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SURFACE TEXTURE ANALYSIS AFTER BALL END MILLING WITH VARIOUS SURFACE INCLINATION OF HARDENED STEEL

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Abstract

In this paper, an analysis of various factors affecting machined surface texture is presented. The investigation was focused on ball end mill inclination against the work piece (defined by surface inclination angle α. Surface roughness was investigated in a 3D array, and measurements were conducted parallel to the feed motion direction. The analysis of machined surface irregularities as a function of frequency (wavelength λ), on the basis of the Power Density Spectrum – PDS was also carried out. This kind of analysis is aimed at valuation of primary factors influencing surface roughness generation as well as its randomness. Subsequently, a surface roughness model including cutter displacements was developed.

It was found that plain cutting with ball end mill (surface inclination angle $\alpha = 0°$) is unfavorable from the point of view of surface roughness, because in cutter's axis the cutting speed $v_c \approx 0$ m/min. This means that a cutting process does not occur, whereas on the machined surface some characteristics marks can be found. These marks do not appear in case of $\alpha \neq 0°$, because the cutting speed $v_c \neq 0$ on the full length of the active cutting edge and as a result, the machined surface texture is more homogenous. Surface roughness parameters determined on the basis of the model including cutter displacements are closer to experimental data for cases with inclination angles $\alpha \neq 0°$, in comparison with those determined for plain cutting ($\alpha = 0°$). It is probably caused by higher contribution in surface irregularities generation of plastic and elastic deformations cumulated near the cutter's free end than kinematic and geometric parameters, as well as cutter displacements.

Keywords: surface texture, ball end milling, hardened steel.

1. Introduction

Nowadays, high speed machining (HSM) of curvilinear surfaces using ball end mills is the subject of a lot of research [1 – 3]. The HSM technology is being widely used in many fields of industry, *i.a.* in production of drop forging dies and casting molds made from hardened steel [4], or in aerospace industry in manufacturing of wing parts made from aluminium alloys and composites [5]. From numerous investigations it results that in curvilinear milling, alternation of ball end mill inclination against the work piece (defined by surface inclination angle α) significantly affects cutting forces [6, 7], tool wear [8], as well as machined surface roughness [9]. From the point of view of above mentioned effects, the most undesirable is plain cutting with surface inclination angle $\alpha = 0°$, because cutting speed near the cutter's free end is close to zero. Thereupon, work material is not being cut but is ploughed and exposed to large elastic and plastic deformations [10]. This ploughing mechanism can induce excessive mechanical load on the cutter, which can lead to chipping, as well as deterioration of surface roughness. From a lot of research it can be seen that real surface roughness significantly varies from the theoretical model, which results from kinematic-geometric projection of the cutter into the work piece. These discrepancies are *i.a.* caused by the tool vibrations related to cutter's run out [11], as well as some phenomena related to the temperature in the cutting

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zone [12]. According to previous research related to cylindrical milling of hardened steel [13–15], the application of a surface roughness model including cutter displacements significantly increases the accuracy of the surface roughness parameters estimation, in comparison with the theoretic basic model. Furthermore, in the range of finish milling (especially, when $f_z \leq 1$ mm/tooth) plastic and elastic deformations of the work material related to minimum uncut chip thickness, can significantly affect generated surface roughness [16]. In addition, investigations conducted by [17] reveal that minimum uncut chip thickness value increases with the cutting speed decline v_c, which consequently leads to surface roughness deterioration. In spite of cutter' run out and minimum uncut chip thickness influence, surface roughness can be also affected by cutting edge notch [18].

Nevertheless, majority of research related to surface roughness generated in ball end milling focuses only on a kinematic-geometric basic model [19, 20]. For that reason this paper comprises the analysis of surface roughness generated in ball end milling including surface inclination angle, cutter's run out and minimum uncut chip thickness. The percentage contribution of analyzed factors in real surface roughness generation was also investigated.

