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Effects of Hard Oxides Reinforcing of Iron-Based MMCs on the Surface Topography Features after Finish Turning

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ABSTRACT

Metal matrix composites (MMCs) are widely used in various industrial applications. Various types of reinforcing particles are added to MMCs to improve their mechanical and functional properties. Optimal processing conditions for the elements manufactured from MMCs ensure the efficiency of their use. This study describes the surface topography parameters of iron-based MMCs reinforced with graphite, alumina and zirconia nanoparticles depending on their percentage. The Simplex Lattice Design (SLD) method was used as the Design of Experiments(DoE) method and the range of additives change was 0–1 wt%. The specimens were machined under dry turning conditions using PVD-coated GC1115 carbide inserts. Depth of cut, cutting speed and feed values were stable, typical of finish turning. The surface topography was analyzed using Sensofar S Neox optical profilometer and Mountains Map software. *Sa* and *Sz* surface amplitude parameters, most widely used in the production industry, were evaluated according to ISO 25178-2:2012 standard. It has been shown that reinforcing additives and their amount in the mixture unambiguously affect the geometric features of the surface after turning process of the iron-based MMCs. Therefore, it is possible to select such a combination of particulates that will provide the expected quality of the machined surface.

Keywords: iron-based metal matrix composites, nanooxide reinforcing, simplex lattice design, finish turning, 3d surface topography.

INTRODUCTION

Metal matrix composites (MMCs) are increasingly used in different mechanical engineering applications due to their amplified physical and mechanical properties. Although MMCs machining is less well understood due to their complex microstructure and poor machinability, a comprehensive scientific study of their cutting processing and related formation of the surface integrity is important, particularly for industrial-scale applications. Evaluation of the surface topography after machining plays an important role for many fundamental problems, i.e., friction and wear, contact deformation, tightness and positioning accuracy of contact bonds, etc. [1].

Xiong et al. [2] analyzed 2D and 3D surface roughness, residual stresses and fatigue strength of TiB_2/7050Al MMCs under milling and found that 3D surface roughness is more suitable for the machined surface profile characterizing. Chen et al. [3] studied the effects of TiB_2 particles on the machinability and surface integrity of TiB_2/2024 and TiB_2/7075 composites after milling and compared them to the conventional 2024 and 7075 aluminum alloys. With the same milling parameters, the surface roughness of the MMCs studied was much lower than that of base aluminum alloys. Okay et al. [4] studied the machinability of Al MMCs with hybrid hardening with boron carbide B_4C and carbon nanofiber under drilling. It was revealed that the surface roughness values increased with the feed rate increasing, but decreased with the cutting speed increasing. Li et al. [5] investigated Ti-MMCs hardened with multi-walled carbon nanotubes. It was found that the surface roughness and the appearance of pores and scratches on it depended on the sintering technology. Nasr et al. [6] studied the machinability of Ti6Al4V-based nanocomposites reinforced with graphene nanoplatelets (GNPs) of different percentages, such parameters as cutting forces, surface roughness and morphology, microhardness and chip morphology were analyzed. Shyam et al. [7] investigated the surface integrity and surface roughness as a function of the cutting speed, depth of cut and feed rate when machining a C_f/SiC ceramic composite based on silicon carbide reinforced with carbon fibers with different cooling conditions. Manna and Bhattacharyya [8] investigated the effect of cutting conditions on the surface roughness when Al/SiC-MMC turning. Based on the Taguchi L27 array, mathematical models related to *Ra* and *Rt* surface roughness parameters were created. Bhushan et al. [9] studied the effect of cutting speed, cutting depth and feed rate on the surface roughness when machining 7075 Al and MMCs with 10 wt.% SiC particulates. Niu and Cheng [10] investigated the B_4C/Al2024 composite and showed that the roughness of the machined surface during precision machining of particle-reinforced MMCs can be reduced by increasing the cutting speed and reducing the depth. Güneş et al. [11] investigated the surface roughness and tribological properties of MMCs based on CuSn10 bronze reinforced with GGG40 cast iron particles. It was found that the temperature and pressure used during the composite fabrication had a dominant influence on *Ra* and *Rz* surface roughness parameters. Ajithkumar and Xavior [12] described the influence of cutting speed, feed rate and cutting depth on the surface roughness under dry turning of three types of hybrid composites, namely, Al7075+10%SiC+0.1% B_4C, Al7075+10%SiC+0.1% graphene and Al7075+10%SiC+0.1% carbon nanotubes. The results revealed that the feed rate had the strongest impact on the surface roughness. Ekici et al. [13] investigated impact of the cutting parameters on the quality characteristics of the surface roughness and dimensional accuracy when drilling of Al/10B_4C and Al/10B_4C/5Gr MMCs. It was determined during drilling that the 5% graphite reinforced composite improved the surface quality and diameter accuracy. Niknam et al. [14] analyzing Ti-MMCs semi-dry turning, found that higher resulting values of *Ra* and *Rq* parameters were observed under higher cutting speed. Tomadi et al. [15] studied the effect of cutting parameters on the surface roughness in the machining of AlSi alloy reinforced with AlN particles under dry cutting conditions. The optimum cutting parameters were predicted. Subramanian et al. [16] focused on the conditions which influence the surface roughness when cutting LM6/SiC_p Al MMCs. Central composite rotatable planes allowed finding direct and interaction effects of the process parameters to keep the surface roughness minimal. Gopal and Prakash [17] investigated the effect of material and machining parameters on the surface roughness in end milling of Mg hybrid MMCs fabricated by reinforcing with cathode ray tubes, E-waste and boron nitride particles. Optimal particle sizes, reinforcement percentage, drill diameter, rpm speed, feed and depth of cut allowed achieving *Ra* ~0.2 μm of the surface roughness.

