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# Statistical evaluation of metal plated polymer surfaces

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**Abstract.** The surface quality of metallized polymer parts plays a crucial role in the functional and aesthetic properties of the final product, especially in the automotive industry and consumer electronics. This study focuses on non-contact measurement of the surface structure of ABS polymer parts, metallized using vacuum technology with the application of copper, nickel and chromium layers. The measurement was performed on the Talysurf CLI 500 device and evaluated according to the current standards ČSN EN ISO 21920-1 and 21920-2, which define the profile roughness parameters and the methodology for their assessment. The measured data were subsequently analyzed using descriptive statistics and multivariate statistical methods including analysis of variance (ANOVA), which allowed to reveal differences between samples manufactured in different time periods and in different plating conditions. The results confirm that the metal coating significantly affects the values of key surface structure parameters ( $R_a$ ,  $R_z$ ), and indicate the need for consistent control of process stability. The study also confirms the benefits of statistical tools for quality assessment and supports their wider use in technological practice.

## 1. Introduction

Polymeric materials, particularly acrylonitrile-butadiene-styrene (ABS), are widely used in contemporary industry. Their popularity arises from a favorable balance of price and performance, ease of processing, and the possibility of replacing metallic components, whose production is costly and technologically demanding. In the automotive industry and consumer electronics, however, high demands are placed not only on functional properties but also on the visual appearance of products. Surface quality therefore becomes one of the key parameters determining both functionality and customer perception. [1]

To achieve a surface comparable to that of metallic components, polymer parts are often subjected to metallization. Metal coatings on polymers bring several advantages beyond the visual effect: increased mechanical strength and dimensional stability, reduced permeability to liquids and gases, and improved resistance to environmental degradation. In addition, a metal surface layer enables electrical conductivity, which is essential in many electrotechnical applications [2-3].

The importance of surface quality can be considered in two distinct aspects: functional and aesthetic. From a functional standpoint, surface roughness directly affects mechanical performance, component lifetime, and resistance to corrosion or wear. From an aesthetic

perspective, the surface is the first feature perceived by the customer and thus plays a decisive role in the perceived value of the product. This is particularly critical in the automotive industry, where design and appearance are as important as functionality, and in consumer electronics, where surface finishing has a significant influence on product acceptance in the market. [4, 5]

The development of modern technologies and the increasing requirements for manufacturing precision have accelerated the advancement of methods that allow quantitative evaluation of surface quality. Whereas visual inspection and operator experience were once dominant, today sophisticated non-contact measurement techniques provide precise and reproducible data. Non-contact profilometry is particularly advantageous because it avoids damaging delicate surfaces and allows complex geometries to be measured with high resolution. Statistical evaluation methods play an equally important role in the interpretation of surface measurements. While individual measurements may offer only a limited perspective, statistical processing such as descriptive analysis or analysis of variance (ANOVA) reveals deeper relationships. These methods make it possible to distinguish whether observed differences are truly significant or merely random fluctuations, thereby providing a more robust basis for decision-making. [6, 7]

Another important aspect is the increasing emphasis on standardization. International standards, such as ČSN EN ISO 21920, establish a unified framework for surface structure measurement and evaluation. They define parameters, methodology, and rules for data interpretation, ensuring comparability of results across laboratories and manufacturing facilities. In a globalized industrial environment, such harmonization is indispensable for consistent quality control. [8, 9]

This study focuses on the evaluation of surface structure in ABS polymer components metallized by vacuum technology with copper, nickel, and chromium layers. Surface quality was assessed using a non-contact laser profilometer, and the results were statistically processed to determine the influence of metallization and process stability on surface parameters.

## 2. Materials and Methods

### 2.1 Material Used

The substrate selected for metallization was acrylonitrile-butadiene-styrene (ABS), an amorphous thermoplastic that offers a highly favorable combination of mechanical and technological properties. The polymer is produced by copolymerization of styrene and acrylonitrile in the presence of polybutadiene rubber. Each component contributes specific properties:

- Acrylonitrile improves strength and chemical resistance.
- Butadiene increases toughness and impact resistance, even at low temperatures.
- Styrene provides surface gloss, rigidity, and enhances processability.

ABS is widely used in the automotive industry, electrical engineering, and consumer goods, in part due to its suitability for surface finishing, including metallization. The presence of polar nitrile groups on the polymer surface promotes adhesion of metallic coatings.

