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# Influence of Sliding Speed and Glass Bead Concentration on 3D Roughness Parameters

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***Abstract:*** *This paper presents an analysis of 3D amplitude and functional parameters for worn surfaces of composites with polyamide 6 as matrix and different glass bead concentrations (0%, 2.5%, 5%, 10%, 20%, 30% and 50%wt). The worn surfaces after dry sliding of a steel pin on a disk, for 10 km, at constant velocity (0.5 m/s, 1 m/s and 1.5 m/s) and under an average pressure of 1 MPa. There were done two tests under the same conditions. On each worn track, there were investigated three surfaces of 500 μm x 500 μm with a contact profilometer. The number of points on the scan line was 200 points and the step between lines was 5μm. The following amplitude parameters were measured and calculated for assessed surfaces: the arithmetic mean deviation, Sa, the root mean square deviation, Sq, the maximum height of surface prominence, Sp, the maximum surface depth, Sv, the maximum height, St, the skewness factor, Ssk and the kurtosis, Sku. The discussed functional parameters are the reduced peak height, Spk, the height of the core of the surface, Sk and the depth of the valley zone, Svk. The comparison of their values makes posible to evaluate if the worn surface could function in a new running or the replacement of the component is recommended. Considering that machine components have intermittent operation, these worn surfaces becoming initial surfaces for the following cycle of contact operation. Based on the average values of amplitude and functional parameters, it was found that a relatively good surface quality is preserved for concentrations of 10...30%wt glass beads, for v=0.5...1 m/s (Sa and Sq having similar trend); for lower concentrations and for 50% glass beads, the parameter values increase but without identifying a distinct relationship with the working regime, especially for 2.5 and 5% glass beads.*

***Keywords****: polyamide 6, composite with polyamide matrix and glass beads, wear, pin-on-disk test, roughness, 3D amplitude parameters, functional parameters*

## 1. Introduction

The important step in the development of tribological surface analysis came in 1990, from the European Community, through an award-winning research contract at the University of Birmingham, coordinated by professor Stout [1, 2]. The research group became involved in a major European initiative to develop a document that could be used as a future standard. Now, there is the family of ISO 25178 Geometrical product specifications (GPS) - Surface texture, that deals with methods and parameters for evaluating surface texture by the help of areal quantities.

Numerical roughness parameters for surface texture, as used in tribological surface analysis, are the tools of linking product design, manufacture and functional performance between a supplier and a customer. These parameters are used not only as a benchmark for manufacturing tolerance for the surface quality, but also to predict functional properties and to assess the influence of regime on tribological behavior and system durability.

From the literature reviewed on surface topography characterization [3-9], the following conclusions emerge:

- surface texture studies are statistical in nature,
- there is no general methodology for characterizing the texture of worn surfaces, even there is not for new (unused) surfaces;

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- the methodology depends on: shape and size of triboelements, - available equipment and software,
- the set of parameters selected, reflecting the knowledge, ingenuity, skills and experience of the engineer.

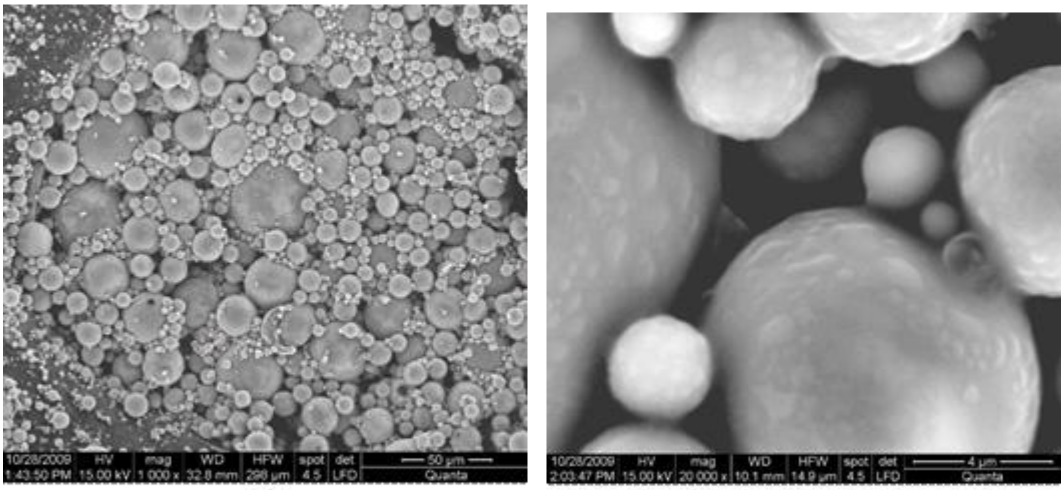
For analyzing the quality of worn surfaces, from the reviewed literature [10-14], the following directions of investigation are outlined:

- the study should correlate the evolution of texture parameters with the operating parameters of the system (working regime, tribological parameters, acoustic emission etc.);
- the study should be carried out for the surfaces of both triboelements, with outline on the more wearable element (s).

## 2. Materials and methods

The trade grade Relamid® B-2Nf-T-(i), was used to obtain the family of composites the disks required for testing on pin-on-disk tribometer. The materials used for the additivation of Relamid® B-2Nf-T-(i) based on polyamide 6 are glass beads and black carbon (1% and in polymer and in each of the composites). The use of additive materials provides the advantages of increased stiffness, improved dimensional stability and reduced shrinkage [15, 16].

Glass beads (Figure 1) have a dispersion of diameters in the range 0.50-35 μm, the weighting (as number of particles) being for 2...5 μm. The use of glass beads leads to a clear increase in the mechanical characteristics of polyamide 6, in particular elasticity, but also improved the thermal performance of the product [17].



a) b)

**Figure 1.** Glass beads used for reinforcing the Relamid® B-2Nf-T-(i)

Black carbon is generally used for rubber additives or for coloring varnishes, paints, printing inks, plastics [18]. The carbon black additive in Relamid® B-2Nf-T-(i) gives the product superior performance as compared to other types of polyamide when exposed to UV radiation. It helps to improve the tribological characteristics under dry regime conditions, reducing the friction coefficient, but also to a good dispersion of micro-particles in the composite, not allowing the formation of conglomerates, thus eliminating local, even severe, erosion and wear processes in the material during tests. The carbon black particles, which have sizes in the nano range, penetrate the PA6 macromolecule lattice, forming a second lattice that significantly reduces the abrasive wear of the polymer.

The family of polymer composites used for this research has Relamid® B-2Nf-T-(i) matrix additivated with 1% carbon black and glass beads in various mass concentrations (0, 2.5, 5, 10, 20, 30 and 50%, wt). The composite recipe was established on the basis of the studied literature and in agreement with the Research Institute for Synthetic Fibres, Monofil SA, Savinești (Romania), which also produced the composites by molding [17].

The addition of glass beads in polyamide was performed in different percentages, which allows comparing the results obtained in pin-on-disk tribological tests and determining an optimal concentration of glass microspheres in polymer matrix for the ranges of test regime parameters.

## 3. Methodology for analyzing the surface quality

Investigations were carried out on 500 μm x 500 μm square areas, in the central area of the wear track obtained from sliding tests, in dry regime, on composite disks, with a steel pin with a surface roughness per disk of Ra=0.8...1.2 μm. The 500 μm x 500 μm measurement area was chosen because it records a larger area of the wear track and in this research is desired to highlight the wear processes. The vertical scale was set up to 500 μm and the scanning speed was set at 35 μm/s [19]. The number of points on the scan line can be selected between 100 points and 1000 points. This research was done for 200 points on each line, and the step between lines was selected at 5μm.