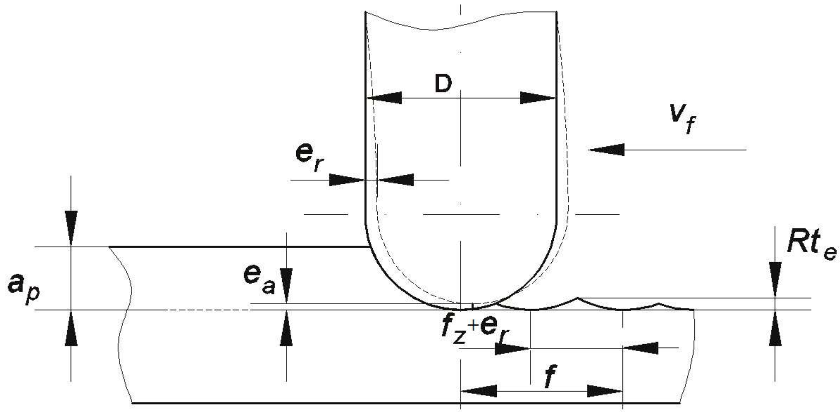
2. Surface roughness in the ball end milling process

Theoretic surface roughness height resulting from kinematic-geometric projection of the cutter into the work piece, measured parallel to feed motion direction v_f, generated after ball end milling can be formulated by the following equation:

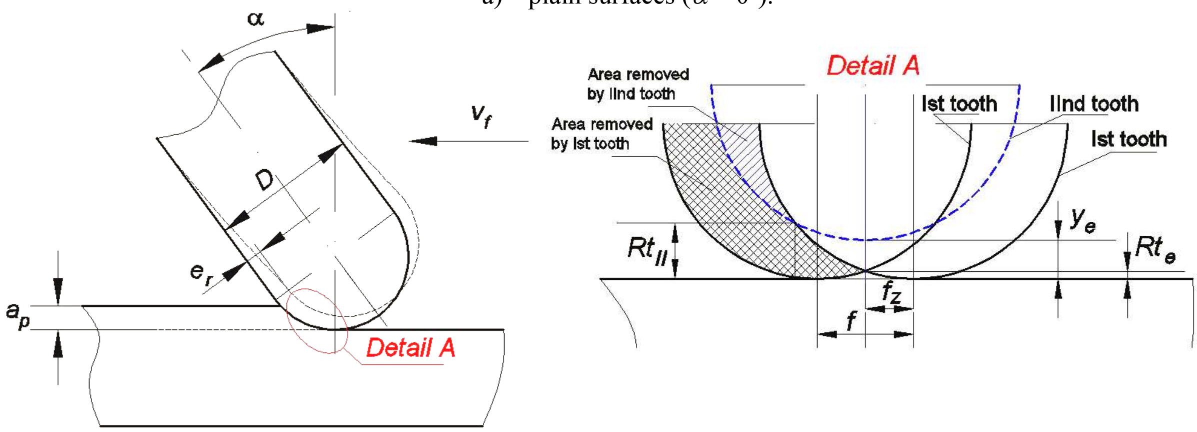
$$Rt_0 = \frac{D}{2} - \sqrt{\frac{D^2 - f_z^2}{4}} \approx \frac{f_z^2}{4 \cdot D}, \tag{1}$$

where: Rt_0– theoretical surface roughness, f_z – feed per tooth, D – tool diameter.

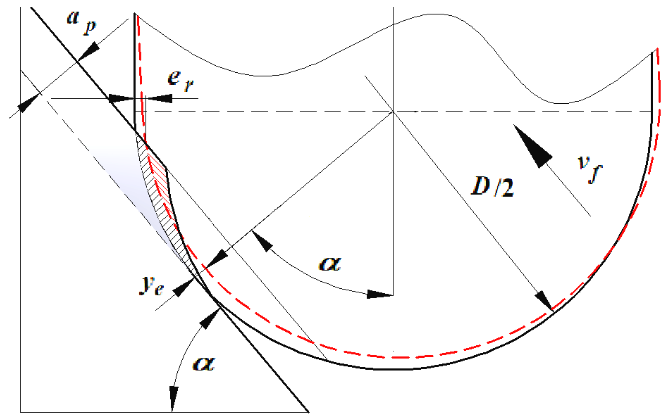
From equation (1) it can be clearly seen that an increase in feed per tooth f_z causes surface roughness growth, whereas an increase in tool diameter D, causes a decline in surface roughness. It is worth to indicate that during calculation of surface roughness height in directions different from the feed motion v_f direction, one should include also the pick feed value [20]. Nevertheless, theoretic models describing alterations of surface roughness parameters in the function of kinematic-geometric parameters often vary from the real surface roughness value, especially for low feed values. One of reasons of these discrepancies, are cutter displacements related to cutter's run out. Thereupon the surface roughness model including cutter's run out in a ball end milling process (Fig. 1) was applied in the conducted investigations. The e_r parameter depicted in Fig. 1 denotes radial displacement between the cutting edges, related to cutter's run out measured at the intersection of the cylindrical and spherical part of the tool. Cutter's static run out can be due to the tool itself (wear, asymmetry, insert setting, dynamic imbalance and thermal deformation) but it is mainly due to the offset between the position of the tool rotation axis and the spindle rotation axis.



