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3D Optical and Mechanical Roughness Measurements of Complex and Irregular Structures on the Basis of Polypropylene Moldings

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ABSTRACT

The most frequently used method for measuring surface roughness is profilographometry. However, with complex and non-homogeneous surfaces, this method may be subject to large errors because of its contact nature and limitations related to the geometry of the measuring head. In this study, the surface topography was examined on polypropylene injection moldings produced using an injection mold with a complex molding cavity surface. The moldings were modified using a Nd:YAG laser, and the obtained structures were examined using two measurement methods, i.e. contact (profilographometry) and optical (3D digital microscopy). Researchers performed a statistical analysis to determine the differences between the measurement results obtained for the two methods. Additionally, the impact of the laser parameters on the modified surface was determined. The obtained results showed significant differences between the values of measurements made using different methods, especially in the case of surfaces that were modified by the laser beam to the greatest extent (laser A parameters). In all cases where a statistically significant difference was found between the measurement results, the mechanical method showed lower roughness values than the optical method, and the average difference between these results was 15%.

Keywords: complex structures, surface roughness, laser marking, electric discharge machining, injection molding.

INTRODUCTION

The plastics processing industry plays a very important role in economic progress. In industries such as automotive, medicine, aviation or electrical engineering, polymer elements are introduced as innovative solutions, often replacing materials such as metal, glass or ceramics [1, 2]. Such activities result from the dynamic progress in the field of processing technologies, the number of which is constantly increasing [3]. The aim of each stage of manufacturing polymer products is to strive to obtain the best quality products while maintaining low production costs [4]. The most common method of plastic manufacturing is high-pressure injection molding. This technique is characterized by a very high repeatability of products and makes it possible to produce elements with a complex structure, often unattainable using other production methods [5, 6]. The surface structure of each of the manufactured elements is characterized by the shape, size and topography of the surface, which are caused by the manufacturing process. In the case of the injection molding method, the quality of the produced structures depends to the greatest extent on the degree of mold cavity surface finish [7, 8]. Other aspects that may affect the condition of the surface include the type of material, mold temperature or processing parameters [9, 10]. In addition, after the injection process, plastic elements are often subjected to additional processing [11]. The correct selection of methods to change the surface of the products makes it possible to give them new features or improve the existing properties [12, 13]. Such a method is the action of a laser beam on the surface of plastics [14]. Laser marking is most often used for decorative, utility or identification purposes. As a result of the laser beam interaction with the material, a local temperature increase occurs, leading to overheating, evaporation or discoloration the surface, and then the formation of a permanent mark [15]. The effects obtained as a result of this process include: foaming, ablation, discoloration and engraving. In addition to marking the surface of polymeric materials, this method is also used for metals [16], wood [17] and ceramics [18]. The most common indicator used to assess the surface structure of plastics after the injection process and after post-production treatment is roughness.

Roughness measurement is a standard method for determining and evaluating surface properties. Among the techniques of its measurement, the most popular are contact methods and optical non-contact methods. The contact profilographometric method consists in determining the numerical values of the roughness profile parameters or mapping it in the form of a profilograph with known vertical and horizontal magnification [19]. During the measurement, the working elements of the tool come into contact with the surfaces of the measured object. To carry out the test using the contact method, a measuring needle with a known geometry is used, moving over the surface at a constant speed, and its vertical displacements are converted into an electrical signal [20]. Non-contact optical methods are based on surface scanning to assess the unevenness of the surface layer [21]. The measured object is illuminated with light of appropriate modulation, transmitted by optics and focused on the surface. The light reflected by it returns through the optical system and reaches a digital detector searching for a focused beam. The whole shape is obtained by vertical scanning of the surface (changing the distance between the lens and the detector) and successive supplementation of areas where previously no focusing was achieved. The image of the surface is shaped by an optical system that allows obtaining both photometric information (brightness, color, etc.) and geometric information (distances, shape). All the collected data from the images are processed into a three-dimensional view [22].

Among the roughness measurement techniques, linear and surface methods are distinguished. In industry, linear 2D measurements are most often made using the profile method, specifying such parameters as Ra and Rz [23]. In this method, it is possible to obtain a two-dimensional graph or profile of inequality, which can be represented mathematically by the height function $z(x)$. This technique has many advantages, including a good reflection of the measured surface and its effective penetration. However, its use is associated with problems, which include differences in test results depending on the type of measuring needle used, the measurement place and changes caused by the direction of scanning. Determination of surface properties using 3D surface methods, on the other hand, allows the evaluation of the entire selected surface. The obtained image can be presented in the form of a mathematical function of the height $z(x, y)$ of two independent variables (x, y). In this method, the most frequently determined parameters are Sa and Sz. Extending the assessment range from line to surface often allows for a more accurate assessment, and up to 1,000,000 individual measurement points can be obtained in one measurement. However, this technique depends to a large extent on the optical properties of the tested surface, because when light is absorbed or scattered by the material, its surface is immeasurable. In many cases, this is the first parameter to consider when assessing using linear roughness is difficult [24].

During laser marking, surfaces with high roughness usually absorb more energy. Such a phenomenon, when using incorrect parameters, can lead to thermal damage to the modified structure. Smooth, even surfaces make it possible to obtain a homogeneous and repeatable graphic sign, but they are characterized by a higher radiation reflection coefficient [25]. This action results in a smaller heat-affected zone, which in turn may affect the difficulties in marking this type of structure [26]. In addition, laser marking of plastics results in surface topography with an irregular structure. This situation is most often the reason for the uneven distribution of marking aids or dyes [27]. It is suspected that linear roughness measurements on such surfaces using the contact method do not fully reflect the complex topography of the structure.