From the literature [20, 21], in tribological studies of composites with polymeric matrix sliding against a steel component, under dry conditions (normal atmospheric pressure and relative humidity, temperature 19.23ºC), it is highlighted the selection of the following parameters: tested material pair, test distance (or time), applied normal force, sliding velocity, with the final goal of stabilizing the friction coefficient, wear parameters and thermal field generated during the test.

Based on the literature [2, 4, 22, 23], the studied materials (Relamid B-2Nf-T-(i) and Relamid B-2Nf-T-(i) matrix composites) were tested under dry sliding conditions, for normal average pressures of 1 MPa and sliding velocities v = 0.5 m/s, 1.0 m/s and 1.5 m/s, using disks made of polymer or composite with different concentrations of glass beads and pins made of steel grade 51VMn11, with hardness of 40...43 HRC and Ra=0.6...08 μm (Figure 2).

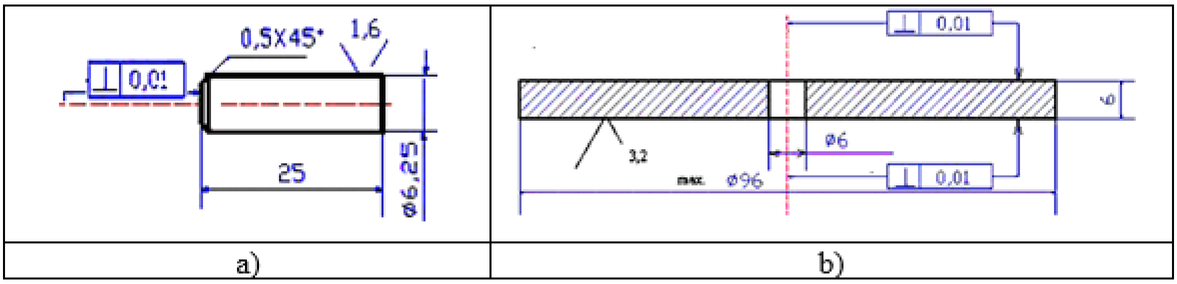



**Figure 2.** Geometry of the triboelements in test rig (pin - left, disk - right)

For each sliding velocity, the time required to cover the distance of 10000 m was calculated. Each test was carried out at a radius of 40 mm from the center of the disk to the axis of the pin, with a single wear track on each disk. Each test was repeated twice, averaging the wear between the values obtained for each test under the same conditions. Tests were performed on the tribometer UMT-2 (CETR®, SUA)

Wear was measured for each pin and disk, as mass loss between the initial measured value and the value after the test was completed. Initially, before being weighed, both disk and pin were washed with industrial alcohol to remove any debris from their surface. After they were dried, they were weighed with a digital balance with an accuracy of ±0.01mg. After each test, both the pin and the disk were weighed again, thus recording the mass loss of the disk and the pin.

The statistical 3D analysis of a texture is more reliable and more representative because the volume of data is larger [2]. 3D analysis can reduce the variance of roughness parameters, especially those extracted for worn surfaces.

The PRO500 3D profilometer with contact is designed to examine the vertical and horizontal roughness parameters of the topography on the analyzed area and the dedicated software can calculate 3D roughness parameters.

All 3D roughness parameters were calculated for the unfiltered texture, called primary recording, because it "reconstructs" the actual surface. The equivalent profilometer contact loading is recommended to be in the range 10...50 mg for hard plastics, and for all recordings in this study this value was used.

A single 3D measurement is not sufficient to assess surface quality, especially when the investigated area is smaller than the width of the wear track [23]. In 3D assessments of the texture quality, three recordings are made on the wear track, at approximately equal angular spacings (~120º). It has been found that, often, at least 5 measurements are needed to obtain a stabilized average value for many roughness parameters, but for some, a larger number of recordings is required [3]. The cause of this differential stabilization is that one or few measurements in the set may deviate from a normal distribution that the researcher is expecting or imagining to be normal.

Using 3D profilometry, tribological processes, such as exfoliation of the polymer matrix, local agglomerations of glass beads in the tribolayer of the disk etc. may be highlighted.

For this study, the number of measurements was set as three for each wear track (the sliding area on the disk), for a test characterized by a set of parameters (p [MPa], v [m/s], concentration of micro glass beads [%]) and the average values of the analyzed 3D parameters were calculated, based on the primary (unfiltered) texture because filtered profiles may alter the values of 3D parameters [Blunt, 2008] [3], especially those involving values of the highest peaks and deepest valleys of the worn topography of the disk, which are important in tribology. An example of the average values of the 3D parameters obtained from the measurements were calculated as shown in Table 1. For the tested composites, SEM images of the polymer surface showed that the wear mechanisms are not uniform in time and space, thus revealing rough surfaces obtained after testing with a certain correlation of friction and wear coefficient.

**Table 1.** Example of calculating average value of several parameters

| **Parameter** | Measurements (v=1.5 m/s) | | | **Average** |
|---|---|---|---|---|
| | 1 | 2 | 3 | |
| **Sa** [μm] | 0.389 | 0.345 | 0.461 | **0.399** |
| **Sq** [μm] | 0.554 | 0.512 | 0.671 | **0.579** |
| **Ssk** [-] | 0.058 | 1.727 | 1.704 | **1.163** |
| **Sku** [-] | 7.610 | 10.748 | 10.264 | **9.541** |
| **St** [μm] | 6.465 | 6.013 | 7.674 | **6.717** |

For 3D recordings, the arithmetic mean deviation of area, Sa [μm], is defined as the arithmetic mean of the absolute values of each point height, within the measurement area:

$$S_a = \frac{1}{M \cdot N} \sum_{j=1}^{N} \sum_{i=1}^{M} \left| z\left(x_i, y_j\right) \right| \quad (1)$$

where N is the number of points through which the surface has been discretized on the x-axis, for i=1…M and on y-axis, for j = 1...N.

The root mean square deviation of the surface is defined as [19]:

$$S_q = \sqrt{\frac{1}{M \cdot N} \sum_{j=1}^{N} \sum_{i=1}^{M} \left| z^2\left(x_i, y_j\right) \right|} \quad (2)$$

where M and N have the same meaning as in the above-mention relationship.

The maximum height of surface prominence, Sp, is the distance measured from the highest point of the profile to the reference surface in the sampling area [19]:

$$S_p = \max\left( z\left(x_i, y_j\right) \right) \quad (3)$$

The maximum surface depth, Sv, is the greatest reference surface valley depth value for the investigated area:

$$S_V = |min\ (z(x_i, y_j\ ))| \qquad (4)$$

The parameters Sp and Sv are sensitive to random irregularities, which are not representative of the surface structure, as they detect the highest peak or the lowest valley, register singular scratches, dirt marks or any atypical defect.

The maximum height, St, is the distance between the highest peak and the deepest valley in the area investigated.

$$S_t = z_{max} - z_{min} \qquad (5)$$

If working with unfiltered profiles, against a reference surface, St is:

$$S_t = \left(\left|S_p\right| + |S_V|\right) \qquad (6)$$

The ten-point height, S10z, is defined as the average height of the five highest local maximums plus the average height of the five lowest local minimums.