a) plain surfaces ($\alpha = 0^0$).



b) inclined surfaces α > 0°.



c) The designation of y_e parameter

Fig. 1. Surface roughness height Rt_e including cutter displacement e_r in ball end milling (number of teeth $z = 2$).

The consequence is a tool rotation around the spindle axis with an eccentricity, which induces cutter displacements e_r. These displacements relocate directly on the work piece (along the closed trajectory in the *X-Y* plane), generating surface roughness (see Fig. 1). Moreover, e_r values can be also affected by cutting forces (generating tool deflections) and at higher rotational speeds *n,* by centrifugal forces [14]. However, in order to simplify deliberations presented in this paper, it was assumed that value e_r is constant along the tool's rotational axis and induced by static radial run out. Furthermore, tool's axial run out is equal to zero.

From Fig. 1a it results that radial displacement between the cutting edges e_r has an influence on the feed per tooth f_z value, and at the same time on the generated surface roughness height Rt_e. It can be also found that parameter e_r affects cutter displacement in the axial direction e_a (despite the assumption that tool axial run out is equal to zero). The value of displacement e_a can be described by the following equation:

$$e_a = l - R - \sqrt{(l-R)^2 - e_r^2}\,, \tag{2}$$

where: l – tool overhang, R– tool radius.
Nevertheless, in the majority of conventional machining processes, where displacement e_r is of the order of few microns and tool overhang is of the order of dozens of millimeters, the e_a displacement acquires very small values. For example: if e_r= 10 μm, and l = 60 mm, then from equation (2) it results that e_a is only $9.6 \cdot 10^{-7}$ mm, which means that the influence of this parameter can be neglected. Therefore, surface roughness height including cutter's displacement e_r, in ball end milling of plain surfaces ($\alpha = 0°$) is expressed by:

$$Rt_e = R - \frac{1}{2} \cdot \sqrt{4R^2 - f_z^2 - 2e_r \cdot f_z - e_r^2} \approx \frac{(f_z + e_r)^2}{4 \cdot D}\,. \tag{3}$$

In ball end milling of inclined surfaces ($\alpha \neq 0^0$ – Fig. 1b, c), cutter displacement in surface irregularities generation zone y_e varies from the e_r parameter. Its value can be determined using equation:

$$y_e = \frac{(R\cos\alpha + l - R) \cdot \sqrt{\left(e_r^2 + (l-R)^2\right) \cdot \cos\alpha + (R-l) \cdot \cos\alpha + e_r \cdot \sin\alpha}}{\sqrt{e_r^2 + (l-R)^2}}\,. \tag{4}$$

The geometrical interpretation of equation (4) for various surface inclination angles is presented in Fig. 2. From this figure it follows that value y_e is increasing monotonously with the surface inclination angle growth and for $\alpha = 90°$ its value is equal to e_r.

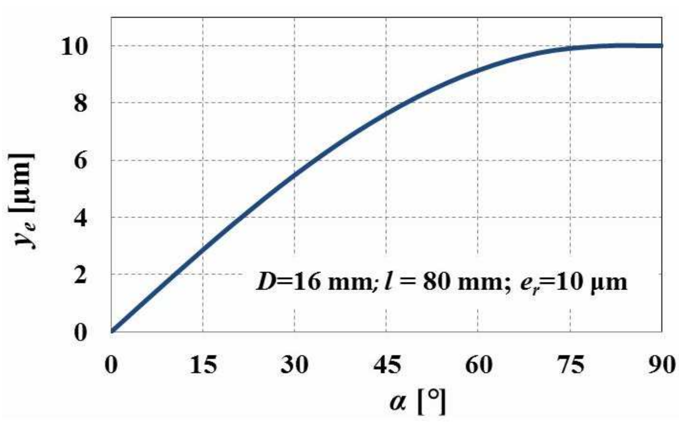


Fig. 2. Cutter displacement y_e in function of surface inclination angle α.

