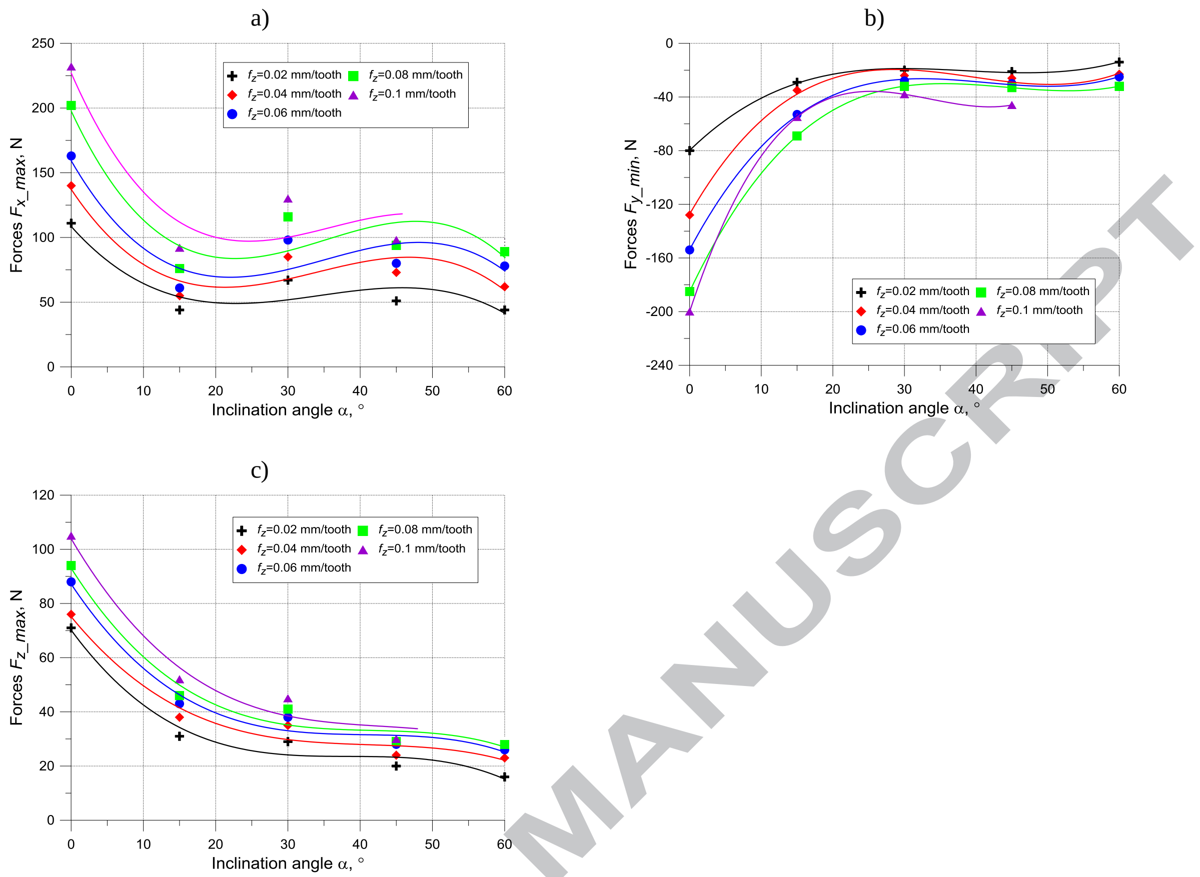


Fig. 8. The influence of surface inclination angle on forces: a) F_{x_max}; b) F_{y_min}; c) F_{z_max}. The cutting speed v_c=100m/min