### 2.2 Metallization Technology

Proper surface preparation is essential for achieving high-quality adhesion of metal layers to polymer substrates. The surface must be thoroughly degreased, cleaned of contaminants, and lightly roughened. It is then activated by etching and sensitization.

In this study, three metallic layers were successively applied to the ABS substrate:

- Copper (Cu) – providing a conductive base layer and evening out surface irregularities.
- Nickel (Ni) – contributing mechanical strength, hardness, and corrosion resistance.
- Chromium (Cr) – forming the top decorative layer with high gloss and durability.

Deposition was carried out using vacuum technology (physical vapor deposition/sputtering) at pressures in the range of  $10^{-3}$ –1 Pa. This technique enables the application of homogeneous thin films and is suitable for both decorative and functional applications. The overall thickness of the layers ranged from several tens of micrometers (Cu ~38–55  $\mu\text{m}$ , Ni ~17–26  $\mu\text{m}$ , Cr ~0.3–1.1  $\mu\text{m}$ ) (table 1).

**Table 1.** Composition and Thickness of Layers.

Layer	Minimum thickness [ $\mu\text{m}$ ]	Maximum thickness [ $\mu\text{m}$ ]
Copper (Cu)	38.0	55.0
Nickel (Ni)	16.9	26.0
Chromium (Cr)	0.3	1.1

Three series of samples were prepared, each in pairs:

- Uncoated base sample (ABS without surface modification).
- Corresponding coated sample (ABS with metallic coating).

Each pair originated from a different manufacturing period. This design made it possible to study not only the effect of metallization itself but also potential differences between production batches.

### 2.3 Measurement Method

The surface structure was characterized using a non-contact profilometer Talysurf CLI 500 (Taylor Hobson). The device employs laser scanning and enables detailed three-dimensional surface analysis on the micrometer scale. The non-contact nature of the method prevents damage to delicate surfaces, which is essential when evaluating metallized polymers with thin coatings.

Measurements were performed on rectangular areas of  $2 \times 4$  mm, scanned in both directions with a resolution of 5  $\mu\text{m}$ . The traverse speed was set to 500  $\mu\text{m/s}$ . In total, 401 profiles in the Y-direction and 801 profiles in the X-direction were collected, providing a dense data set sufficient for accurate surface reconstruction. The resulting data were processed using the TalyMap software, which enabled both 2D/3D visualization and calculation of roughness parameters.

### 2.4 Standards and Evaluation Parameters

Evaluation was performed in accordance with the standards ČSN EN ISO 21920-1 :2023 and ČSN EN ISO 21920-2 :2023, which represent internationally accepted frameworks for surface structure assessment. These standards define measurement methodology, parameters, and interpretation rules, thereby ensuring comparability of results across laboratories and industrial practice.

From the wide range of available parameters, two key indicators were selected for this study:

- Ra – arithmetical mean roughness.
- Rz – maximum height of the profile.

Ra provides a general measure of average surface roughness, while Rz is more sensitive to extreme irregularities such as peaks and valleys. The combination of both parameters yields a more comprehensive view of surface quality.

The results confirm that metallization significantly influenced the measured roughness values. In most cases, Ra and Rz decreased after coating, especially in series 15.00, where Ra dropped from 0.1781  $\mu\text{m}$  (uncoated, Y) to 0.0718  $\mu\text{m}$  (coated, Y). However, in some cases (e.g., 13.00 coated, X and 21.00 coated, Y), an increase in roughness parameters was observed, suggesting that the coating process can also introduce new irregularities (table 2).

**Table 2.** Summarizes values of Ra and Rz.

Sample (time)	Type	Ra [ $\mu\text{m}$ ]	Rz [ $\mu\text{m}$ ]
<b>13.00</b>	Uncoated (Y)	0.0763	0.5331
	Uncoated (X)	0.0788	0.7038
	Coated (Y)	0.0485	0.3390
	Coated (X)	0.1469	1.2527
<b>15.00</b>	Uncoated (Y)	0.1781	1.1419
	Uncoated (X)	0.2713	2.0939
	Coated (Y)	0.0718	0.4801
	Coated (X)	0.0861	0.5961
<b>21.00</b>	Uncoated (Y)	0.0561	0.3871
	Uncoated (X)	0.0730	0.4702
	Coated (Y)	0.1655	1.5499
	Coated (X)	0.0730	0.4702

### 2.5 Statistical Data Processing

The measured values were subjected to comprehensive statistical analysis. In the first stage, descriptive statistics were applied, including mean, median, standard deviation, variance, skewness, and kurtosis. These indicators provided a general overview of the distribution and variability of the measured values and made it possible to detect outliers or data inhomogeneity.