The aim of the conducted research was to verify methods for evaluating the roughness of surfaces characterized by an irregular structure on the surface of plastics, both before and after treatment of samples by laser marking. In addition, the influence of the laser beam parameters on the change of the surface structure of plastics was evaluated.

MATERIALS AND METHODS

Materials

A commercial polypropylene homopolymer intended for injection molding processing under the trade name Moplen HP500N (Basell Orlen Polyolefins, Płock, Poland) was used in the research. According to manufacturer's declaration the melt flow rate (MFR) of the material was 13 g/10min (230 °C/2.16 kg). The average value of Young's modulus (E) and the stress at yield were 1400 MPa and 34 MPa, respectively. A dyeing concentrate Weiss K70 (Lifocolor Farben GmbH & Co. KG, Lichtenfels, Germany) was added to the polypropylene matrix in a concentration of 2% by mass. and an LMA additive called Lifolas M 117009 UN (Lifocolor Farben GmbH & Co. KG, Lichtenfels, Germany) at a concentration of 2.5%.

Samples preparation

Homogenization of the material with additives was carried out in the plasticizing system of the single-screw extruder W25-30D manufactured by the Institute of Plastics Processing Metalchem (Toruń, Poland). The screw diameter (D) was 25 mm, and the ratio of the screw length to its diameter (L/D) was 30. Additionally, in the feeding zone of the screw, there were elements increasing the intensity of mixing. The temperatures in the individual zones of the plasticizing system were: 135 °C (in the feeding zone), 180 °C (in the compression zone), 200 °C (in the metering zone), and 200 °C (in the head). The rotational speed of the screw was 150 rpm. The obtained cylindrical extrudate with a diameter of about 3 mm was subjected to cold granulation and after that process was dried in a Binder FED 115 temperature chamber (Tuttlingen, Germany) for 24 hours at 110 °C. Test samples were made using a Battenfeld Plus 350/75 injection molding machine (Battenfeld Kunststoffmaschinen GmbH, Kottingbrunn, Austria). The moldings with dimensions of 108×94×2 mm were produced in a specially prepared injection mold, the interior of which was divided into three zones with different degrees of surface finish. Diversified surface parameters of mold cavity were obtained as a result of the electrical discharge machining (EDM) process. The plasticized material, as a result of the injection process under high pressure reflected the surface of the cavity on the obtained moldings to a certain extent. The most important parameters of the injection process used during the preparation of the samples are presented in Table 1.

Laser marking

The surfaces of the test samples were subjected to a laser beam using the TruMark Station 1000 device (Trumpf Group, Ditzingen, Germany). With the use of TruTropsMark software (Trumpf Group, Ditzingen, Germany), four 20 × 20 mm graphic marks were applied to each of the three zones of the molding, using different parameters of the laser beam, whose wavelength λ was 1064 nm. The adopted test program included such variables as: laser path width (0.03–0.09 mm), beam travel speed (450–5000 mm/s) and a constant parameter in the form of pulse incidence frequency (15 kHz). The parameters of the laser beam used during the marking of specific fields are presented in Table 2. Figure 1 shows the images of the applied graphic signs created as a result of the laser beam on the surface of the moldings. The attached drawing shows that adjustable laser beam parameters not only affect the roughness of the marked surfaces. Changing the characteristics of the laser beam also changes the color of the marked graphic fields.

Surface roughness measurements

In the first stage, the degree of mapping the roughness of the obtained moldings in relation to the roughness of the surface of the forming cavity was analysed. Measurements were made on the forming mold cavity plate and the results were compared to those obtained on the surfaces of the moldings. In the second stage of the research, the

Table 1. Selected parameters of injection molding process

Processing parameters	Value
Feed zone temperature [°C]	200
Transition zone temperature [°C]	210
Metering zone temperature [°C]	220
Nozzle temperature [°C]	220
Injection mold temperature [°C]	20
Holding time [s]	8
Cooling time [s]	14
Injection time [s]	0.75
Injection velocity [cm^3/s]	50
Holding pressure [MPa]	7.5

Table 2. Parameters of laser beam

Process parameter	Value			
Description of marked area	A	B	C	D
Head velocity [mm/s]	450	750	1050	1350
Path width [mm]	0.03	0.05	0.07	0.09
Pulse frequency [kHz]	15			
Efficency [%]	100			
Mode of work	pulse			

impact of the laser beam and its parameters on the change in the state of the surface obtained during the reflection of the injection mold cavity was analysed. During the tests, 2D linear roughness and 3D surface roughness were analyzed. The roughness parameters determined in the tests are Ra (2D) and Sa (3D).

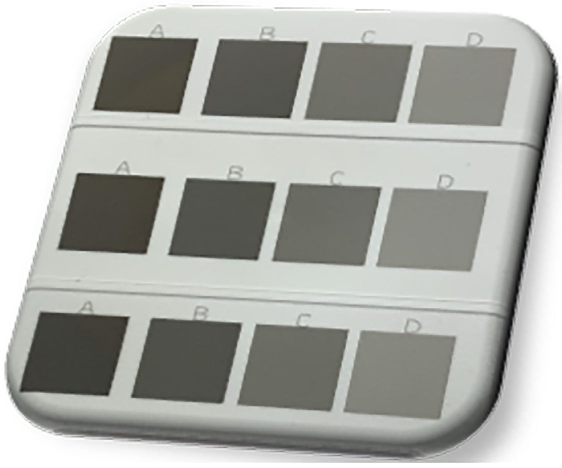

Figure 1. Test sample with laser marked signs with various parameters of laser beam