From Fig. 1b it follows also that during cutting, the cutter's second tooth – displaced by the value y_e, generates an irregularity whose height is equal to parameter Rt_{II}. However, this irregularity is being removed by the consecutive position of the first tooth. Therefore surface roughness height including cutter's displacement e_r, in ball end milling of inclined surfaces ($\alpha \neq 0°$) is dependent on the feed per revolution f instead of feed per tooth value f_z. The Rt_e value can be calculated on the basis of the following equation:

$$Rt_e = \frac{f^2}{4 \cdot D}. \tag{5}$$

The equation (5) is only valid in the range of small feed per tooth values, *i.e.*, when the following condition is fulfilled:

$$f_z < \sqrt{R^2 - \left(R - \frac{2 \cdot y_e}{z}\right)^2}, \tag{6}$$

where: z – number of teeth.

In case, when condition (6) is not fulfilled, then surface roughness height can be calculated on the basis of the equation presented in [14].

In order to include the plastic and elastic deformations of work material, related to minimum uncut chip thickness, one should apply the Brammertz dependency [16]. The modified Brammertz dependency, including cutter's displacement e_r is described by the equation:

$$Rt_{eB} = \frac{f_i^2}{8 \cdot R} + \frac{h_{\min}}{2}\left(1 + \frac{R \cdot h_{\min}}{f_i^2}\right), \tag{7}$$

where: h_{min} – minimum uncut chip thickness.

The parameter f_i in equation (7) is equal to feed per revolution value f, for cutting with surface inclination ($\alpha \neq 0^0$), and described by the equation (8) for plain cutting ($\alpha = 0^0$):

$$f_i = f_z + e_r. \tag{8}$$

The minimum uncut chip thickness can be described by the following expression [17]:

$$h_{\min} = k \cdot r_n, \tag{9}$$

where: k – a coefficient determined empirically, r_n - the radius of the tool arc cutting edge.

3. Experimental details

3.1. Research range and method

The investigations have been carried out on a hardened hot-work tool steel plate (55NiCrMoV6, hardness approx. 55 HRC). The monolithic ball end mill (z = 2, number of teeth, D = diameter 16 mm, λ_s = 30° tool major cutting edge inclination angle, r_n = 9 µm radius of tool arc cutting edge) was selected as a milling cutter (Fig. 3).

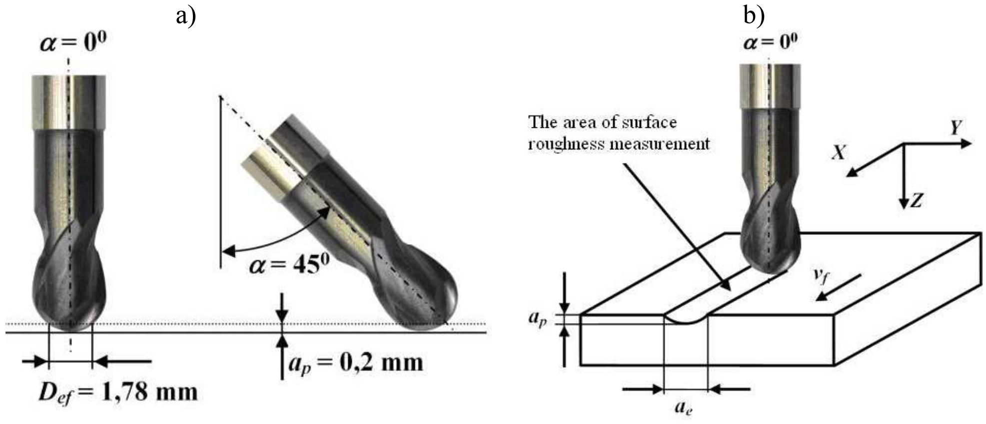


Fig. 3. The description of the ball end milling process: a) geometric parameters; b) the area of surface roughness measurement method.

The cutting edges were made from fine-grained sintered carbide (mean grain size approx. 0.4 µm) in TiCN anti-wear resistance coating. Experiments were conducted on a 5-axe CNC milling workstation (DECKEL MAHO Co., model DMU 60monoBLOCK). Surface roughness parameters were measured in 3D (*Sa*, *Sz*) and 2D array (*Rt*, *Rz*), using an optical surface profiler Veeco NT 1100. The measurements were made with 5x magnification. The scanning area was equal to 0.9 mm x 1.2 mm and the distance of vertical points was 1.65 µm. The Power Density Spectrum – PDS of surface irregularities in function of frequency (wavelength λ) was also determined. The PDS charts were obtained on the basis of 3D surface topographies, which were measured by the stylus profile meter Hommelwerke T8000. The area of surface roughness measurement is depicted in Fig. 3b. Cutting parameters applied in the research are presented in Tab. 1.