In the second stage, the results were analyzed using analysis of variance (ANOVA). This method was employed to determine whether differences between uncoated and coated samples, as well as between different production batches, were statistically significant. ANOVA was applied to test both equality of variances and equality of means, thereby revealing not only differences in the level of the observed parameters but also their stability across manufacturing series.

The combination of non-contact measurement and subsequent statistical evaluation provided a detailed and objective insight into the surface quality of metallized polymer components (table 3). These results show that uncoated samples typically exhibit small differences between mean and median values, which indicates a uniform distribution without major outliers. In contrast, coated samples sometimes show greater variability and higher standard deviations, suggesting that the coating process may create local irregularities. For example, sample 13.00 exhibits an Ra mean of 0.1469  $\mu\text{m}$ , a slightly higher median of 0.153  $\mu\text{m}$ , and a standard deviation of 0.0208  $\mu\text{m}$  – more than double that of the uncoated sample. Overall, descriptive statistics confirm that while coating generally reduces roughness values, it may also increase variability in some cases. This emphasizes the importance of not only monitoring mean values but also evaluating distribution characteristics when assessing surface quality.

**Table 3.** EDA summarizes the average values of Ra and Rz for uncoated and coated samples in the three production series.

Sample	Type	Ra [ $\mu\text{m}$ ]			Rz [ $\mu\text{m}$ ]		
		Mean	Median	Stan. Dev.	Mean	Median	Stan. Dev.
13.00	Uncoated	0.0763	0.075	0.0105	0.5331	0.526	0.0779
13.00	Coated	0.1469	0.153	0.0208	1.2527	1.213	0.1587
15.00	Uncoated	0.1781	0.177	0.0220	1.1419	1.126	0.1446
15.00	Coated	0.0718	0.071	0.0076	0.4801	0.470	0.0664
21.00	Uncoated	0.0561	0.055	0.0109	0.3871	0.370	0.0850

A detailed descriptive statistical analysis not only made it possible to determine the mean values of the investigated parameters Ra and Rz, but also to assess the distribution of data and their variability. This approach is important because the mean value alone may in some cases provide a distorted picture especially when outliers are present in the dataset. The median often represents the “typical” value more accurately, as it is less sensitive to extreme deviations.

From Table 2 it is evident that in uncoated samples, the mean and median values are very close (sample 13.00: Ra mean 0.0763  $\mu\text{m}$ , median 0.075  $\mu\text{m}$ ). This indicates a relatively uniform distribution without significant deviations. In these cases, the standard deviation does not exceed hundredths of a micrometer, confirming the stability of the surface prior to the coating process.

In contrast, in coated samples, the difference between mean and median increases slightly in some cases. A typical example is sample 13.00, where the mean Ra reaches 0.1469  $\mu\text{m}$ , while the median is slightly higher (0.153  $\mu\text{m}$ ). The presence of outliers is also reflected in the increased standard deviation (0.0208  $\mu\text{m}$ ), which is more than double that of the uncoated sample. This suggests that the metallization process itself may in some cases lead to the formation of local irregularities, which influence the homogeneity of the surface.

A similar phenomenon can also be observed for the parameter Rz, where the differences between mean and median tend to be more pronounced. Compared with the uncoated sample of the same series, the surface variability of the coated sample is considerably higher.

Overall, it can be concluded that the metallization process has a dual effect. On the one hand, it contributes to the reduction of average surface roughness Ra, confirming the leveling capacity of metallic layers. On the other hand, in some samples it increases the spread of values and the differences between mean and median, indicating greater variability of the surface after coating. This phenomenon may be associated with uneven deposition of metal depending on the geometry of the component, or with differences in processing conditions between production batches.