Contact-type surface roughness

Roughness measurements using the contact-type method were performed using the MarSurf GD 120 device (Mahr GmbH, Göttingen, Germany), equipped with the MFW-250 measuring head. Each measurement was made using a needle with a radius of 2 µm, shown in Figure 2. During the 2D linear roughness measurement, ten measurements were made along the *x* and *y* axes, on the basis of which the average value was calculated. The length of the reference section λc was determined during the preliminary tests, respectively: 2.5 mm for the graphic symbols and background on the EDM A and EDM B surface, and 8 mm for the graphic symbols and background on the EDM C surface. In order to obtain the parameters of 3D surface roughness, 11 parallel passes of the measuring head were made on the tested surfaces, each with a reference section length of 2.5 mm (EDM A, EDM B) and 8 mm (EDM C).

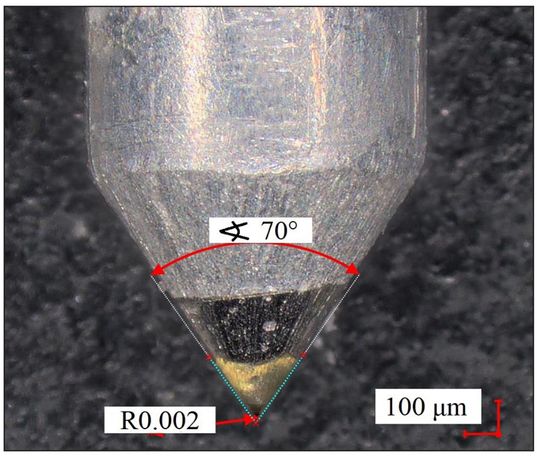

Figure 2. Measuring needle used for roughness measurements

Optical surface roughness

Optical roughness measurements were made using a Keyence VHX-7000 digital microscope (Osaka, Japan). The device was equipped with a zoom lens VH-Z100R. All measurements were made at a magnification of 500*x*. To obtain the results of 2D linear roughness, 10 profiles in the *x* and *y* axes were used. The length of the measurement reference section had the same value as in the case of roughness testing using the profilographometric method. For the 3D surface roughness test, 100 individual 2D images were taken between the highest and lowest points, and then these images were superimposed. This measurement was made automatically using the "precise depth composition" function. Each measurement was made using a coaxial type of light.

RESULTS AND ANALYSIS

In the first stage, the degree of mapping the surface roughness of the specimens in relation to the cavity of the injection mold was analyzed. The measurement using a digital microscope on the surface inside the mold cavity with the designation EDM A resulted in obtaining an average Ra(*x*) value of 2.51 ± 0.44 µm. In the case of the sample part reflecting this zone, the described parameter was equal to 2.82 ± 0.62 µm (Table 3). This means that the average roughness of the molding surface was nearly 13% higher than that of the injection mold cavity surface. In the case of contact-type measurements for the same surface, the average value of the Ra(x) parameter for the molding cavity was equal to 2.24 ± 0.18 µm, while the molding surface was characterized by a value of this parameter about 14% higher – 2.56 ± 0.27 µm. In the zone with the highest roughness - EDM C, the average value of Ra(x) for the mold cavity is 12.91 ± 1.75 µm (optical method), while in the case of the molding it is 14.21 ± 1.61 µm. Thus, an approx. 10% increase in the Ra(x) parameter was noted. For the same area, the mechanical results were 11.83 ± 0.78 µm and 13.09 ± 0.53 µm, respectively. In this case, the average increase of Ra(x) was also about 10%. In the case of the EDM B surface, the reported increase for both methods was 7%. Based on the obtained results, it was found that the surface of the injection moldings was characterized by a higher value of the average linear roughness in relation to the average linear roughness of the molding cavity. Such a relationship was observed both during measurements using the optical and contact methods. In addition, optical and mechanical measurements result in a similar percentage increase in the average linear roughness of moldings in relation to the mold cavity for the same surfaces. There was no significant advantage of the described parameter for measurements carried out along one of the axes. Although for measurements along the y axis, in most cases a higher average Ra value was obtained, it cannot be unequivocally stated by analyzing the standard deviations that greater roughness is obtained when measuring in carrying out in this direction.

During the analysis of the surface parameter Sa, similar relationships were obtained between the 3D average roughness of the molding and the mold cavity. For the described parameter, the surface of the injection molding was also characterized by a higher average roughness than the surface of the mold cavity. The average Sa value for the surface of the EDM A zone in the mold cavity during the optical measurement was 2.68 ± 0.26 µm, while for the molding the result was nearly 13% higher – 3.01 ± 0.28 µm. In the case of surfaces with the highest roughness (EDM C), the difference in the Sa parameter between the molding and the mold cavity was about 10%. The recorded results were respectively 14.08 ± 1.23 µm (mold cavity) and 15.11 ± 1.13 µm (molding) - optical method. The percentage differences were therefore similar to those obtained during the measurements of the average 2D linear roughness.