The skewness factor of the assessed surface, Ssk, is a measure of the asymmetry of the surface heights' deviation from the reference plane. The calculation of Ssk takes into account profile heights, equally spaced in an evaluated surface and it is strongly influenced by isolated peaks or valleys.

$$S_{sk} = \frac{1}{M \cdot N \cdot S_q^3} \sum_{j=1}^{N} \sum_{i=1}^{M} \left|z^3\left(x_i, y_j\right)\right| \qquad (7)$$

For a Gaussian surface, which has a symmetric shape of the height distribution curve, the parameter Ssk ≅ 0, i.e. the number of peaks is approximately equal to the number of valleys. For an asymmetric height distribution surface, the skewness can be negative if it has a terminal distribution more at the bottom than the reference plane (e.g. a surface with removed peaks or with valleys of frequent scratches) or positive if it has a terminal distribution above the reference plane (a surface with sharp and high peaks).

The kurtosis factor, Sku, is a measure of the "sharpness" of the surface height distribution curve.

$$S_{ku} = \frac{1}{M \cdot N \cdot S_q^4} \sum_{j=1}^{N} \sum_{i=1}^{M} \left|z^4\left(x_i, y_j\right)\right| \qquad (8)$$

For a Gaussian surface with uniformly distributed peaks and valleys, the value of the 3D parameter is 3. Physically, the excess indicates peaks on a surface.

According to [3, 7-9, 23], functional parameters are defined on the bearing area curve (for 3D analysis), and characterize the bearing capacity of the surface. These parameters are global parameters (field parameters) and should be considered as statistical parameters.

The reduced peak height, Spk, estimates the small peaks above the main surface plane. These peaks will be removed (by deformation or cutting as wear particles) during the running-in period. In order to have the least amount of particles removed from the surface, a lower value for this parameter would be desirable. This parameter is used for surface evaluation in the sense that small values mean surfaces without peaks.

The relative height of the core (middle zone) of the surface, Sk, represents the functional part of the surface. After the running-in period (after the peaks, represented by Spk, are worn), this part of the surface will support the load during operation.

The depth of the deepest valleys of the analyzed surface, Svk, is an estimate of the depth of the valleys that will retain lubricant during operation.

These functional parameters, Spk, Sk and Svk, selected for this analysis (Figure 3), could better reflect a correlation with tribological parameters (friction coefficient, wear etc.), as also shown in [2, 3]. These parameters also have suggestive names: Spk - "roughness height zone" or contact region (in this zone, in the wear process, roughness peaks are deformed or/and detached in contact with the mating surface), Sk - texture "core" or "load bearing zone" in operation, Svk - "lubricant retention zone".

It is important to note that there are various other functional parameters available for characterizing surface roughness, the choice of parameters depends on the specific requirements of the analysis and the standards or conventions followed in a particular industry or application.

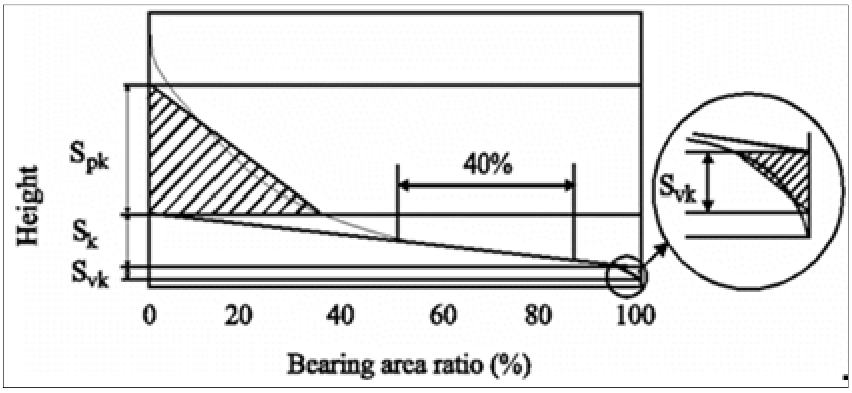



**Figure 3.** 3D functional parameters [19]

## 3. Results and discussions

### 3.1. Tribological behavior of the composite family

The results are presented in the following figures, as a function of glass bead concentration. As such an analysis of 3D roughness parameters has as objective a relationship between roughness parameters and tribological parameters, as wear, friction coefficient [17] etc. Figure 4 presents the wear of the disks made of polyamide or a blend of Relamid B-2Nf-T-(i) and different glass bead concentrations (a) and the average values of the friction coefficient (b). The values on the plot are the average values, obtained from two tests and wear represents the mass loss of the disk after being tested.

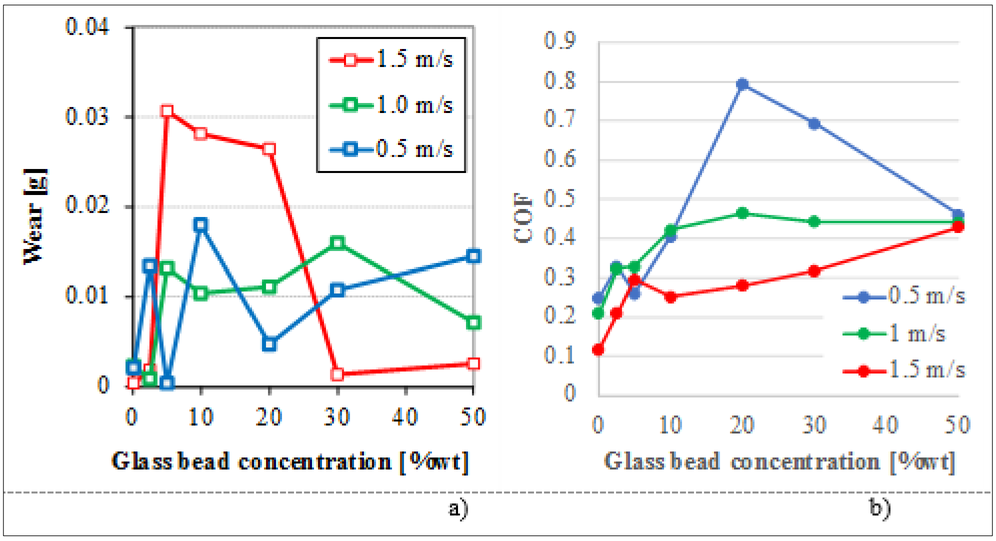



**Figure 4.** Tribological characteristics of the pin-on-disk system: a) Wear of the disks (0 means disks made of PA6 +1% black carbon), b) average value of friction coefficient

The polymer has lower values as mass loss, but it has the disadvantage that do not support higher temperature as the composites do [17]. It is obvious that low concentrations (2.5%, 5% glass beads) are not recommended as the beads are not uniformly distributed in the composites and wear consists of tearing off agglomerations of beads or large volume of polymer without beads. A concentration of 20…30% glass beads seems to be recommended for low wear. Higher concentration (50% glass beads) has also good results because the self-organization of glass beads within the superficial layer during sliding is favorable for maintaining the polymer among the beads. The presence glass beads of different diameters is favorable to generate a tribolayer that fixes the polymer.

Characteristic for this composite family is the oscillations of friction coefficient for concentrations of 10%, 20% and 30% glass beads (Figure 5). Higher values were obtained for the lowest sliding velocity (v=0.5 m/s), meaning pulling apart larger wear debris. The tribolayer remain rich in polymer and the friction coefficient decreases or it remains rich in glass beads, the friction coefficient increasing. At higher values for sliding velocity, the polymer is softened and allows for embedding the glass beads.