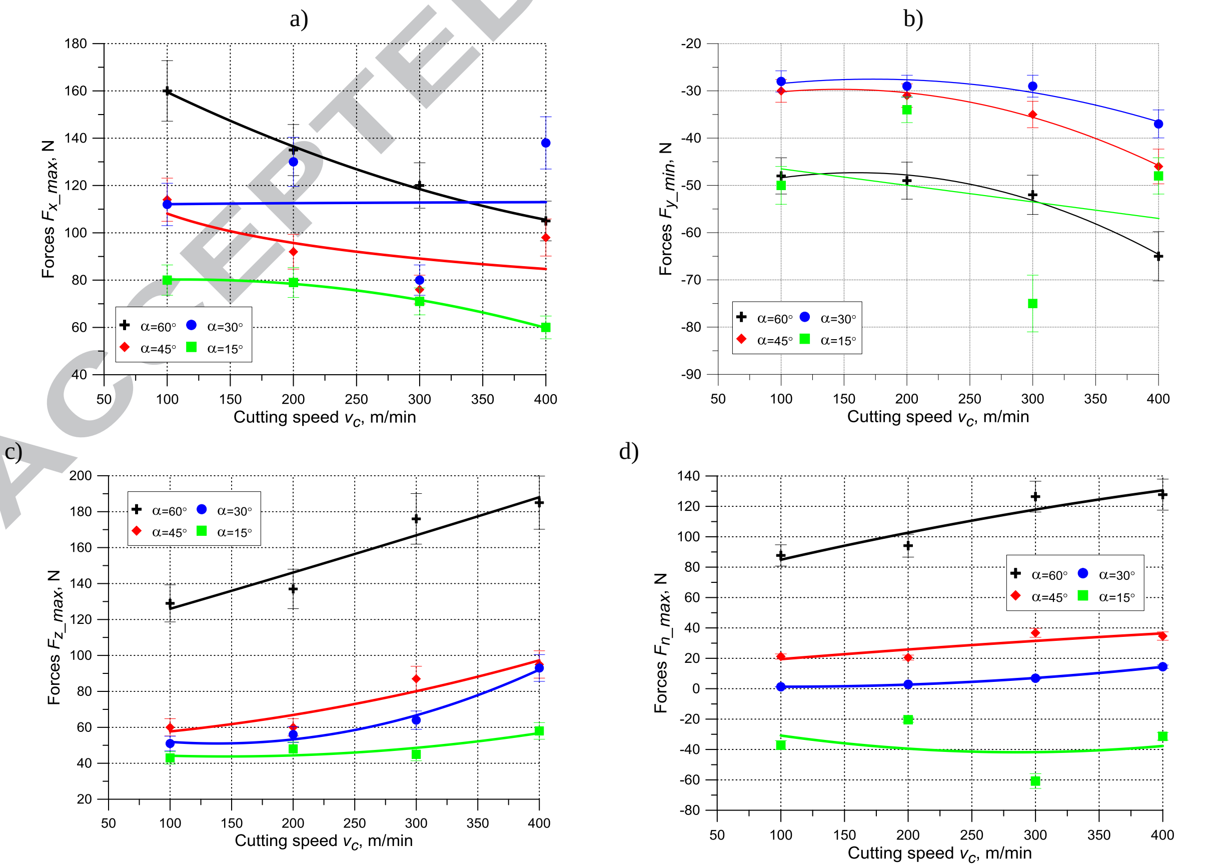


Fig. 9. The influence of cutting speed on forces: a) F_{x_max}; b) F_{y_min}; c) F_{z_max}; d) F_{n_max}. The feed per tooth f_z=0.1 mm/tooth

The response surfaces generated using this method are shown in figure 11. In order to determine the statistical significance of the cutting speed and surface inclination angle on the F_n and F_x force's mathematical models described by the equations (14) and (15), the analysis of variance (ANOVA) was applied. ANOVA results are given in the table 6. The analysis was made for the level of confidence 95% (the level significance was of 5%). It can be observed that both surface inclination angle and cutting speed have statistically relevant influence on the formulated forces' equations, because the obtained P values are lower than 0.05.

Table 4. Experimental data obtained during optimisation research

Experimental no.	α [°]	v_c [m/min]	F_x [N]	F_y [N]	F_z [N]	F_n [N]	Q_V[mm^3/min]
1	15	100	80	-50	43	-37.1	301.8
2	15	200	79	-34	48	-20.4	603.7
3	15	300	71	-75	45	-60.7	905.6
4	15	400	60	-48	58	-31.3	1207.5
5	30	100	112	-28	51	1.2	262.2
6	30	200	130	-29	56	2.8	524.5
7	30	300	80	-29	64	6.8	786.7
8	30	400	138	-37	93	14.4	1049.0
9	45	100	114	-30	60	21.2	219.0
10	45	200	92	-31	60	20.5	438.1
11	45	300	76	-35	87	36.7	657.2
12	45	400	98	-46	95	34.6	876.3
13	60	100	160	-48	129	87.7	196.6
14	60	200	135	-49	137	94.1	393.2
15	60	300	120	-52	176	126.4	589.9
16	60	400	105	-65	185	127.7	786.5

Table 5. The constants of force models defined by equations (14) and (15).

Equation (14)							
a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
-9.61200	-0.79860	-0.26870	0.00620	0.03290	0.00046	0.00003	-0.00001

Equation (15)									
b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9	b_{10}
-172.6	20.21	1.105	0.009718	-0.6022	-0.006187	-0.000236	0.00001	0.005802	0.000008

Table 6. ANOVA for the force models.