Tab. 1. Cutting parameters applied in the research.

n [rev/min]	v_f [mm/min]	a_p [mm]	a_e [mm]	α [°]	f_z [mm/tooth]
3000	600	0.2	1.78	0, 45	0.1
7500	1500				
12000	2400				

Cutter's displacement related to radial run out e_r was measured offline using a dial indicator. The value of parameter e_r was equal to 10 µm. It means that in the research carried out the condition expressed by equation (6) was fulfilled, and hence surface roughness height can be calculated on the basis of equations (5) and (7).

In order to calculate the minimum uncut chip thickness expressed by the equation (9), one should assess the k coefficient value. Its value can be selected as 0.25 on the basis of work [21] related to cutting of hardened bearing steel with hardness 61 HRC, in the range of cutting speeds: v_c= 40÷120 m/min. Nevertheless, according to [17], in the range of very low cutting speeds, the value of k coefficient is greater, which can reduce the accuracy of h_{min} estimation in ball end milling of plain surfaces – α = 0° (because the cutting speed near cutter's free end is close to zero).

The percentage contribution of analyzed factors in real surface roughness generation was calculated on the basis of equation:

$$C_i = \frac{100 \cdot Rt_i}{Rz}, \tag{10}$$

where: Rt_i – is the theoretical surface roughness affected only by the i-th factor (*e.g.* kinematic – geometric projection or cutter's run out), Rz – measured surface roughness height.

3.2. Experimental results and analysis

Figure 4 depicts the influence of the surface inclination angle α and rotational speed n on surface roughness parameters (Rz, Rt) after ball end milling.