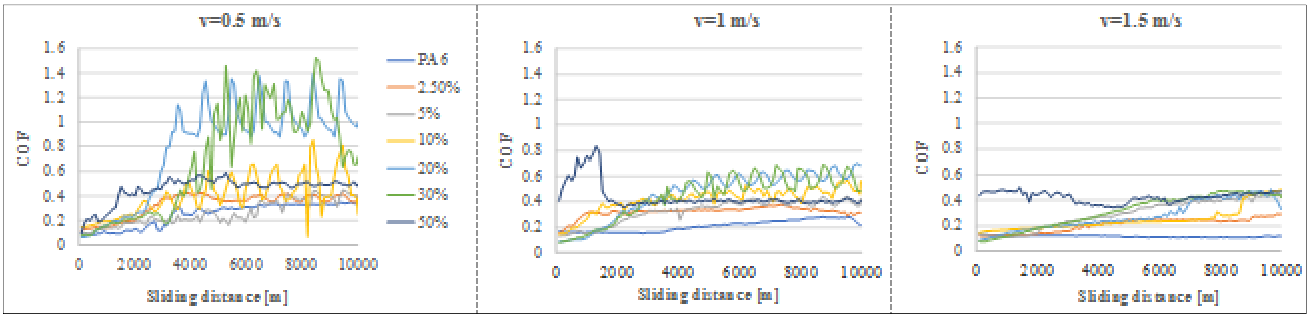



**Figure 5.** Evolution of friction coefficient for tested sliding velocities, average pressure 1 MPa and sliding distance 10 km (color code is the same for all plots)

The wear is a dynamic process, alternating these two situations during the test. It is obvious that test lasting only for 2000 m of sliding are not relevant as the friction coefficient becomes stables after this value. At v=0.5 m/s, the friction coefficient has higher oscillations for composites with 20…30% glass beads. This could be explained by the fact that under low velocity, the polymer is not softened within the superficial layer and there are pull off larger volume of material. Lower values are for 50% glass beads, with very small oscillations and a value that could be of interest for actual applications, because the tribolayer is not reach in polymer and the sliding does not pull-off conglomerates polymer + glass beads. At v=1.5 m/s, due to the polymer softening, the oscillations are attenuated and the composites with 10…50% glass beads have the friction coefficient 0.43…0.48.

Except for the composites with 20 and 30% glass beads tested under v=0.5 m/s, that have an unexpected too high value, the other values are below 0.47. At v= m/s the friction coefficient is almost not influenced by glass bead concentration for the composites having glass beads in the range 10-50%wt. For v=1.5 m/s, the average of friction coefficient is slightly increased from 10 to 50% glass beads. It is worthy to notice that the composite with 50% glass beads has close values for all tested velocities.

### 3.2. Analysis of amplitude parameters

The amplitude parameters depend on the variation in the height of the roughness of the evaluated surface. In order to describe the amplitude parameters related to worn surfaces under the following test conditions: p=1 MPa and v=0.5 m/s, v=1 m/s, v=1.5 m/s, 8 amplitude parameters were used for evaluating the quality of worn surfaces: Sa, Sq, St, Sv, Sp, S10z, Ssk and Sku.

Parameters Sa and Sq have a similar evolution (Figure 6a and b). There is a misconception that there is a difference of about 11% between these two parameters, recorded on the same areal or profile. Grounding and polishing processes could induce Rq values with 20 to 50% greater than those for Ra. The 11% difference would only occur if the surface shape is a sine wave. Tests have shown Rq to be 30% higher than Ra on average [24]. For the investigated surfaces, the ratio Sq/Sa is included between 1.16 and 1.45 (Figure 6c). Sq has very low sensibility to sampling step, but it is sensitive to the investigated area. From Figure 6, where the ratio Sq/Sa is plotted against glass bead concentration, one may notice that for the initial surface, this ratio interval is the smallest, but for worn surfaces, its variation is larger.