Summarizing, it can be said that currently the changes in the topography of the machined surface are most often studied with MMCs based on aluminum and titanium alloys. Other materials are considered much less frequently. Hard ceramic particles and carbon nanotubes are mostly used for reinforcement. Aspects concerning spatial 3D changes in the surface topography as well as the synergetic effects of different additives are considered to a much lesser extent. Therefore, considering that iron-based materials are very widely used in industry, the aim of this research was to analyze changes in the surface topography under finish turning of iron-based MMCs reinforced with hard oxides depending on their percentage.

MATERIALS AND METHODS

Materials

Iron and carbon, in the form of Gr graphite powders, were used to produce the base material, while alumina and zirconia oxides and additional graphite were used as reinforcing additives. The average size of iron particles was less than 200 μm, while the average size of of graphite particles was 3 μm. The particle size of ZrO_2 ranged from 50 to 150 nm and that of Al_2O_3 from 30 to 70 nm.

The powder components were mixed in a mixer of "drunk barrel" type for over 90 min. Next, the roll-shaped samples were extruded using a hydraulic press and in the final stage of the manufacturing process, the samples were sintered in theendothermic gas atmosphere at 900–1100 °C over 60 min. The diameter of the rolls was of 50 mm, while their width was of 16 mm.

Turning process conditions

The turning process was carried out under dry cutting conditions using CKE6136i CNC lathe of DMTG with SDJCR 2020K 11 tool holder and DCMX 11 T3 04-WM 1115 indexable inserts at the cutting speed of 200 m/min, feed rate of 0.1 mm/rev, and depth of cut of 0.25 mm. Coated inserts made of GC1115 cemented carbides were used. The depth of cut and feed rate values selected are typical for finish processing and the cutting speed values are within the range of cutting speeds used currently to ensure the life of favorable cutting tool. The parameters used are in accordance with the manufacturer's, Sandvik Coromant, recommendations.

Topography characterization

Surface topography of the specimens turned was measured using Sensofar S Neox optical profilometer with the confocal technique and Mountains Map software. A λc (the limit wavelength between waviness and roughness) filter was used while performing the measurements according to ISO 16610-21 standard.