ANOVA for F_{x_max}					
Factors	Sum of squares, SS	Degree of freedom, DF	F ratio 5%	P	R^2
cutting speed v_c	3714	1	9.31	0.003936	0.9828
inclination angle α	12570	1	31.52	0.000001	
ANOVA for F_{n_max}					
cutting speed v_c	1210	1	9.94	0,002988	0.9999
inclination angle α	64996	1	533.8467	0.000000	

The response surfaces obtained have been used to calculate the utility function (equation 13). The utility function value over the full range of the cutting parameter variables is shown in figure 12. It can be concluded from figure 12a that the optimum cutting parameters are for the lower range of inclination angle and the higher range of cutting speed. A more detailed optimisation using $15^0 \le \alpha \le 24^0$ and $300\ \mathrm{m/min} \le v_c \le 420\ \mathrm{m/min}$ is shown in figure 12b. This figure shows that the minimal value of utility function (equalled to 0.049) is achieved with cutting speed v_{c_opt} = 375 m/min and surface inclination angle $\alpha_{\_opt} = 15°$. The application of these optimal cutting parameters gave cutting forces: $F_{x\_\max} = 57$ N, $F_{n\_\max} = -34$ N and material removal rate $Q_V = 1132$ mm^3/min.

a) b)

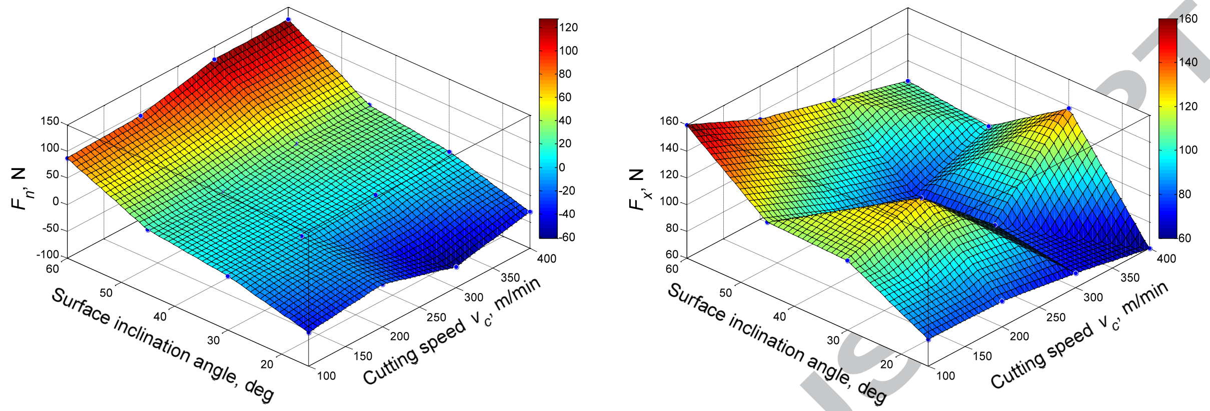


Fig. 10. The experimental raw data of the feed normal force, F_n (a), and the normal force, F_x (b) in function of surface inclination angle and cutting speed

a) b)

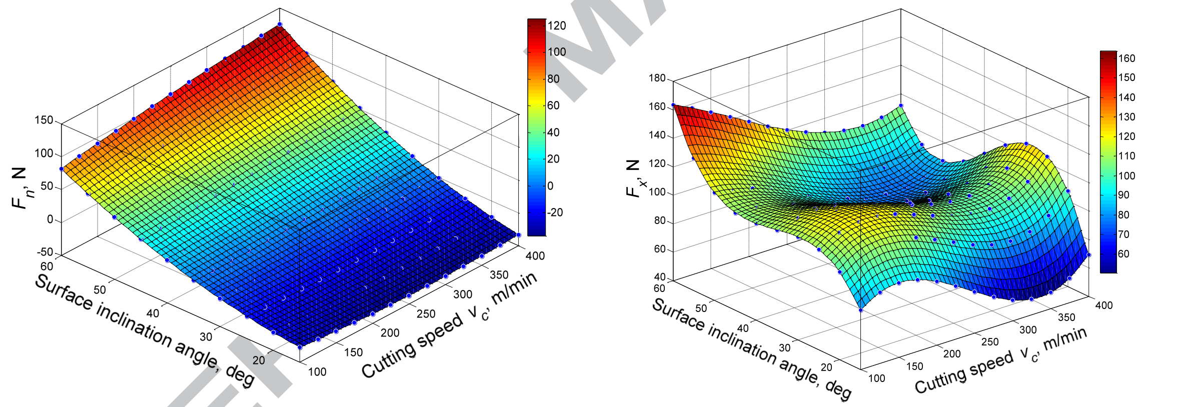
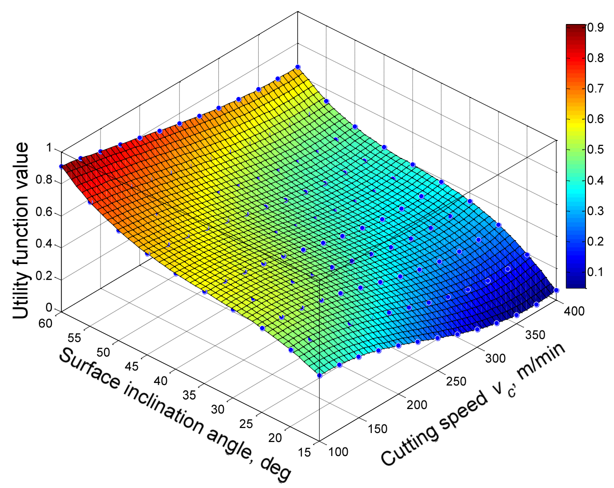