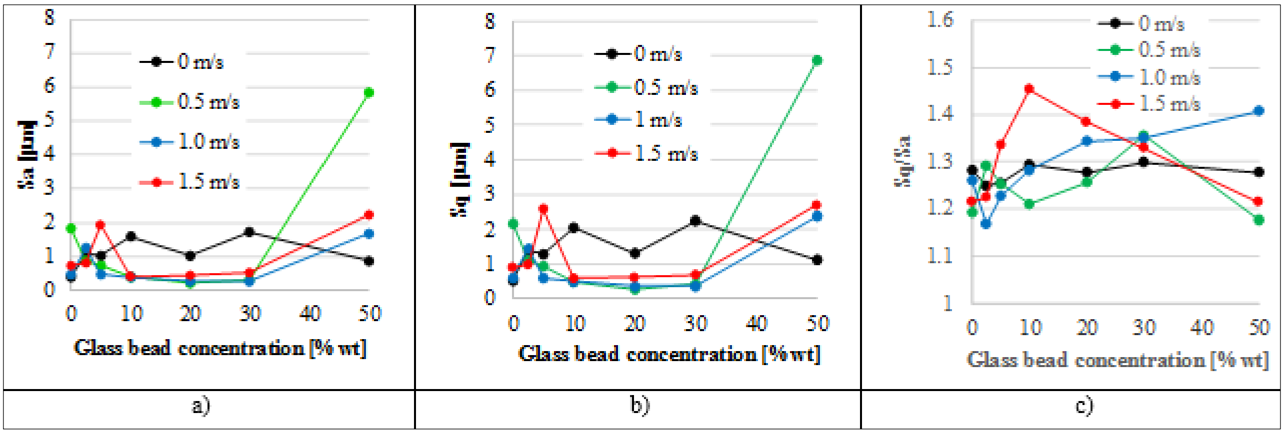



**Figure 6.** Values of Sa, Sq and Sa/Sq parameters, depending on sliding velocity and glass bead concentration

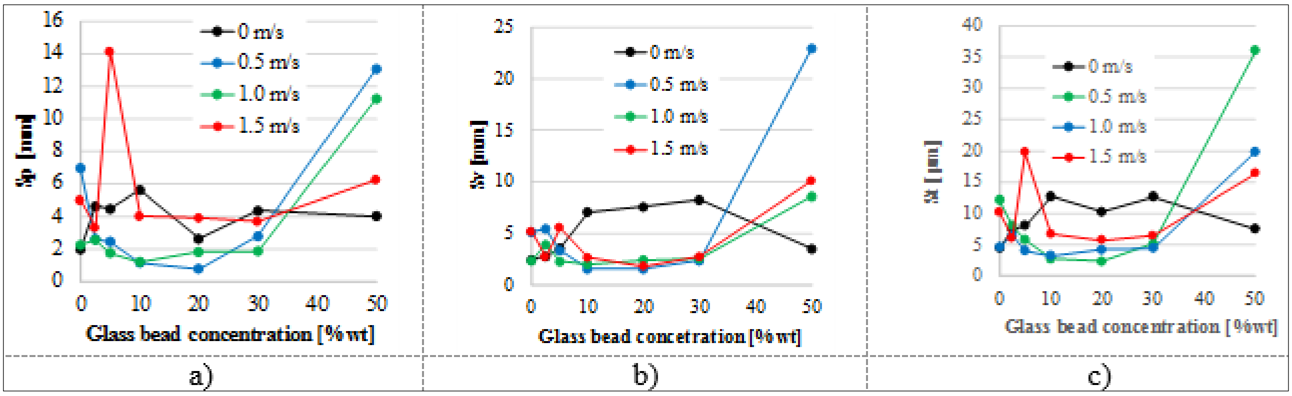



**Figure 7.** Values of Sp, Sv and St parameters, depending on sliding velocity and glass bead concentration

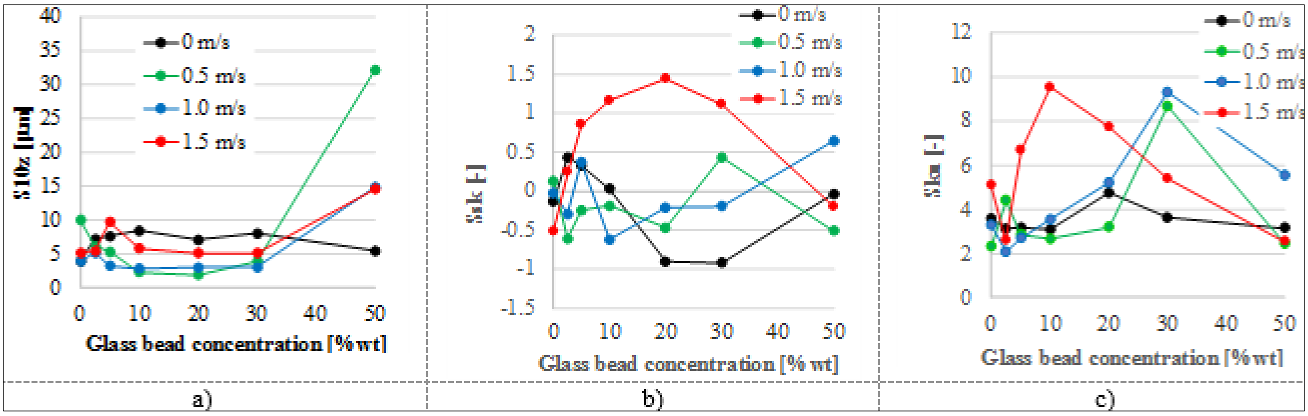



**Figure 8.** Values of S10z, Ssk and Sku parameters, depending on sliding velocity and glass bead concentration

Figure 7 presents three parameters that are related. For raw surfaces, St should be the sum of Sv and Sp. Initial surfaces have lower values for Sp meaning not too high peaks and not too deep valleys (both around 2 μm) for the polymer, higher values being obtained for the composites. Higher values were obtained for the worn surfaces of composites with extreme concentrations of glass beads (5% and 50%). The composites with 10…30% have these parameters lower than the initial values, meaning that the matrix could be smoothened and eventually beads that were initially too proeminent are pushed into the matrix and the surface becomes smoother.

For tribologists, the extreme values as St and even the average of highest 10 points are important, especially for lubricated contact as the highest peaks could disrupt the fluid film. St and S10z could be similar (Figure 7c and Figure 8a). For composites with 10…30% glass beads, S10z is lower than the values for initial surface, meaning a very mild wear that leveled the initial surface.

If a surface was planarized, such that only few peaks or valleys remain, then Rsk oscillates around zero and Rsk could inaccurately suggest that a surface with higher roughness is superior to a surface with lower roughness. Therefore, analyzing Rsk, and, accordly, Ssk, alone is not relevant enough to differentiate rough surfaces from smooth surfaces. The parameter Ra could be „tricky" when using alone, too, for texture characterization as surfaces could have the same Ra (or Sa) value but the texture could be different [25]. An analysis of surfaces with the same value for Rq and Rsk [26] (Figure 9) pointed out that a more reliable analysis of surface quality has to be based on a set of parameters, here Rq, Rsk and Rku. This is why the authors took into account 8 amplitude parameters and compared their evolution as a set characterizing the functioning of the tribosystem, in given conditions.

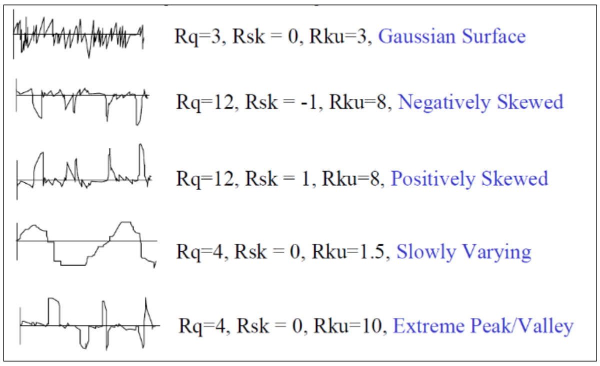
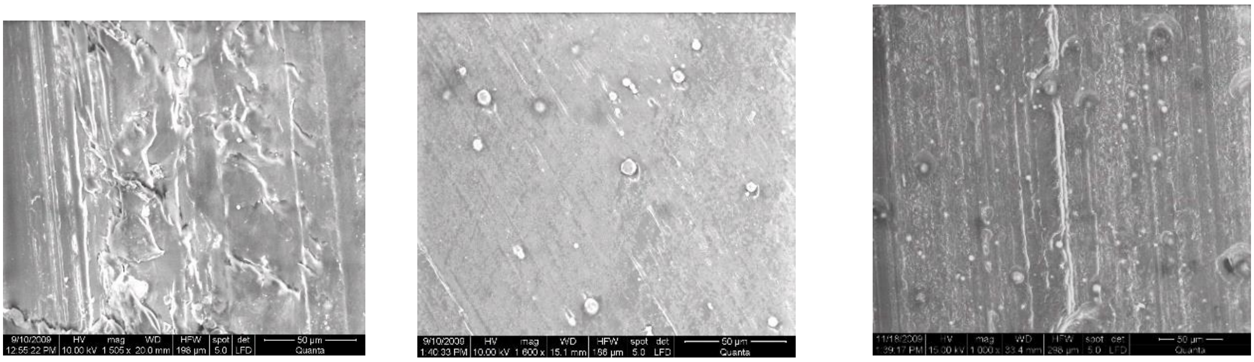



**Figure 9.** Values of Rq, Rsk and Rku parameters and the aspects of compared surfaces [26]

For all three tested velocities, there were noticed similarities in the evolution of amplitude parameter pairs (Sa and Sq and St and S10z, respectively), but for Ssk and Sku, things are significantly different. For the Relamid disks (Figure 10a) and composites with 10, 20 and 30% glass beads, at v=0.5 m/s and v=1.5 m/s, the disks do not have much changes when comparing the initial values with those obtained after wear tests, as reflected by Sa and Sq. At v=1 m/s, the surfaces of the composites with 10%, 20% and 30% are less rough than the composite with 50% glass beads, which surface shows very high voids and peaks; if one takes into account the value of St, this exceeds 35 μm and S10z is around 32 μm, a sign that there are many glass beads that cannot be buried in the polymer matrix because that has not been melted or softened, yet, this conclusion being supported by the SEM images (Figure 10b and c). At v=1.5 m/s, the polymer has melted and is "stretched" over the glass beads (Figure 12b and c), and even the profilometer virtual image (Figure 10b) shows this.

The wear mechanisms are not revealed by values of 3D parameters, but SEM images and virtual re-build images based on recording the surfaces as set of (x, y, z) points could.