Figure 3 shows the surface topography for individual zones of the molding cavity and the topography of the molding reflecting the given zone after the injection molding process. The digital images show a local intensification of the

Table 3. Comparison of the average roughness of the injection mold interior with the obtained moldings

Type of surface		Ra(x) [µm]	Ra(y) [µm]	Sa [µm]
Mold cavity (Optical)	EDM A	2.51 ± 0.74	2.57 ± 0.58	2.68 ± 0.36
	EDM B	5.05 ± 0.82	5.53 ± 0.69	6.02 ± 0.38
	EDM C	12.91 ± 2.36	13.78 ± 2.16	14.08 ± 1.73
Molding (Optical)	EDM A	2.82 ± 0.62	2.84 ± 0.57	3.01 ± 0.8
	EDM B	5.43 ± 1.17	5.61 ± 1.34	6.04 ± 0.38
	EDM C	14.21 ± 1.61	13.89 ± 1.81	15.11 ± 1.13
Mold cavity (Contact)	EDM A	2.24 ± 0.58	2.32 ± 0.39	2.43 ± 0.16
	EDM B	4.78 ± 0.73	4.94 ± 0.93	5.36 ± 0.31
	EDM C	11.83 ± 1.78	12.91 ± 1.71	12.84 ± 0.63
Molding (Contact)	EDM A	2.56 ± 0.47	2.51 ± 0.46	2.56 ± 0.18
	EDM B	5.13 ± 0.69	5.32 ± 0.51	5.72 ± 0.34
	EDM C	13.09 ± 1.53	13.12 ± 1.23	14.31 ± 0.46

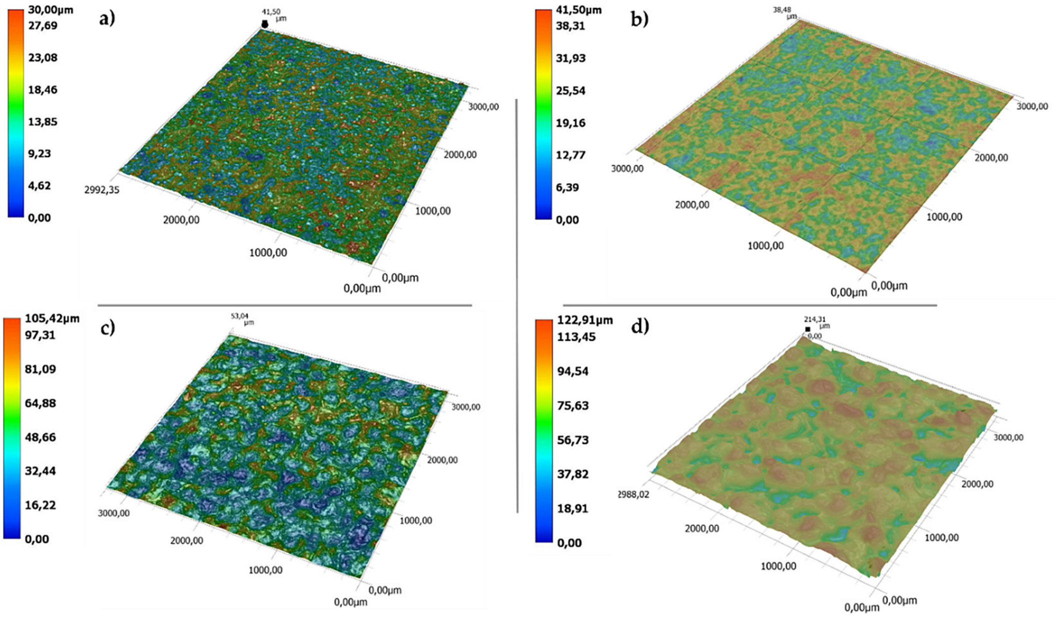

Figure 3. Topography of the tested surfaces of the molding insert and polypropylene moldings obtained using digital microscope: (a) surface of the EDM A molding cavity, (b) surface of the EDM A molding, (c) surface of the EDM A molding cavity, (d) surface of the EDM C molding

micro-elevations formed by the material. Their presence and quantity result in a higher value of the average roughness for the molding in relation to the mold cavity. On the EDM A zone of the molding cavity, the biggest difference between the highest and the lowest point is equal to 30.00 µm, while for the molding it is 41.5 µm. In the case of the EDM C surface, the values of 105.42 µm (mold cavity) and 122.91 µm (molding) were obtained. Higher values of roughness parameters for injection moldings may result from the viscosity of the material. As a result, polypropylene does not penetrate into the sharp depressions visible in the image of the topography of the forming cavity, despite maintaining the correct processing parameters. This could be due to the formation of a thin insulating layer formed by air molecules, which was closed in the irregularities of the surface of the interior of the mold.

Analyzing the mentioned and other results, it can be said that although the average values of Ra and Sa for optical and mechanical measurements were not the same, the increase in the surface roughness of the moldings relative to the interior of the mold cavity was at a similar percentage level. However, it is not possible to directly compare the results for both measurement methods due to the way the measurement is carried out by both devices. During the analysis of the measurement methods used, it was found that the average values of roughness parameters obtained during optical measurements were higher than those obtained by the mechanical method. In the case of measuring the average roughness Ra(x) of the EDM B surface of the forming cavity, the measurement using the optical method showed a result of 5.05 ± 0.52 µm, while for the contact method it was 4.78 ± 0.23 µm. Thus, an increase of over 5% was recorded. However, this difference is insignificant and the results are within the standard deviation range. For the EDM A and EDM C surfaces, an increase of 11% and 9% was recorded, respectively. In the case of the average roughness of the injection molding, the results remained at a similar level, with differences ranging from 6% (EDM A) to 9% (EDM C). In addition, when comparing the optical method with the mechanical method, differences in standard deviations for measurements of the same surface were noted. The values of standard deviations determined during measurements using a digital microscope are higher than those obtained by the profilographometric method. Such a difference may be due to the greater measurement accuracy of the optical microscope. This device for measuring indentations uses a beam of light, which is reflected from the tested surface and returns to the device, where the distance between the highest and lowest point of the tested surface can be determined with high accuracy. The profilometric device uses a needle with a given radius, which does not penetrate as precisely as a beam of light between the cavities on the surface, resulting in lower measurement accuracy. The principle of measurement by both devices, which allows to explain the differences in both research methods, is illustrated in Figure 4.