The 3D surface topography parameters allow a more accurate and detailed characterization of the surface compared to the 2D parameters. The 3D surface roughness amplitude parameters according to ISO 25178-2:2012 were analyzed, namely, *Sa* – arithmetic mean height, *Sz* – maximum height, *Ssk* – skewness, *Sku* – kurtosis.

Additionally, 3D and 2D images, Abbott-Firestone (material ratio) curves, and height's distribution of machined surfaces microroughness were evaluated.

Design of experiment (DoE)

The planning of mixture studies is based on the Simplex Lattice Design (SLD) method that allows generation of a lattice of simplexes located in the space tested. Designs based on a simplex

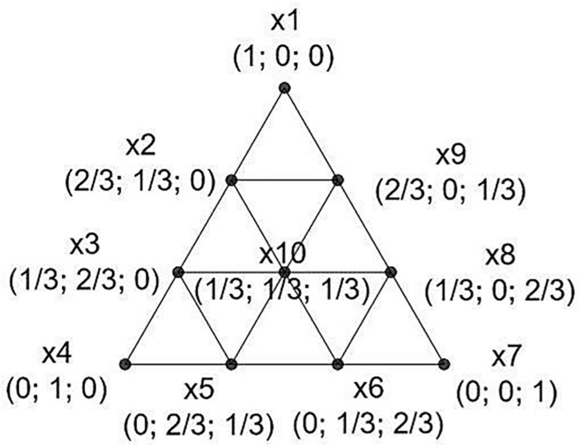

Fig. 1. Simplex lattice scheme for ten mixtures of metal nano oxides and graphite

Table 1. Mass proportions of various components of the mixtures tested

Mixture number	Composition and marking of mixtures					
	Gr [Gr]		Al_2O_3 [Al]		ZrO_2 [Zr]	
	Mass content, %	Code {0,1}	Mass content, %	Code {0,1}	Mass content, %	Code {0,1}
1	2	1	0	0	0	0
2	1	0	1	1	0	0
3	1	0	0	0	1	1
4	1.33	0.33	0.67	0.67	0	0
5	1.33	0.33	0	0	0.67	0.67
6	1	0	0.33	0.33	0.67	0.67
7	1.67	0.67	0.33	0.33	0	0
8	1.67	0.67	0	0	0.33	0.33
9	1	0	0.67	0.67	0.33	0.33
10	1.33	0.33	0.33	0.33	0.33	0.33

lattice are most commonly used to study the effects of different mixture components on the final properties of the composition tested [18]. The triangular simplex matrix for the components under the study consists of the points with defined coordinate positions. The assumed proportions of the components have uniformly distributed values between 0 and 1, with the maximum of those values being reached at the tops of the triangle.

In case of the studies performed for ten mixtures of metal nano oxides and graphite, the simplex lattice scheme is shown in Figure 1, and the detailed compositions are presented in Table 1. Total mass fraction of the additive mixture in the complete composite is 2%, the variation of the mixture composition is carried out only in this range.

The use of an equiangular triangular simplex lattice resulted in 10 test points, which allowed statistical analysis to be performed for the results obtained. The program Statistics 13 was used to perform the statistical analysis of the test results and the cubic polynomials in a canonical form for the third order asymmetric curvature were generated as:

$$\eta = \sum_{1\le i\le q} \beta_i x_i + \sum_{1\le i<j\le q} \beta_{ij} x_i x_j + \sum_{1\le i<j\le q} \gamma_{ij} x_i x_j (x_i - x_j) + \sum_{1\le i<j<k\le q} \beta_{ijk} x_i x_j x_k \quad (1)$$

where: β and γ are regression coefficients;
x_i, x_j, x_k – code values for points tested.