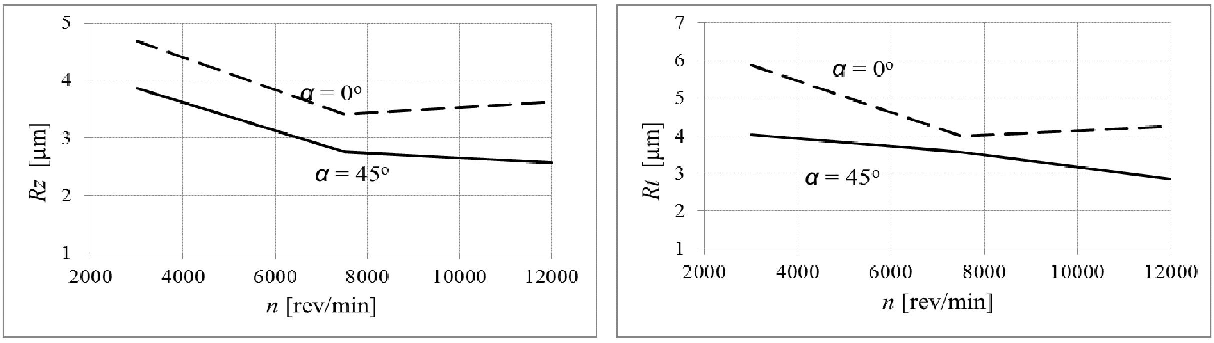


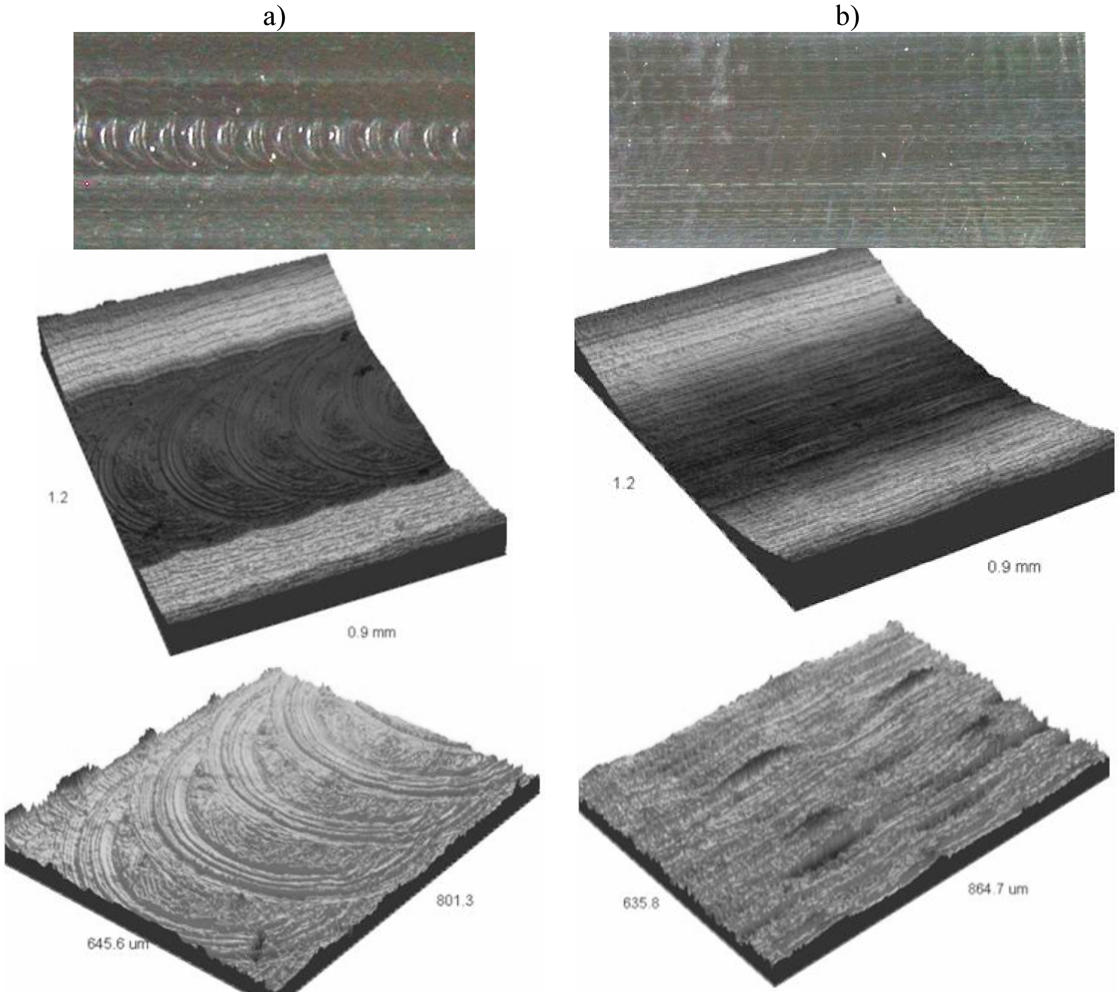
Fig. 4. Surface roughness parameters in function of surface inclination angle α and rotational speed n.

From Fig. 4 it is seen that surface roughness parameters (Rz, Rt) have lower values for surface inclination angle α = 45°, in the whole investigated range of rotational speed n. This dependency confirms the fact that in case of plain milling, the cutting speed near cutter's free end is close to zero, and thus the appearance of the ploughing mechanism induces large elastic and plastic deformations, which as a consequence influences surface irregularities. It was also found, that independently of the value of the inclination angle α, cutting speed growth induces a decrease of surface roughness parameters.

Figure 5 depicts an image of the machined surface and 3D views of surface irregularities for two investigated surface inclination angles α. In case of plain milling with α = 0° , some characteristic marks on the machined surface can be seen (Fig. 5a). Their presence is caused by the ploughing mechanism, which induces excessive elastic and plastic deformations of the work material. These marks do not appear in case of α = 45° (Fig. 5b), because the cutting speed $v_c \neq 0$ on the full length of the active cutting edge and as a result, the machined surface texture is more homogenous. This phenomenon is also confirmed by the 3D views of the machined surface, which reveal that during milling with α = 45°, surface irregularities are more homogenous, and their texture is highly related to the kinematic – geometric projection of the cutter into the work piece. Circumstantial analysis of the surface irregularity form was carried out in the frequency domain (wavelength λ), on the basis of so-called Power Density Spectrum – PDS (Fig. 6). The PDS analysis reveals that in case of plain milling α = 0°, no occurrence of a peak with wavelength corresponding to the feed per tooth f_z value is found. Its presence is usually related to the kinematic – geometric projection of the cutter into the work piece. On the other hand, occurrence of peaks with wavelengths λ > 0.2 mm can be found. Their presence is attested to a ploughing mechanism, as well as some random phenomena. In case of surface inclination milling with α = 45°, the peak related to the λ = 0.2 mm is dominant, which corresponds to the feed per revolution f value, instead of feed per tooth f_z. It means that in surface texture generation, cutter's run out has a crucial contribution.