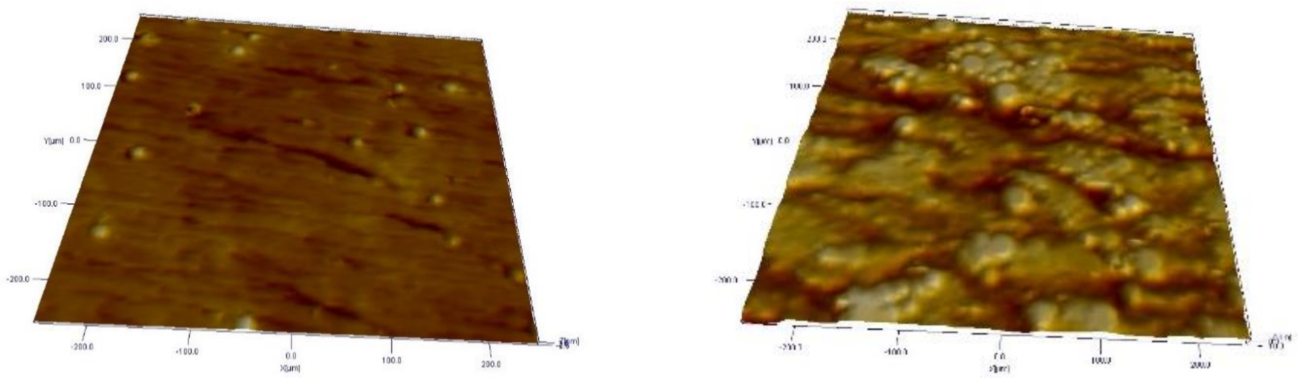
Figure 10 presents SEM images that point out different wear mechanisms: a) the polymer reveals leveling by elasto-plastic deformation of the texture, abrasive micro-grooves and even fatigue cracks (almost perpendicular to the sliding direction), b and c preferential wear of the polymeric matrix and dislocation of the small glass beads that are not anymore sustained in the matrix. Figure 11 presents two virtual surfaces, re-built with the help of the dedicated soft [SPIP] [19], revealing that the glass beads concentration influence in a high degree the texture of the investigated surfaces: a. lower concentration allow for wearing the polymer, the glass beads remain visible on the surface and they



a) Relamid® B-2Nf-T-(i), v=0.5 m/s | b) Composite with 20% glass beads, v=1 m/s | c) Composite with 30% glass beads v1=m/s

**Figure 10.** SEM images of tribolayers generated on polymeric disks, after tests done at, 1 MPa and sliding distance of 10 km

could be drag or embedded in the polymer, b. the highest glass beads concentration reveal a more "dramatic" surface, and the amplitude parameters are reflecting that, many glass beads are rolled and dragged on the surfaces and the polymer adhere to them, covering them as a blanket that reduce friction and adhesive wear (Figure 12).



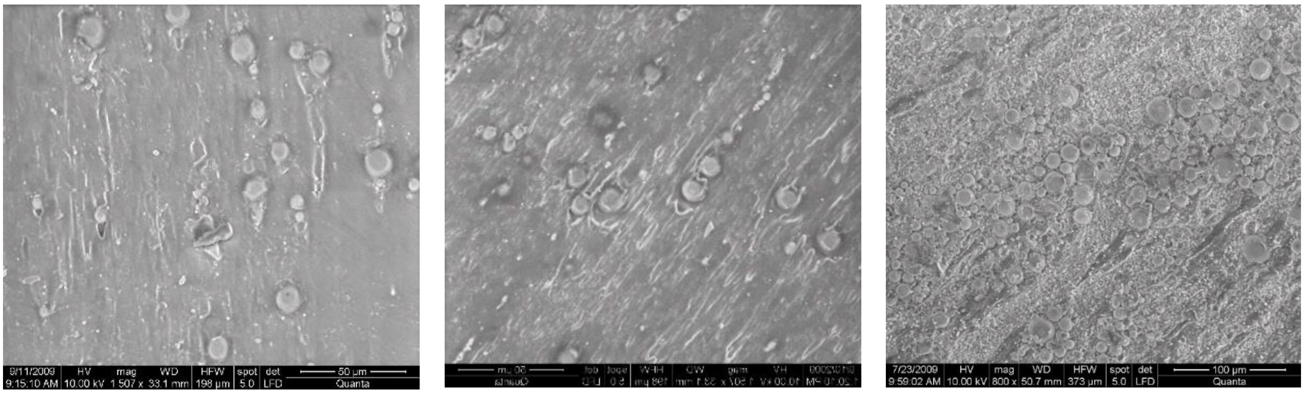
a) Composite with 10% glass beads | b) Composite with 50% glass beads

**Figure 11.** Surfaces of the investigated areas, as re-constructed with the help of dedicated soft [19], for sliding velocity v=1.5 m/s

Figure 12 presents worn surfaces of the composites for the highest sliding velocity, 1.5 m/s: a. a rolled polymeric wear debris is visible, dragged glass beads in the sliding direction and load is supported by the glass beads remained on the surface, b. the composite with 30% glass beads, there is visible a very thin melted film of polymer, but surface is still quite smooth as sustained by low values of amplitude parameters, c. the composite with 50% glass beads, surface is rougher, the superficial layer becomes richer in glass beads as the polymer is preferentially torn-off from the tribolayer, but many polymeric wear debris are re-grabed among beads and wear is not so intense.

The variation of Ssk and Sku is totally different as compared to the other amplitude parameters. For v=0.5 m/s and v=1 m/s, the highest values of the asymmetry factor, Ssk, are recorded for composites with concentrations of 20, 30 and 50% beads, as a result of extracting large glass beads or conglomerates from the superficial layer. As the matrix is softening during the test, especially for v=1…1.5 m/s, the glass beads are pushed into the polymer matrix, thus reducing the high asperities and deep valleys on the surface (Figure 12b and c).

The distribution of heights is uniform over the studied surfaces for v=0.5 m/s and v=1 m/s, as confirmed by the value of Ssk, which is kept in the vicinity of zero. Increasing the sliding velocity at v=1.5 m/s, the value of Ssk increases towards 1, and the symmetry of the height distribution increases; the explanation could be the clustering of glass beads in the surface layer. The only composite that preserves the symmetry of the height distribution on the worn surface is the one with 50% glass beads. At v=1 m/s and at v=1.5 m/s, the similar evolution trend seems to be preserved for the whole family of composites.



a) 10% glass beads b) 30% glass beads c) 50% glass beads

**Figure 12.** SEM images for three composites, at v=1.5 m/s

The composite with 50% glass beads keeps approximately the same values for Sy and S10z at v=0.5 m/s and at v=1 m/s, but they increase at v=1.5 m/s, with Sy and S10z tripling in value due to the existence of high heights or valleys on the worn surface. The friction coefficient does not follow the same law of variation and, as the sliding velocity increases, the coefficient of friction decreases because the glass beads are covered with “blankets” of polymer (Figure 12b and c). It is recommended that for p=1 MPa, the composite with 50% glass beads should be used only for low speeds.

For v=0.5 m/s, Ssk registers zero for the group of composites with 10, 20 and 30% glass beads due to the uniform height distribution on the worn surface, one may say that there is a Gaussian surface; the rest of the group of composites has a value below zero, negative, due to the valleys on the worn surface, located not much below the reference plane. The composite with 5% glass microspheres shows a high Sku value, greater than 3, for all three test velocities due to the formation of very high and sharp protrusions on the surface.

At v=1 m/s, composites with 5, 10, 20 and 30% glass beads keep constant the value of the pair of parameters Sa and Sq, but the values of the parameters Sku, Sy, S10z increase due to the accentuation of the formation of deep voids. For Relamid® B-2Nf-T-(i) and the composite with 50% microspheres, the values of the Sa and Sq parameters decrease with increasing the sliding velocity due to flattening of the heights. The only composite showing a Gaussian distribution of heights on the evaluated surface is the one with 30% glass beads. The increased value of Sku (>3) for the whole family of composites at all test velocities indicates high peaks on the surface.

The composite with 50% glass beads retains approximately the same values at v=0.5 m/s and at v=1 m/s, but these increase at v=1.5 m/s, with Sy and S10z tripling in value due to the existence of high height on the worn surface. Recommended for p=1 MPa, the 50% glass bead composite should only be used for low velocities. At v=1.5 m/s, the micro beads on the surface (Figures 11 and 12) are seen to be pushed or dragged, generating local micro grooves.