Fig. 11. Response surfaces generated for feed normal force, F_n (a) and the normal force, F_x (b)

a)



b)

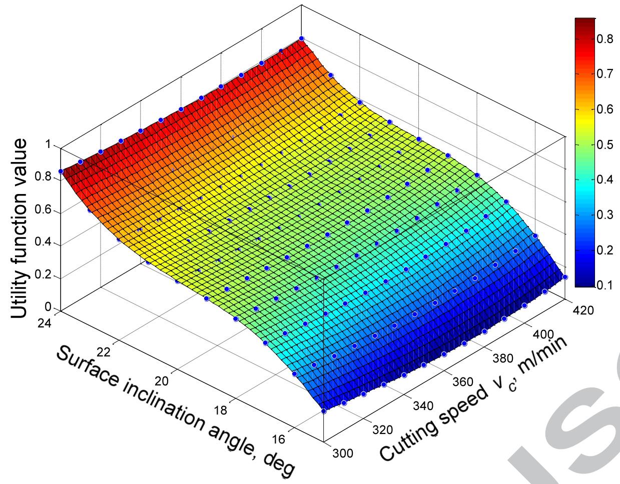


Fig. 12. Utility function for the cutting speed and surface inclination angle: a) over the full range of investigated parameters; b) for $15^0 \le \alpha \le 24^0$ and $300\ \mathrm{m/min} \le v_c \le 420\ \mathrm{m/min}$

It is also worth mentioning that the selection of optimal cutting parameters: v_{c_opt}, $\alpha_{\_opt}$ during ball end milling of free-form surfaces with constant tool axis inclination along the toolpath can also contribute to the improvement of the machined surface's geometrical quality. This is achieved because the tool's deflection is decreased since it is subjected to lower forces.

4. Conclusions

In this study, the analysis of forces and process efficiency during finish ball end milling of hardened 55NiCrMoV6 steel was presented. The research included measurements of cutting forces during the milling tests with variable input parameters, as well as calculation of process efficiency accounting for cutting parameters and surface inclination. Based on the experimental results a multi-criteria optimisation of the machining process, in the aspect of cutting forces and efficiency, was carried out.

The research revealed that surface inclination angle has a significant influence on all the investigated forces (F_{x_max}, F_{y_min}, F_{z_max}, F_{n_max}). The highest force values were observed during the slot milling with $\alpha = 0$, independently of the selected feed per tooth and cutting speed values. This observation can be attributed to the large elastic-plastic deformations of work material at the low cutting speeds, which consequently cause the growth of the ploughing force values. However, in the range: $15° \le \alpha \le 60°$, the influence of the surface inclination angle on forces is low. The cutting speed only had a significant influence on the thrust force F_{z_max}.

It was shown that the material removal rate of the ball end milling process in constant cutting speed mode is not only dependent on cutting parameters (a_p, f_z, b_r, v_c), but also on surface inclination angle α. Increasing α caused a reduction in the material removal rate.

The optimisation carried out enabled the selection of optimal cutting speed v_{c_opt} = 375 m/min and surface inclination angle $\alpha_{\_opt}$ = 15°. The application of these cutting conditions gave a high material removal rate ($Q_V \approx 1132$ mm^3/min) and low normal (F_{n_max} = - 34 N) and feed normal forces (F_{x_max} = 57 N). Thus, the selection of optimal milling parameters in practical applications (e.g. finish milling of the forging dies and casting moulds made of hardened steels) can lead to the reduction of tool deflections and cutting time. As a consequence, it can cause the simultaneous improvement in surface finish and tool life at the relatively high removal rates.

The method demonstrated here allowed the milling process' technological and economic effects to be improved. The proposed approach, based on the minimisation of a total utility function may also be utilized in the optimisation of other machining processes and responses.

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Highlights

- reduction of forces and improvement of efficiency during finish ball end milling
- multi-criteria optimisation in terms of cutting forces and efficiency
- relations between ball end milling process efficiency and surface inclination angle
- optimised forces and process efficiency achieved for v_c = 375 m/min and α = 15°