The analysis of 3D surface roughness Sa resulted in obtaining similar relationships. In this case, each of the surfaces was also characterized by higher Sa values during the optical measurement. The average value of Sa roughness on the EDM B surface of the mold cavity determined by the optical method was equal to 6.02 ± 0.58 µm. When measuring the same area using the contact-type method, the result was 5.36 ± 0.31 µm. In the case of surfaces with higher roughness (EDM C), the measurement of the Sa parameter using the optical method showed the result of 14.08 ± 1.23 µm, while the measurement using the mechanical method gave the result of 12.84 ± 0.83 µm, so 9% lower. Surface roughness measurements carried out on the molding were characterized by similar changes. These differences are most likely caused by the measurement accuracy and the method of measuring the parameter by both devices. The profilographometer for measuring Sa uses 11 parallel passes of the needle of a given measuring length over a defined area. The distances between the individual passages of the needle have a certain length, therefore it is not possible to examine the entire analyzed area, but only a part of it. The digital microscope collects information about

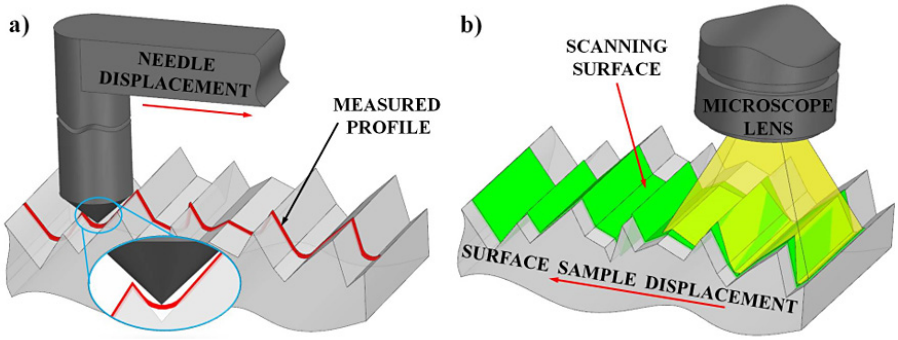

Figure 4. Mapping of the surface by measuring devices: (a) contact-type device with a measuring needle (b) digital microscope

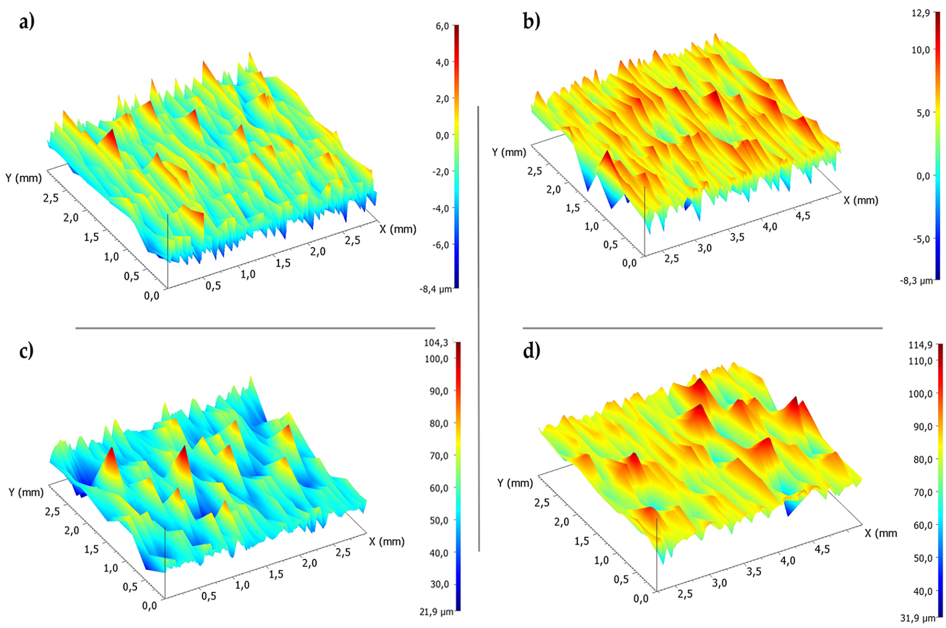

Figure 5. Topography of the tested surfaces of the molding insert and polypropylene moldings obtained using contact-type device: (a) surface of the EDM A molding cavity, (b) surface of the EDM A molding, (c) surface of the EDM A molding cavity, (d) surface of the EDM C molding

the difference between the cavities from the entire examined surface. The probability of dimples in the entire area is therefore much greater than when examining with a needle. Figure 5 shows the surface topography for individual zones of the molding cavity and the topography of the compact reflecting the given zone after the injection molding process, obtained from the device using the contact method for testing roughness.

The test results obtained during the second stage of the experiment (Table 4) prove that the action of the laser beam on the molding surface in some cases results in an increase and in others a decrease in roughness in relation to the base value (background). The adjustable parameters of the laser beam are responsible for this fact. The average linear roughness of the compats surfaces marked as EDM A and EDM B increased in relation to the background after the laser marking process, regardless of the beam parameters used. On the other hand, in the case of the EDM C surface, reverse relationships were obtained. The highest increase in Ra, both on the surface of EDM A and EDM B, was recorded during the application of graphic marks using the operating parameters of laser A (0.03 mm, 450 mm/s, 15 kHz). Laser marking using the other parameters also resulted in an increase in average roughness, but the increase was not as high. The average roughness of the moldings on the EDM A surface was 2.82 ± 0.42 μm, while after marking with beam A operating parameters, an increase of Ra(*x*) to 5.13 ± 0.43 μm was noted (optical measurements). The recorded increase was 80%.