Figure 7 depicts the comparison of measured (Rz) and calculated (Rt_{eB}) surface roughness. Surface roughness parameters calculated on the basis of the model including cutter's run out and minimum uncut chip thickness Rt_{eB} (see – equation 7) are in good agreement with measured ones, independently of the surface inclination angle α. Some differences between measured and calculated values result from simplifications enclosed in the model *i.e.* assumption that the milling process is only affected by the static radial run out or the assumption that minimum uncut chip thickness is independent of the cutting speed value.

a) b)



Sa = 0.368 µm
Sz = 3.83 µm

Sa = 0.323 µm
Sz = 2.57 µm

Fig. 5. Images of machined surfaces and 3D views of surface texture after ball end milling with n = 12000 rev/min and surface inclination: a) α = 0°, b) α = 45°.

a)

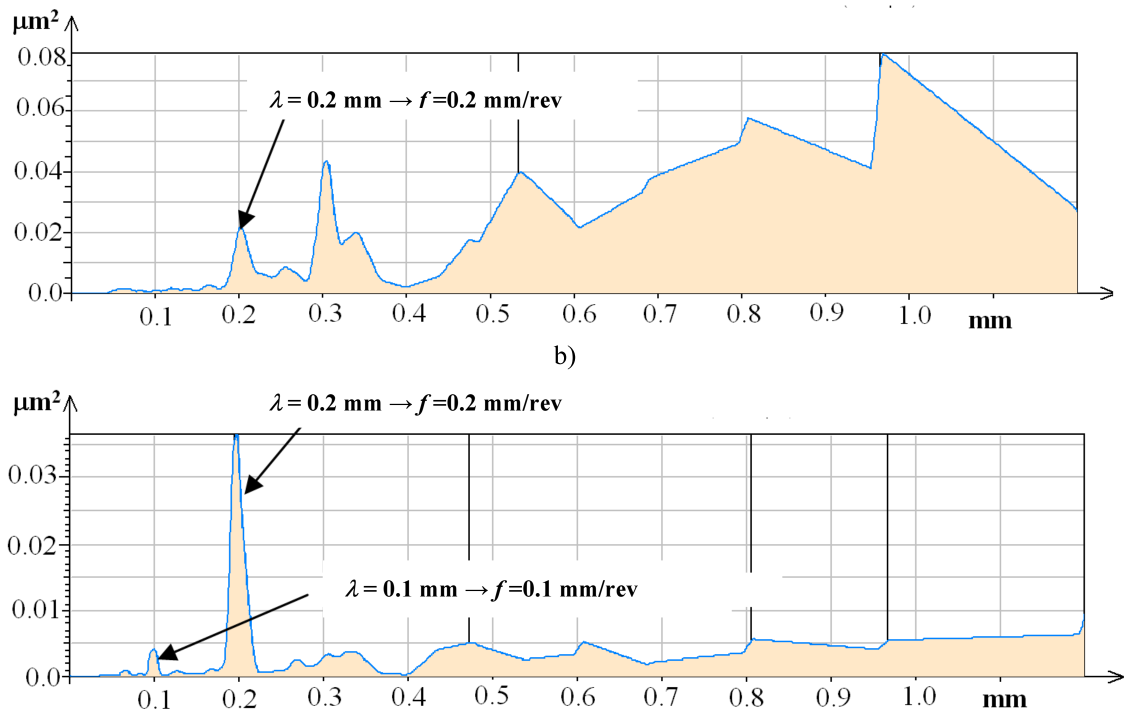


Fig. 6. PDS function for milling with n = 12000 rev/min and: a) $\alpha = 0^0$, b) $\alpha = 45^0$.

The discrepancies mentioned above are also caused by the other phenomena not included in the model. On the basis of surface roughness models presented in chapter 2, equation (10), as well as measured values, the percentage contribution of analyzed factors in real surface roughness generation was developed (Fig. 8). The analysis revealed that a dominant contribution, in case of plain milling ($\alpha = 0°$) has the minimum uncut chip thickness, and thus deformation of the work material. The influence of the kinematic – geometric projection of cutter into the work piece and cutter's run out is in this case negligible and totally amounts to 5%.