RESULTS AND DISCUSSION

Analysis of the amplitude parameters of surface topography

The obtained results of tests and statistical analysis software enabled generation of the regression models for the *Sa* and *Sz* amplitude parameters of the surface topography after turning depending on the mixture composition:

$$Sa = 1.27\text{Gr} + 2.16\text{Al} + 2.84\text{Zr} + 4.98\text{GrAl} - 28.8\text{GrAlZr} \quad (2)$$

$$Sz = 21.84\text{Gr} + 59.4\text{Al} + 43.57\text{Zr} - 53.62\text{AlZr} + 180.91\text{GrAl}(\text{Gr} - \text{Al}) \quad (3)$$

where: Gr, Al and Zr – code designations of additives used according to Table 1.

Based on the regression models, three-dimensional graphs and contour plots of the changes in *Sa* and *Sz* parameters of the surface topography after turning were generated as a function of the additive content of the MMCs tested, as shown in Figure 2.

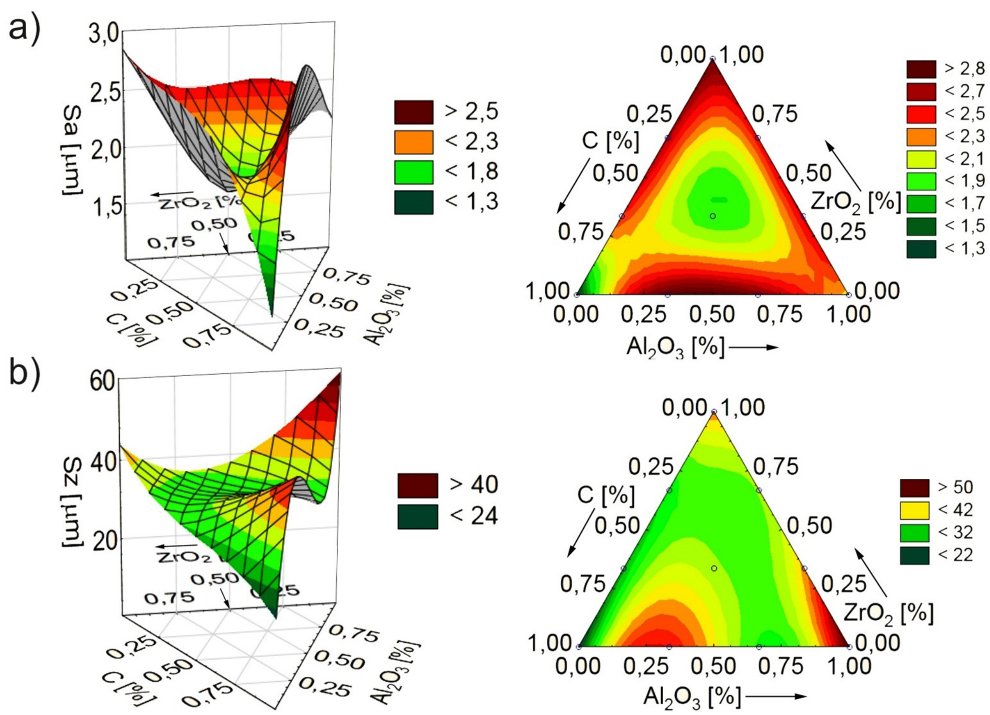

Fig. 2. Three-dimensional grphs and contour plots of changes in the amplitude parameters of the surface topography: (a) *Sa* and (b) *Sz*

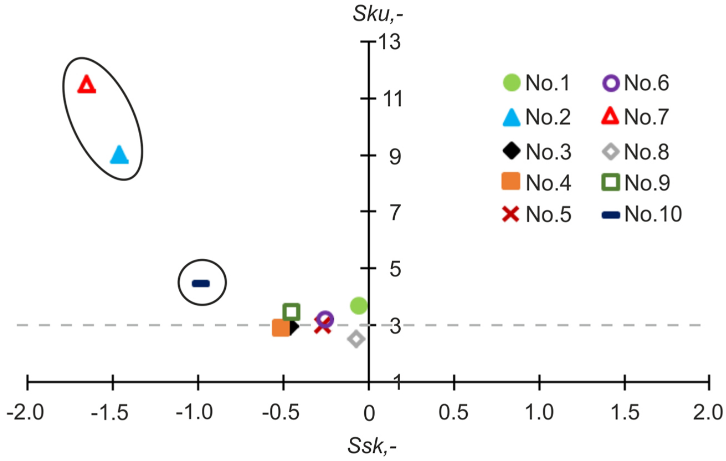

Fig. 3. The *Sku-Ssk* map of the surface for ten mixtures with metal nano oxides and graphite