Table 4. Comparison of roughness parameters made by optical and mechanical methods obtained on the moldings and laser marked surfaces

Type of surface		Ra(x) [μm]	Ra(y) [μm]	Sa [μm]
Background (Optical)	EDM A	2.82 ± 0.42	2.84 ± 0.37	3.01 ± 0.28
	EDM B	5.43 ± 1.17	5.61 ± 1.34	6.04 ± 0.68
	EDM C	14.21 ± 1.61	13.89 ± 1.81	15.11 ± 1.13
Background (Contact)	EDM A	2.56 ± 0.27	2.51 ± 0.16	2.56 ± 0.18
	EDM B	5.13 ± 0.39	5.32 ± 0.51	5.72 ± 0.44
	EDM C	13.09 ± 0.53	13.12 ± 0.23	14.31 ± 0.36
EDM A (Optical)	A	5.13 ± 0.43	5.24 ± 0.49	5.54 ± 0.43
	B	3.62 ± 0.61	3.24 ± 0.51	3.88 ± 0.36
	C	3.23 ± 0.39	3.33 ± 0.72	3.41 ± 0.47
	D	3.05 ± 0.66	2.88 ± 0.61	3.19 ± 0.45
EDM A (Contact)	A	4.62 ± 0.23	4.49 ± 0.42	4.76 ± 0.11
	B	3.01 ± 0.17	3.32 ± 0.09	3.44 ± 0.09
	C	2.99 ± 0.16	2.91 ± 0.21	3.23 ± 0.12
	D	2.61 ± 0.31	2.89 ± 0.32	3.14 ± 0.06
EDM B (Optical)	A	11.19 ± 1.13	10.59 ± 1.15	11.58 ± 0.89
	B	5.63 ± 0.96	5.67 ± 0.71	6.01 ± 0.67
	C	5.54 ± 0.48	5.91 ± 0.55	5.86 ± 0.39
	D	5.44 ± 0.81	5.68 ± 0.52	5.92 ± 0.45
EDM C (Contact)	A	9.74 ± 0.41	9.26 ± 0.48	10.12 ± 0.21
	B	5.39 ± 0.46	5.61 ± 0.43	5.93 ± 0.18
	C	5.34 ± 0.35	5.27 ± 0.27	5.66 ± 0.26
	D	5.36 ±0.32	5.56 ± 0.09	5.67 ± 0.23
EDM C (Optical)	A	11.54 ± 1.36	11.67 ± 1.61	11.94 ± 1.34
	B	12.39 ± 3.27	14.21 ± 2.8	15.46 ± 1.97
	C	12.71 ± 1.46	11.51 ± 2.56	13.85 ± 0.78
	D	13.49 ± 1.88	13.16 ± 2.52	14.36 ± 1.12
EDM C (Contact)	A	10.08 ± 0.64	10.66 ± 0.91	10.43 ± 0.78
	B	12.59± 1.28	11.27 ± 0.51	15.26 ± 0.98
	C	12.19 ± 0.32	12.95 ± 1.44	13.84 ± 0.52
	D	12.33 ± 0.98	12.79 ± 1.03	13.94 ± 0.84

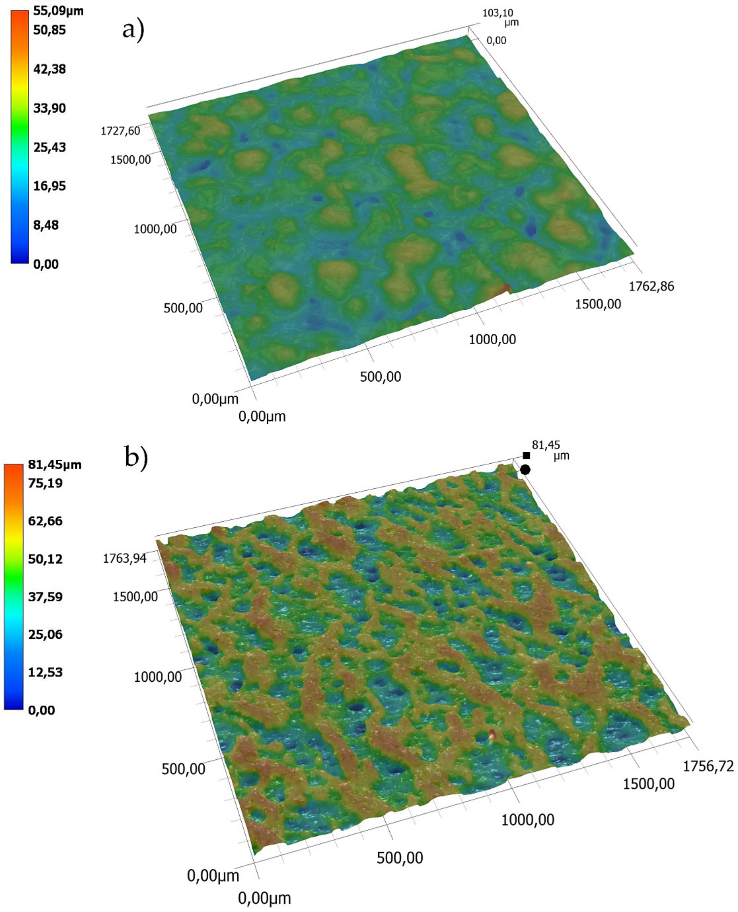

Figure 6. Comparison of the surface topography after the laser marking process in relation to the background on the surface marked as EDM B a) background topography of the EDM B compact b) topography of the graphic mark on the EDM B surface obtained with laser operating parameters A (0.03 mm, 450 mm/s, 15 kHz)