Figure 13 presents on the same graph the values for Sq, Ssk and Sku for the initial surface and for each of the tested sliding velocities. Initial surfaces are less influenced by the glass beads concentration. This could be explained by the characteristics of the molding process that allow the melted polymer to pass among glass beads and to generate a smooth surface after cooling. For v=0.5 m/s and v=1 m/s, Ssk have values around zero and positive values around 1 for v=1.5 m/s. The dependence of Sku on the concentration is hard to be determined from these measurements.

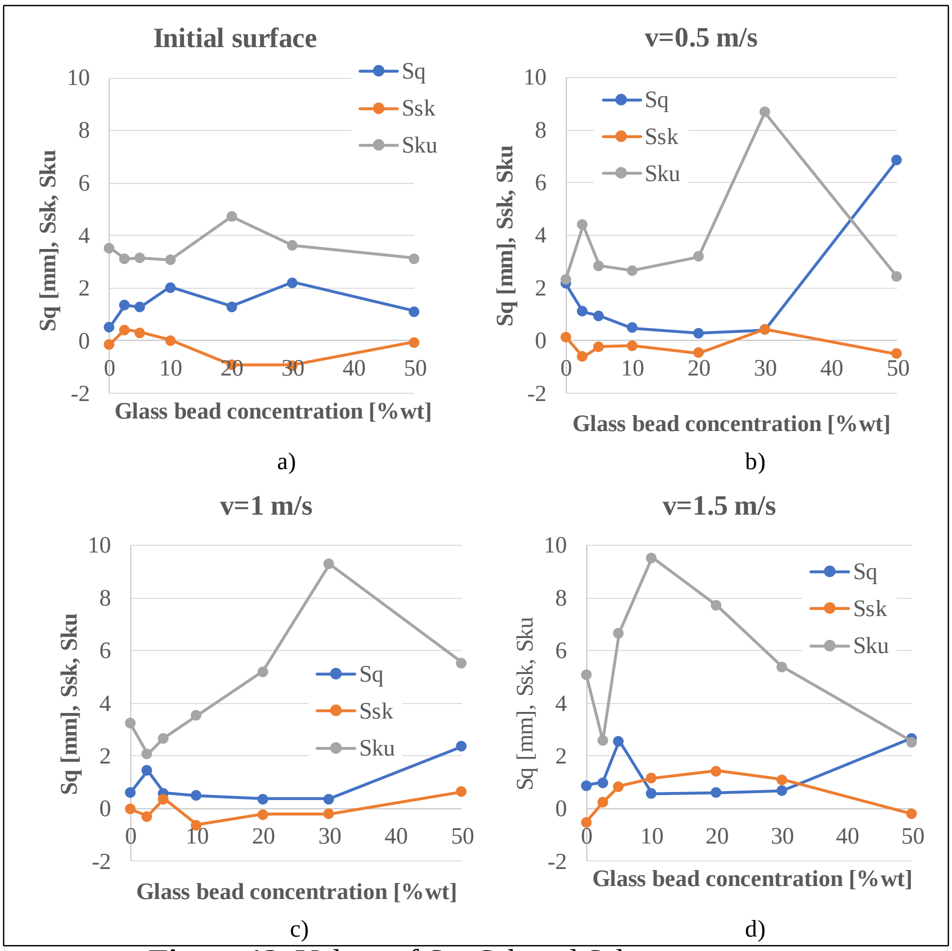



**Figure 13.** Values of Sq, Ssk and Ssk parameters

### 3.3. Functional parameters

Pawlus et al. [27] published a recent review that underlined the importance of extracting and discussing the parameters deduced from the material ratio curve, the examples being given on 2D plots (material profile curve), but the methods may be also applied for the 3D parameters (Sk, Svk and Spk) [19, 28, 29] and recommend to use these parameters for evaluating mild wear, especially in order to assess the fair oil retaining capacity of a texture.

Niemczewska-Wójcik et al [30] reported research on processed aluminum metal matrix composites reinforced with 10 wt.% of $Al_2SiO_5$ (aluminum sillimanite) and tested on block-on-ring tribotester, in dry and lubricated conditions. Analyses of the surface topography (i.e., 3D roughness parameters, including functional parameters, Abbott–Firestone curve etc.) were related to tribological characteristics (friction coefficient, linear wear and wear intensity).

The standard ISO 25178-2:2012 [28] defines the "k" series: Spk, Svk and Sk. Franco and Sinatore presented an analysis of these parameters related to the new ones, including Vmp, Vmc, Vvc, and Vvv (the volumes of the reduced peaks, core material, core void, and valley void, respectively), and they discussed the definition of Spk and recommended Sk to be kept, but to introduce the new volume parameters [31].

Keeping the same scale for all the plots, Figure 14 presents these functional parameters. As comparing to the initial values, the following conclusions could be formulated. High values for Spk at v=1 m/s could be explained by an more intense abrasive wear and the surface temperature of the composites do not allowed for re-attaching polymeric wear debris to surface. Sk is lower for composites with 10…30% glass beads. Svk is lower for worn surfaces, meaning that valleys are small also due to the elasto-plastic deformation of the micro grooves generated by abrasion.

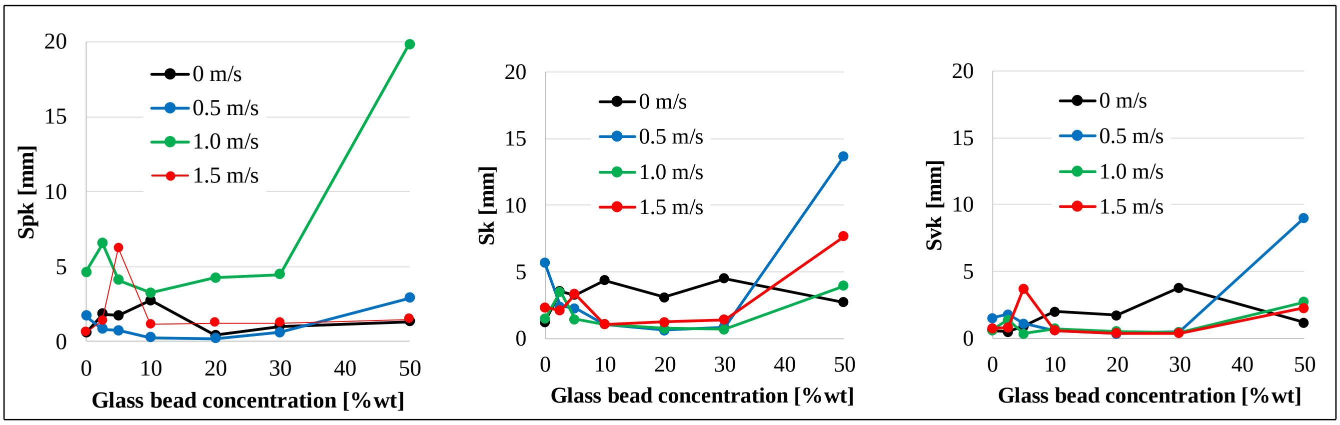



**Figure 14.** The functional parameters Svk, Sk and Spk

Figure 15 presents the values of the sum (Svk+Sk+Spk). This representation allows for distinguish which of these parameters dominates the texture.