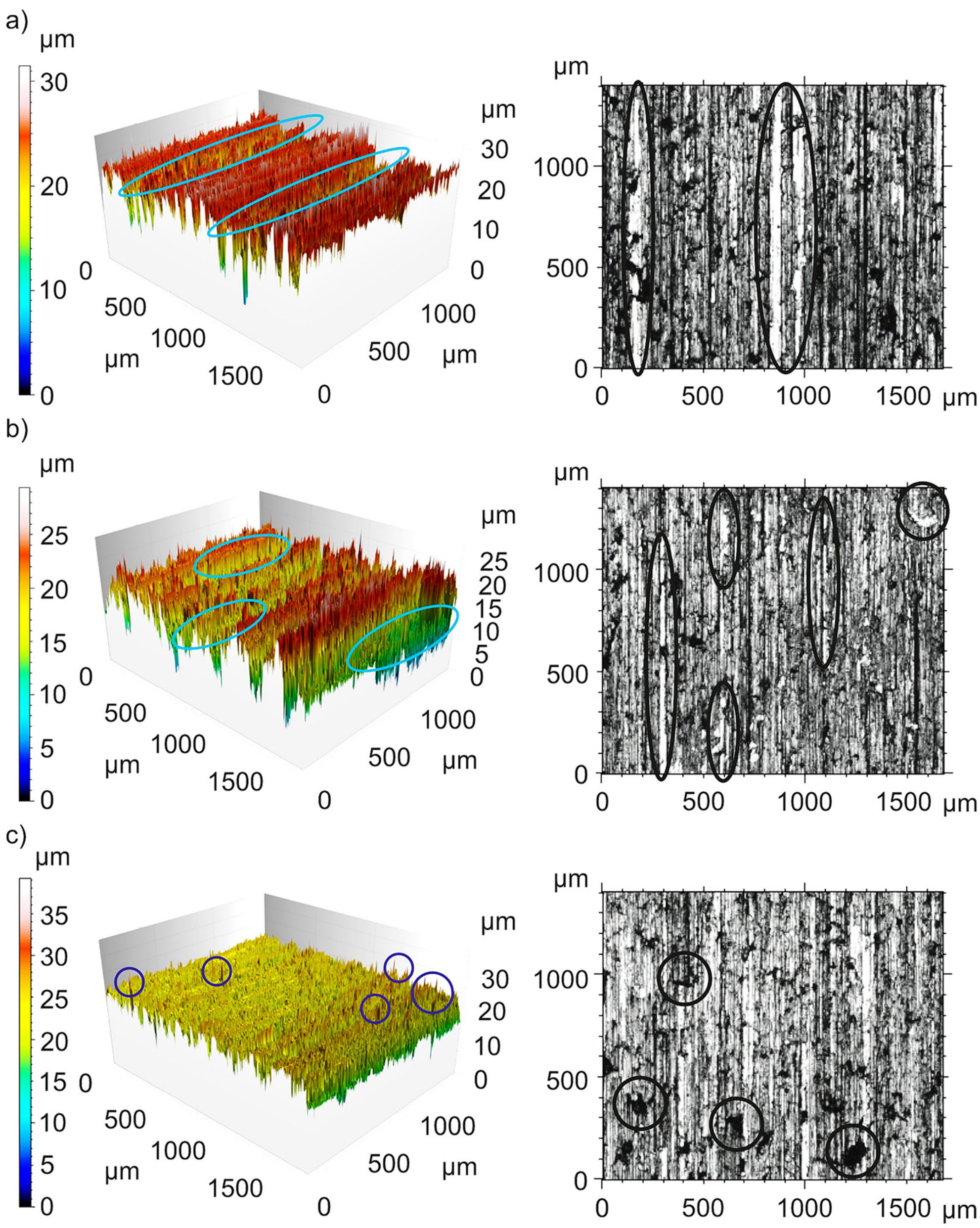

Fig. 4. 3D and 2D images of the surfaces after turning for mixtures: (a) Gr and Al_2O_3, (b) Gr and ZrO_2, (c) Gr, Al_2O_3 and ZrO_2; single defects are marked with ellipses

Analyzing these graphs, the interaction of the mixtures studied with the *Sa* and *Sz* parameters of the surface topography can be observed. Ensuring Gr content in the range of 0.8–1% and simultaneously reducing the content of Al_2O_3 and ZrO_2 to the range of 0–0.1% results in minimum values of the *Sa* and *Sz* surface topography parameters, which are used in industry to evaluate the product quality [19]. Reductions in the *Sa* and *Sz* parameters were also achieved when all three additives were simultaneously introduced into MMCs at the amount of 0.45–0.55%.

Figure 3 shows the *Sku-Ssk* map of the surface after turning for ten mixtures of metal nano oxides and graphite. The *Sku* skewness parameter informs about the prevalence of peaks or pits on the machined surface. The *Ssk* kurtosis parameter > 3 informs about the presence of high peaks or deep pits on the surface and their absence at *Sku*< 3 [20]. Surfaces of the samples containing only Gr and Al_2O_3 in their composition (mixtures of No. 2 and No. 7) are characterized by irregular shape. A high positive value of the *Sku* parameter indicates the presence of a large number of