In the case of the EDM B zone, with the same laser parameters, the increase was even more visible – from the value of 5.43 ± 1.17 µm to 11.19 ± 1.13 µm, i.e. by more than 100%. The operating parameters of laser A caused a stronger interference of the laser beam on the tested surface, which significantly deteriorated the surface parameters. The topography of the EDM B surface before and after the laser marking process is presented on digital microscopic photos. The process of foaming and carbonization took place on the surface of the moldings as a result of thermal effects. In Figure 6, there are some bubbles enclosed under the top layer, the amount of which resulted in the observed increase in roughness. In addition, it was observed that by changing the adjustable laser parameters within one zone of the plate, it was possible to obtain an average roughness that differed by about 31% for EDM A, 68% for EDM B and 47% for EDM C. Taking into account the remaining parameters of the laser (B, C, D), it can be concluded that with the increase in the width of the beam path and the speed of the laser head, the difference between the roughness of the graphic mark and the background was smaller. Parameters B, C and D result in too low power density of the laser beam, which makes the surface roughness close to the background. The comparison of the results obtained during measurements made using the contact and optical methods confirms the conclusion obtained during previous measurements that the optical method results in higher roughness values. A graphical summary of measurements made by two methods for each of the analyzed surfaces is shown in Figure 7 (Ra roughness) and Figure 8 (Sa roughness). As mentioned earlier, a different relationship between the average roughness of the compact and the graphic mark was observed when marking the EDM C zone, for which the average linear roughness of each graphic field was lower in relation to the background roughness. In this case, the marking of moldings using the A parameters resulted in a

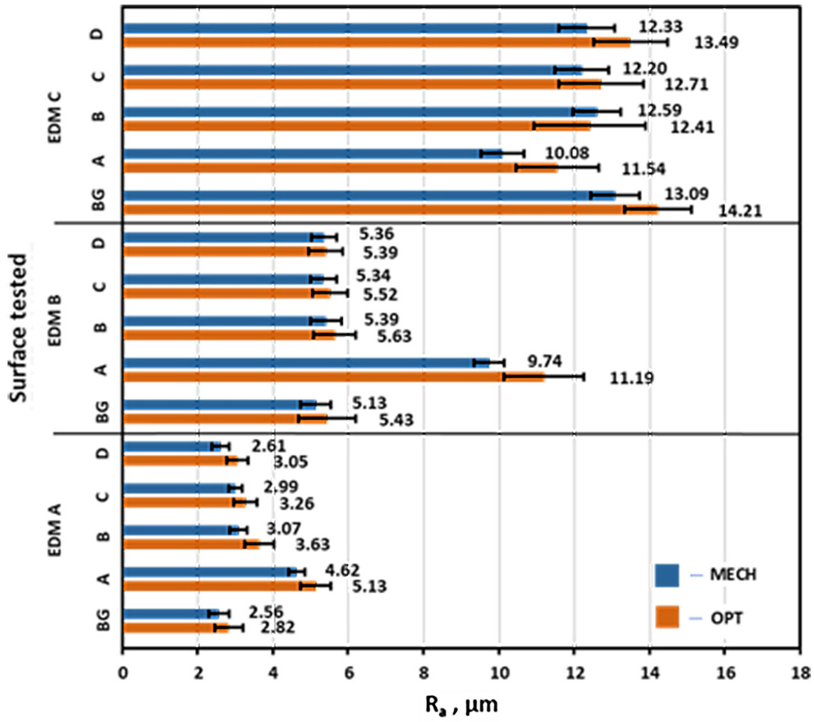

Figure 7. Comparison of the Ra roughness parameter for all surfaces made by optical and mechanical methods

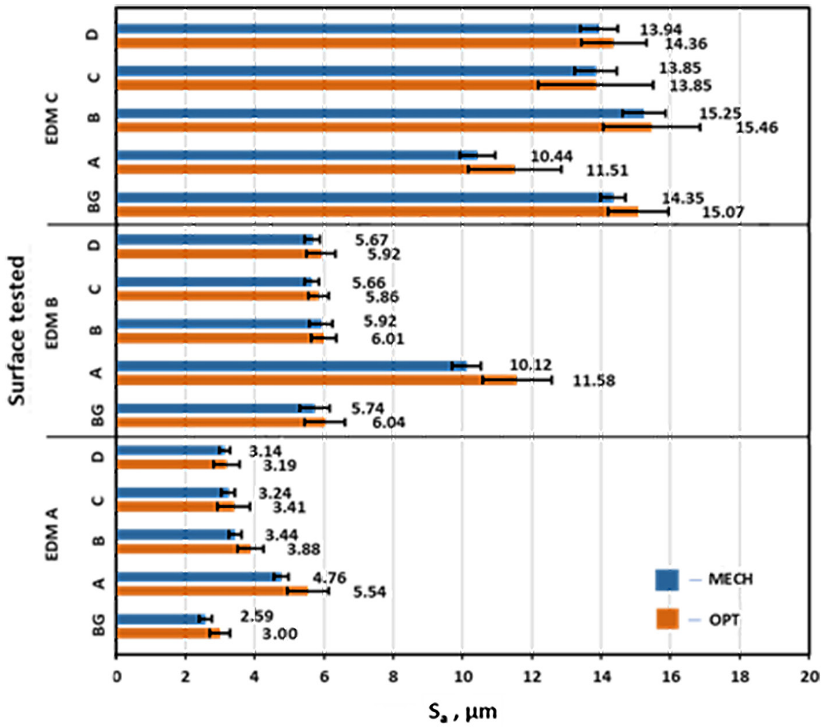

Figure 8. Comparison of the Sa roughness parameter for all surfaces made by optical and mechanical methods