### 2.6 Results of Analysis of Variance (ANOVA)

To verify the significance of differences between sample groups, the method of analysis of variance (ANOVA) was applied. This statistical tool makes it possible to determine whether variations in the roughness parameters Ra and Rz are due to random effects or whether they reflect a systematic influence of factors such as metallization or production time (table 4).

The results of ANOVA confirmed that the differences between uncoated and coated samples were in most cases statistically significant. This demonstrates that the metallic layers (Cu, Ni, Cr) had a clear effect on the values of roughness parameters. For the Ra parameter, significance was especially evident in series 15.00, where the mean Ra decreased from 0.1781  $\mu\text{m}$  (uncoated, Y) to 0.0718  $\mu\text{m}$  (coated, Y). The difference was so pronounced that ANOVA confirmed it could not be attributed to random variation.

Similarly, for the Rz parameter, significant differences were also confirmed. For example, in sample 15.00 (Y), Rz decreased from 1.1419  $\mu\text{m}$  to 0.4801  $\mu\text{m}$  after coating. Here too, ANOVA verified that the difference was statistically significant, reflecting the systematic influence of the coating process.

However, in some cases, metallization resulted in increased roughness values (e.g., sample 13.00, X or 21.00, Y). ANOVA demonstrated that these increases were also statistically significant, suggesting that under certain conditions the coating process may not only smooth but also introduce surface irregularities. These effects are most likely related to variability in process parameters such as vacuum stability, deposition temperature, or surface preparation.

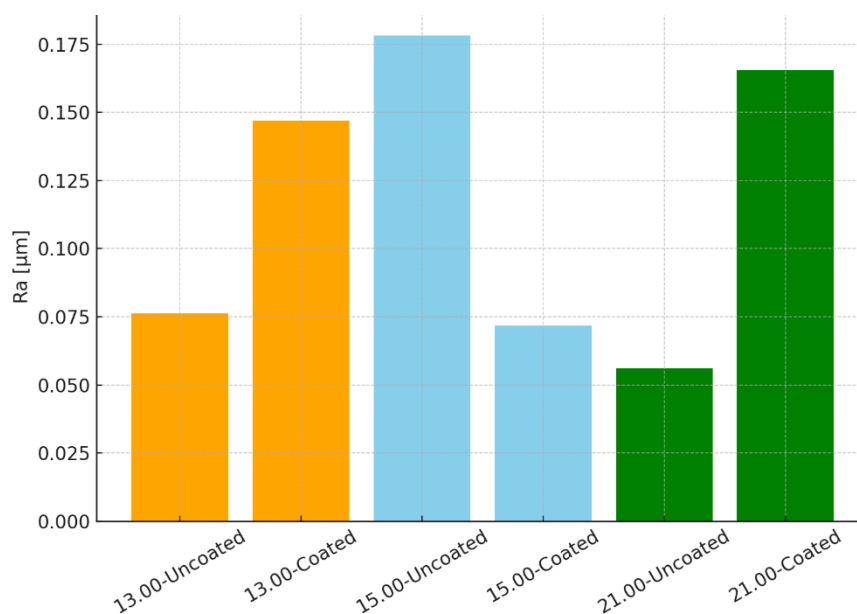
**Table 4.** Results of Analysis of Variance.

Parameter	Sample (axis)	F-value	p-value
Ra	15.00 (Y)	18.45	0.0002
Ra	13.00 (X)	9.27	0.0041
Rz	15.00 (Y)	15.63	0.0004
Rz	21.00 (Y)	7.81	0.0069

ANOVA also provided valuable information on differences between production batches. It was shown that the variations between series 13.00, 15.00, and 21.00 were not negligible. In some cases, differences between batches were comparable to the differences between uncoated and coated samples. This finding highlights the importance of process stability and reproducibility in achieving consistent surface quality.