In inclined surface milling with $\alpha = 45°$, the greatest contribution has again the minimum uncut chip thickness (but less than for $\alpha = 0°$). Nevertheless, in this case, cutter's run out has also a significant influence. Its percentage contribution to surface texture generation is approximately 20%. From Fig. 8 it can be seen that surface texture is also affected by some phenomena not included in the investigations. These remaining phenomena include *i.a.* plastic fash of the work material, cutting edge notch, high frequency vibrations and some random factors. However the total influence of the remaining phenomena, in the range of carried out research did not exceed 15%.

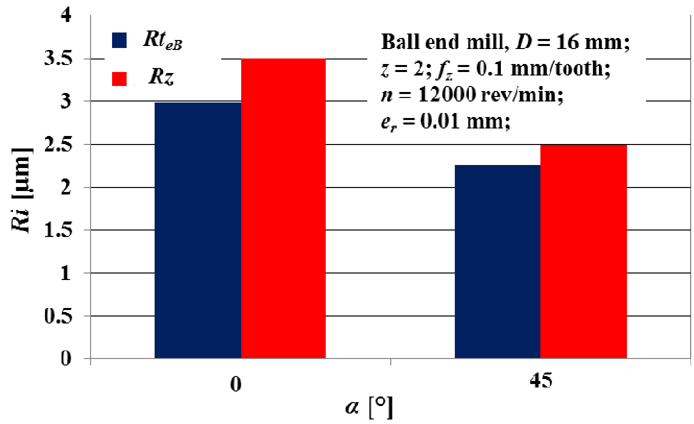


Fig. 7. Measured and calculated surface roughness for different inclination angles α.

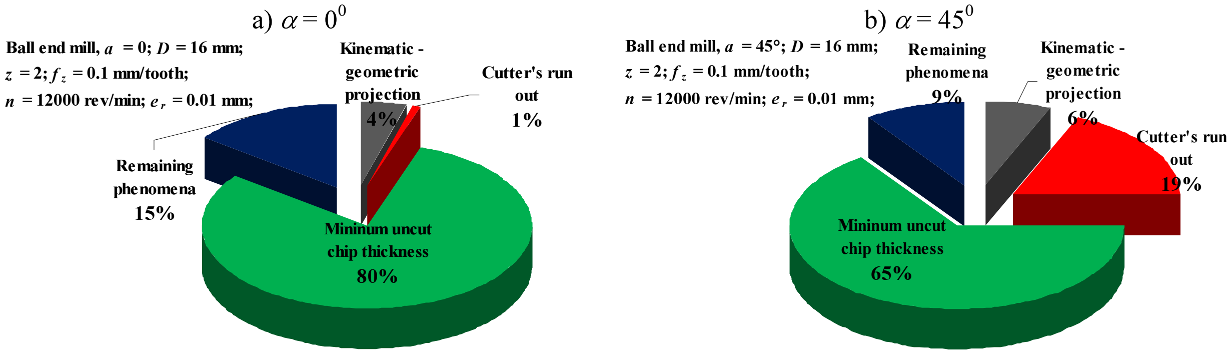


Fig. 8. The percentage contribution C_i of analyzed factors in real surface roughness generation.

4. Conclusions

This paper investigated the surface texture generated during the ball end milling of hardened steel including surface inclination angle, cutter's run out and minimum uncut chip thickness. A surface roughness height model including the above-mentioned factors was developed. The percentage contribution of analyzed factors in real surface roughness generation was also investigated.

The research revealed that surface roughness parameters, generated in ball end milling of hardened steel have lower values (in the investigated range of rotational speed n) for surface inclination angle α = 45°, in comparison with those obtained for plain milling (α = 0°). During plain milling with α = 0°, the ploughing mechanism has a dominant contribution to surface texture generation. The influence of the kinematic – geometric projection of the cutter into the work piece and cutter's run out is in this case insignificant and totally amounts to 5%. In inclined surface milling with α = 45° surface irregularities are also generated by the ploughing mechanism and minimum uncut chip thickness. Nevertheless, in this case, cutter's run out has also significant influence. Its percentage contribution to surface texture generation is approximately 20%.

The carried-out analysis reveals that surface inclination has significant influence on the generated surface texture. Therefore, the appropriate selection of the surface inclination angle related to the specified machining strategy can improve the surface quality by the reduction of surface roughness.

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