decrease in the average value of the Ra parameter from 14.21 ± 1.61 µm to 11.54 ± 1.36 µm, i.e. by about 20%. The other parameters of the laser operation (B, C, D) also caused a decrease in the average roughness value, which remained at a similar level and amounted to about 10%. The EDM C surface of the sample is the surface with the highest roughness among those analyzed. With such selected parameters of the laser operation, there are difficulties in even greater violation of the structure of the surface layer. Based on the decrease in the average roughness value,

Table 5. Results of the Student's t-test for roughness measurements made using two methods (optical and mechanical)

Type of surface		p-value	
		Ra	Sa
BG	EDM A	0.0785	0.0028*
	EDM B	0.1964	0.3319
	EDM C	0.0185*	0.0319*
EDM A	A	0.0055*	0.0038*
	B	0.0014*	0.0090*
	C	0.0692	0.3230
	D	0.0013*	0.7600
EDM B	A	0.0013*	0.0031*
	B	0.4022	0.5538
	C	0.3680	0.1220
	D	0.7910	0.0633
EDM C	A	0.0059*	0.0549
	B	0.7237	0.7142
	C	0.2191	0.9980
	D	0.0090*	0.2391

it can be concluded that by using the appropriate parameters it is possible to smooth the surface. In the previously conducted own research [26], the surface roughness Ra of moldings containing 10 wt. microsilica ranged from 1.5 (laser parameters B, C, D) to about 9.5 (laser parameters A). As in the described studies, the laser parameter A (450 mm/s, 0.03 mm) resulted in the greatest degree of interference in the surface layer of the material.

Statistical analysis was performed based on the Student's t-test for dependent samples, and the p-values are presented in Table 5. The analysis was aimed at determining whether the measurement method (contact or optical) had an impact on the determined roughness values for specific surfaces. Statistical significance was assumed for $p < 0.05$. The test showed that the methods used to determine roughness may give different results. The Ra parameter differed depending on the measurement method used for 8 out of 15 tested surfaces, while for the Sa parameter it was 5 out of 15 surfaces. This is due to the fact that the measurement of the Ra parameter is burdened with a larger measurement error than the Sa parameter.

Both the Sa and Ra parameters, measured using the two measurement methods considered, differed from each other for each laser-modified surface with A parameters, except for EDM C (Sa value). It should be noted, however, that for this surface the p-value was 0.0549, which is a value close to the significance level of the test. Set of parameters A caused the greatest changes in the surface topography, and the roughness of the surface obtained in this way reached higher values in optical measurements than in contact measurements. It can therefore be concluded that providing sufficiently high thermal energy results in the creation of a surface with a complicated topography that cannot be fully characterized by profilographometry. Significant differences in measurement results between the two methods were also observed in the case of EDM surface A, where, in addition to differences for the set of laser parameters A, significant differences were also observed for parameters B (Ra and Sa) and D (Ra). EDM surface A was characterized by the lowest roughness, and its laser modification using parameters A and D caused a significant change in the surface topography, which resulted in an increase in its roughness. In the case of the EDM B surface, the measurement method had the least impact on the obtained roughness result. No significant differences were observed between the values of the Ra and Sa parameters obtained using different methods, for the background surfaces and those modified with a laser with parameters B, C and D. This may be due to the fact that in the case of EDM B surfaces, laser modification with parameters B, C and D did not significantly change the roughness of this surface in relation to its background.

CONCLUSIONS

The conducted research verified the possibility of replacing the contact method of measuring the roughness of surfaces with complex structures with an optical method using 3D digital microscopy. Additionally, the influence of Nd:YAG laser parameters on the roughness of the structure of polypropylene moldings was examined. Based on the test results, it was determined that a laser with appropriately selected parameters is able to significantly change the topography of the surface of polypropylene moldings. Roughness change up to 106% were noticed as a result of laser treatment. Additionally, it was found that in the case of surfaces with high base roughness (Ra ~ 10 μm), laser processing reduces the surface roughness by up to 24%. The opposite tendency was observed for surfaces with lower roughness (Ra ~ 5 μm and Ra ~ 3 μm), where laser modification only resulted in an increase in roughness. The largest changes in roughness relative to the background occurred as a result of the use of laser parameters guaranteeing the delivery of the greatest amount of energy to the sample surface (parameters A).

Comparison of roughness values determined using two measurement methods allowed for the conclusion that the roughness determined using the optical method was in all cases greater than or equal to that measured using the contact method. It can therefore be concluded that the optical method allows for a more accurate characterization of surfaces with complex topography because it takes into account surface areas that are inaccessible to the measuring head used in profilographometry. The average Ra and Sa roughness values determined using the microscopy method were, respectively up to 15% and 14% higher than the values calculated for the contact method. The analysis carried out allows us to conclude that the 3D microscopy method (stitching images in the vertical axis) allows for very accurate characterization of complex structures, such as the surface after electro-discharge machining or after laser marking.

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