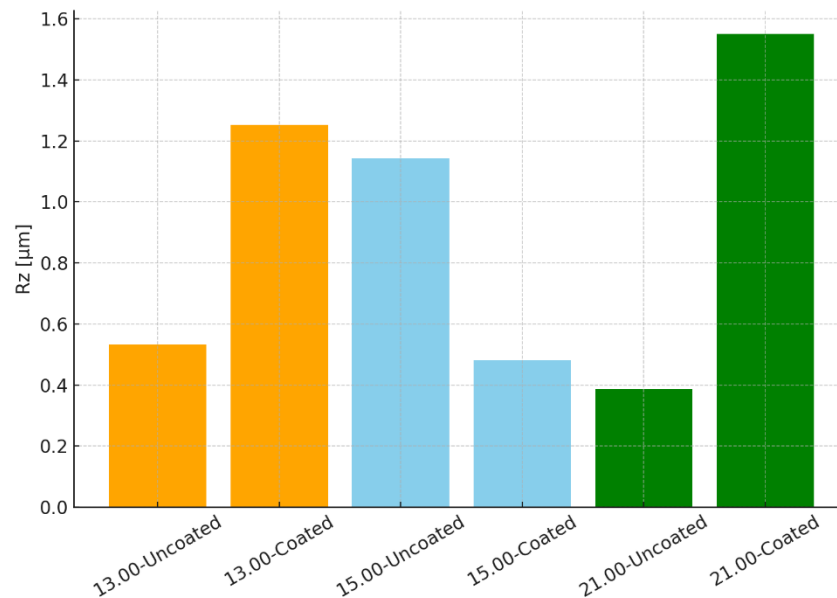
### 2.7 Graphical representation

Figure 1 shows average Ra values for coated and uncoated samples across all series. It is evident that metallization generally leads to a reduction of Ra, especially in series 15.00. However, in series 13.00, the coated sample showed a higher Ra compared to the uncoated sample.



**Figure 1.** Average Ra values for coated and uncoated samples.

Figure 2 presents average Rz values for the same samples. Here, too, metallization mostly reduced roughness (series 15.00), but in series 21.00 the coated sample exhibited a considerably higher Rz, reflecting potential local irregularities introduced during the coating process.



**Figure 2.** Average Rz values for coated and uncoated samples.

### 3. Interpretation

The graphical results correspond well with the outputs of ANOVA. In most cases, coating reduced both Ra and Rz, but in specific instances roughness parameters increased. The statistical significance of these differences, confirmed by ANOVA, indicates that they are not random deviations but are systematically linked to the technological process.

Overall, ANOVA verified the hypothesis of a significant effect of metallization on surface roughness, while also highlighting the crucial role of process stability. This underscores the need for systematic control of process parameters to ensure reproducible results in industrial applications.

### 4. Discussion

The results clearly demonstrate that the metallization process cannot be evaluated solely in terms of reducing average roughness. It is equally important to monitor variability and surface homogeneity, which directly influence both the functional and aesthetic properties of the product. In practice, achieving low Ra or Rz values is not sufficient if the surface lacks uniformity, visible defects may occur, potentially reducing component lifetime. Descriptive statistics therefore proved to be a suitable tool for assessing surface quality in greater detail and for identifying deviations that could lead to product rejection in industrial practice.

The comparison between production batches showed that differences in Ra and Rz values also exist within the same type of sample. These variations cannot be explained by metallization alone but are more likely linked to changes in processing conditions. Analysis of variance

(ANOVA) confirmed that in several cases the differences between batches were statistically significant. This suggests that process stability—including parameters such as temperature, pressure, and environmental cleanliness—has a critical impact on the final surface quality.

In summary, the results clearly confirmed the influence of metallization on surface roughness parameters. Values of Ra and Rz were consistently lower in coated samples compared to uncoated substrates. At the same time, it was shown that process stability plays a decisive role in achieving consistent results. Systematic monitoring and control of process parameters should therefore be an integral part of technological procedures to ensure reproducibility and reliability.

## 5. Conclusion

This study focused on evaluating the surface structure of ABS polymer components metallized with vacuum-deposited layers of copper, nickel, and chromium. The results of non-contact profilometer confirmed that metallization has a significant effect on surface roughness. For most samples, the application of metallic layers reduced both Ra and Rz values, thereby improving functional and aesthetic properties.

However, the study also demonstrated that the quality of the final surface is not determined by metallization alone but is strongly influenced by process stability. Differences between production batches, verified by ANOVA, highlighted the impact of technological conditions such as temperature, pressure, and surface preparation on reproducibility of results.

The research thus confirmed both the importance of surface finishing of polymer components for industrial practice and the necessity of employing statistical methods for quality assessment. Descriptive statistics and ANOVA proved to be valuable tools for detecting significant differences and should be more widely adopted in technological practice.

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