defects on the machined surfaces. In contrast, a high negative value of the *Ssk* parameter indicates that such surfaces are characterized by deep pits. Deep pits are characterized by surfaces containing a large amount of Gr in the composition with a low content of Al_2O_3 and ZrO_2 (mixture No.10).

Evaluation of the surfaces treated

The surface topography and material ratio curves (or Abbott Firestone curves) of three mixtures (these are sample numbers 4, 5 and 10 according to Table 1) were analyzed. Sample No. 4 is a mixture in which 0.33% Gr was added and the average content of Al_2O_3 was of 0.67%. Sample No. 5 is a mixture in which 0.33% Gr and 0.67% ZrO_2 are present. Sample No. 10 is a mixture in which 0.33% Gr, 0.33% Al_2O_3 and 0.33% ZrO_2 are present in equal amounts.

3D and 2D images of the surface after turning for the selected mixtures are shown in Figure 4. On the surface of sample No. 4, fairly regular, very high peaks and very deep valleys are observed. Such a surface formation is typical of the turning process. In contrast, very irregular peaks and valleys are observed on the surface of sample No. 5. On the surface of sample No. 10, irregularly occurring pits and single peaksare observed. Under the friction process, the peakscan be sheared off and the resulting debris can affect negatively the work at the friction junction [21].