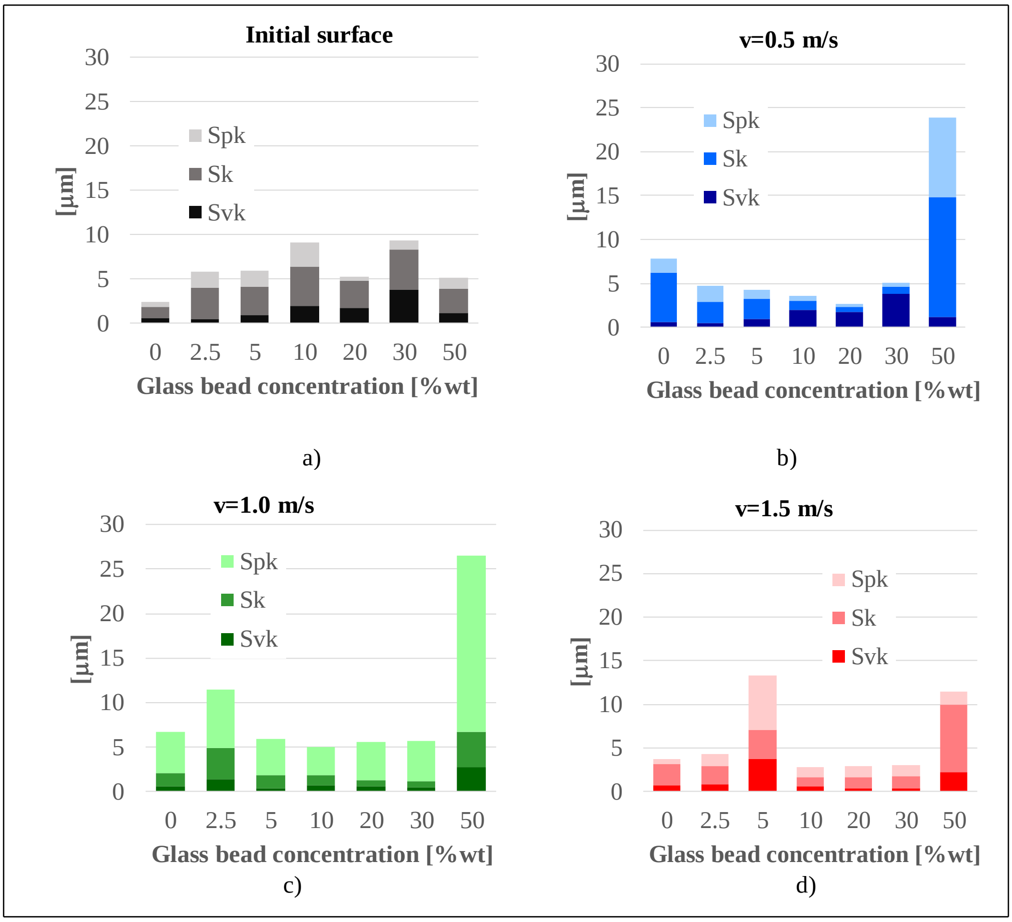



**Figure 15.** Plots of the sum (Spk+Sk+Svk) for the tested materials

Of course, it would be better that Sk is dominant (or larger) meaning a resistant core region of the texture. High participation of Spk means asperities that could be worn and Svk means how deep is the bottom region of the texture. It would be better to be small, but for lubricated system, this region is favorable to retain the lubricant and to avoid dry contact. The sum has the minimum value for the initial surface of the polymer (approximatively 2.5 μm), the sum for the composites being 5…9 μm.

At v=0.5 m/s, this sum is lower for the composites with 10-20% glass beads (2.5-5 μm). The polymer has the sum equal to 7 μm, the highest value being for the composite with 50% glass beads, meaning that texture extends to 24 μm, presuming that among the beads within the superficial layer, there are deep valleys.

At v=1 m/s, this sum is not sensitive to concentration in the range of 5-30%. The value is higher for the composite with 50% glass beads, for the same reason, but the Spk component is larger.

For v=1.5 m/s, the insensibility to concentration is restrained to 10-30%. This sum is smaller (around 12 μm) for the composite with 50% glass beads as compared to values obtained for the same composite, but at v=0.5-1 m/s. This result could be explained by the fact that the polymer is softened during sliding at this high velocity and the beads are not prone to be pull-out from the tribolayer, but prone to be embedded in the soft matrix of polyamide.

## 4. Conclusions

The identification of the composite with the best tribological behavior in dry sliding was performed by the help of an analysis of two tribological characteristics (disk wear and friction coefficient) and an analysis of 3D amplitude and functional parameter values, measured and calculated for initial and worn samples of textures. Amplitude parameters were analyzed for disk made of polymer and its composites with different concentrations of glass beads, tested at the average pressure p=1 MPa, applied for the three sliding velocities v=0.5 m/s, v=1 m/s, v=1.5 m/s, for the sliding distance of 10 km.

Disks made of Relamid® B-2Nf-T-(i) show low wear, low surface roughness, reflected by low values of amplitude parameters (Sa, Sq≈1 μm) due to polymer melting/softening in the last period of the test;

If at low concentration of 2.5% glass beads, the disk wear is small, its value increases in the composite with 5% glass beads with the increase of the sliding velocity.

The increase in amplitude parameters with increasing velocity for 0...10% glass bead concentration is reflected in the roughness of the worn 3D surfaces and in the high wear values, accentuated by increasing the velocity.

For composites with 2.5%...5%glass beads, the values are lower than those for the 50% glass bead composite. At p=1 MPa and v=0.5 m/s, the composite with 5% glass beads aligns with the 10...30% glass bead group. With increasing sliding velocity their values decrease, except for the 5% glass bead composite, whose values increase quite a lot.

Composites with 20...30% glass beads show a rough character of worn surfaces, but with low wear, except for the 30% glass bead composite, which shows a slight tendency to increase wear with increasing sliding velocity; the roughness of the surfaces is not due to high wear, but to the accumulation of glass beads in the surface layer, which fixes the polymer, thus explaining the considerable reduction in wear.

For disks with concentrations of 0...30% glass beads, there is a correlation between increased wear and increased roughness of worn surfaces in relation to increased sliding velocity.

If in low concentration composites there is a slight correlation between the roughness of worn surfaces, amplitude parameters, wear and sliding velocity, this correlation is not found in the 50% glass bead composite; in this composite the wear is small, insignificant for all three tested sliding velocities, but the roughness of the worn surfaces is maintained for all worn surfaces due to the accumulation of glass beads in the surface layer and the decrease of amplitude parameters is insignificant.

Following the investigation of the worn surfaces, no broken, cracked, micro glass beads were identified, unlike fiber composites, where fibers are broken, shattered, becoming factors of abrasive wear.

The study of 3D parameters on worn surfaces allowed for determining the influence of the sliding regime on the quality of worn surfaces after completion of the tests, studies that are necessary for possible applications of the materials, considering that the machine components have intermittent operation, these worn surfaces becoming initial surfaces for the following cycle of operation.

Based on the average values of the studied amplitude and functional parameters, it was found that a relatively good surface quality is preserved for concentrations of 10...30%wt glass beads for v=0.5...1

m/s (Sa and Sq being similar as trends to a fine grinding); for lower concentrations and for 50% glass beads, the parameter values increase, but without identifying a distinct relationship with the working regime, especially for 2.5 and 5% glass beads.

The experimental tests showed that the family of polymer composites with Relamid® B-2Nf-T-(i) matrix and addition of glass beads may have applications in the field of seals and slideways.

The authors pointed out by this analysis, that worn surfaces are better characterized by a set of 3D roughness parameters and this study presents a comparison of a set of parameters, the values depending on the testing condition and disk material.

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