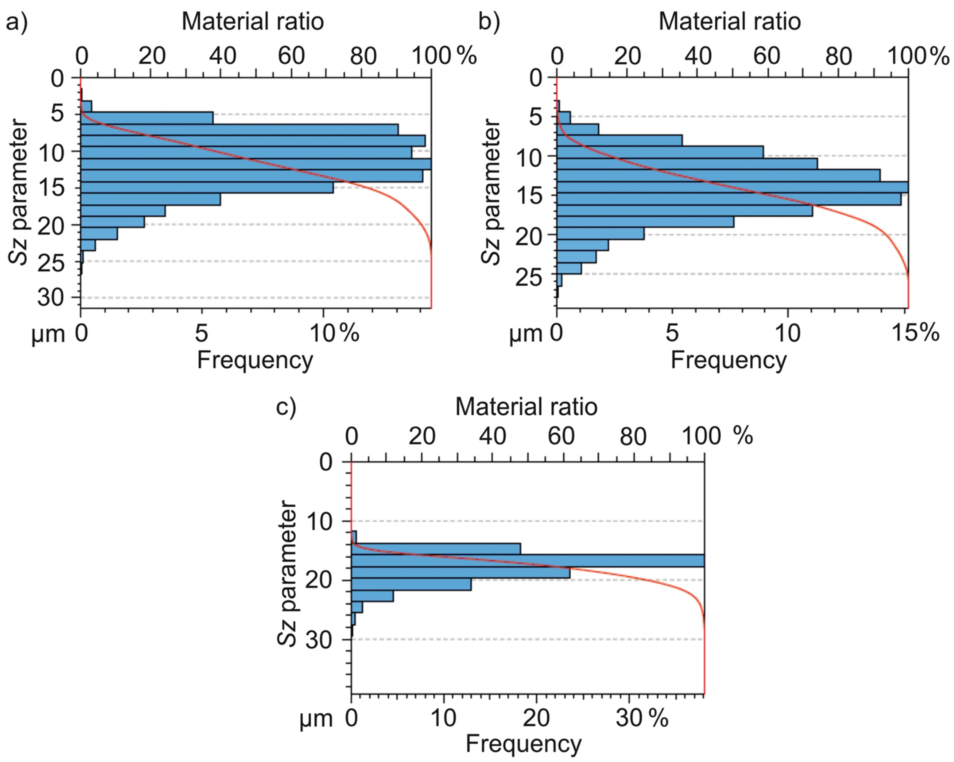

Fig. 5. Material ratio curves and peak height distribution on the surfaces after turning for mixtures: (a) Gr and Al_2O_3, (b) Gr and ZrO_2, (c) Gr, Al_2O_3 and ZrO_2

Material ratio curves for the surfaces after turning for the selected mixtures are shown in Figure 5. The material ratio and distribution of roughness peaks on the surface are important to determine the surface properties [22]. Samples No. 4 and 5 are characterized by anisotropic mixed peaks of the machined surfaces. In contrast, sample No. 10 characterizes the anisotropic mixed character of peaks with a very high frequency of occurrence.

CONCLUSIONS

Changes of the surface topography parameters after finish turning of iron-based MMCs reinforced with graphite and hard nano oxides depending on their percentage were investigated and the following summary conclusions were found. Ensuring Gr content in the range of 0.8–1% and simultaneously limiting the content of Al_2O_3 and ZrO_2 to the range of 0–0.1% results in minimum values of *Sa* and *Sz* surface topography parameters. Samples containing only Gr and Al_2O_3 in their composition are characterized by erratically shaped irregularities and the occurrence of a large number of defects on the machined surfaces, including deep pits. Deep pits also occur on the surfaces of samples containing a large amount of Gr and small amounts of Al_2O_3 and ZrO_2. Quite regular, very high peaks and very deep valleys are observed on the surface of the sample with 0.33% Gr and 0.67% Al_2O_3, very irregular peaks and valleys are observed on the surface of the sample with 0.33% Gr and 0.67% ZrO_2 and irregularly occurring pits and single peaksare observed on the surface of the sample with 0.33% Gr, 0.33% Al_2O_3 and 0.33% ZrO_2. Samples with addition of 0.33% Gr and 0.67% Al_2O_3, as well as 0.33% Gr and 0.67% ZrO_2 are characterized by the anisotropic mixed character of the peaks of the machined surfaces. In contrast, the sample with addition of 0.33% Gr, 0.33% Al_2O_3 and 0.33% ZrO_2 characterizes the anisotropic mixed character of the peaks with a very large random part. The content of reinforcing additives affects significantly the geometric characteristics of the surfaces treated of iron-based MMCs. Thus, it is possible to select such a combination of particulates that will provide the expected surface quality after the turning process.

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