ROUGHNESS MEASUREMENT OPTIMIZATION OF REFLECTIVE SURFACES BY FOCUS VARIATION METHOD

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Abstract: *The quality of the treated surface is one of the key characteristics of each product. The functionality of the workpiece during its exploitation directly depends on the size of the surface roughness. Determining the quality of the machined surface comes down to measuring the roughness amplitude parameters, which can be linear (2D) parameters or surface (3D) parameters. According to the method of collecting data from the examined surface, roughness measurement techniques can be classified into contact (tactile profilometry) and non-contact methods. An example of a non-contact roughness measurement is the focus variation method. In this paper, a device based on focus variation, InfiniteFocus SL, was used to measure the roughness on the workpiece, which has an arithmetic mean roughness Ra less than 260 nanometers. Surfaces that have small micro-geometric irregularities are an issue when sampling with optical methods, due to the appearance of surface reflectivity. Using the L9 Taguchi design of the experiment, the optimal brightness, contrast, and vertical resolution parameters were determined for measuring the Ra, Rz, and Rt roughness parameters. The levels of the factors included in the study were optimized concerning the reference values of the roughness amplitude parameters obtained on the tactile profilometer.*

Key words: Roughness measurement, focus variation, Taguchi design of experiment

1. INTRODUCTION

The quality of the machined surface ensures the functionality of the product during exploitation. In the manufacturing industry, this fact is of particular importance when it comes to responsible components that ensure the relative movement of elements or the correct clearance tolerance of other system elements (Hadžistević et al., 2015; Runje et al., 2019). For example, in medicine, determining the relationship between the quality of the machined surface and its tribological behavior ensures a long working life of the implant (Orošnjak et al., 2016). The quality of the machined surface is defined based on the measured values of the surface roughness. Surface roughness is a set of micro-geometrical irregularities on the surface. These irregularities occur during the processing of the workpiece or may be caused by other influences, e.g. corrosion. Different roughness parameters are used to quantify surfaces. Given the importance of measuring micro-geometrical irregularities, various methods of data collection from the examined surface have been developed. The most commonly used methods for measuring surface roughness are tactile profilometry and optical measuring systems**.** In tactile profilometry, during data acquisition, the probe makes physical contact with the machined surface, and by swiping it, records a profile of a certain length. The use of profilometers is associated with a long data acquisition time and the possibility of scratching the examined surface, but with these methods, there is no issue when measuring reflective and/or transparent workpieces (Leach, 2011).

Measurement systems based on focus variation are devices that have precise lens systems, which enable measurements with different resolutions. The semitransparent mirror directs the beam of light from the source through the optical path of the system, and the lenses focus it on the surface of the workpiece. Depending on the topography of the surface, light rays are reflected differently. All reflected light rays that reach the lens are registered by the sensor. Due to the shallow depth of field of the optical system, only a small part of the surface is sharpened. To map the entire surface, the optical system must move relatively along the vertical *Z* axis concerning the workpiece (Grochalski et al., 2020; Jotić et al., 2023).

During this movement, a constant acquisition of sharpened images of the observed surface is performed, which means that the complete geometry is collected in a satisfactory resolution and sharpness. After that, the algorithm converts the collected data from the sensors into three-dimensional information, point cloud (Runje et al., 2019).

According to Leksycki (2021) trends in metrological analysis of surfaces are focused on the development of optical measuring devices, based on different measuring techniques. Such approaches allow for obtaining a vast amount of information from the examined surface during the measurement. However, devices based on focus variation have difficulties in measuring surfaces with low values of surface roughness like polished workpieces (Giusca et al., 2014) and transparent workpieces.

Also, many factors can affect the accuracy of data acquisition. Some of those factors are brightness and contrast. If the exposure time is too short, a dark image is obtained, conversely, if it is too long, the image is too bright. In such conditions, the device will not collect the data. Along with illumination settings, it is possible to use a polarizer that filters the reflected light from the workpiece. A polarizer can help collect the data from highly reflective surfaces. The intensity of the light in combination with the "ring light" can also affect the final result. The ring light is a hardware piece that can switch on or off segments that emit light. Vertical resolution defines the smallest height difference that can be measured. The values of the vertical resolution depend on the selection of the apparatus (lenses of a certain magnification). If the surface roughness of the workpiece is less than the minimum vertical resolution value for a particular lens, then data acquisition will be difficult or impossible. Data can be collected in Single mode, where roughness parameters are estimated based on one recorded image, or in ImageField mode, where sensor movement in the *XY* plane and a certain range along the vertical *Z* axis are defined. Other factors, which were not considered in this paper, are lateral resolution and data collection in ImageField mode.

In this work, by applying the *L9* Taguchi design of the experiment, the optimization of the influencing factors on data collection was carried out using focus variation. Factors that were included in the study were brightness, contrast, and vertical resolution. Each of the factors was varied on three levels. Reference values for all three measurement locations were obtained on a tactile profilometer. Analysis of variance, ie. by fitting a general linear model for all three outputs from the study, statistically significant factors with a confidence interval of 95% were determined. The study aimed to determine those factor levels that will give the least deviation of the roughness parameters *Ra*, *Rz*, and *Rt* from the reference values.

2. EXPERIMENTAL RESEARCH

The measuring device used in the study is the InfiniteFocus SL, from Alicona Bruker. The working volume of the device is 50 × 50 × 155 mm, and the load capacity of the work table is 4 kg. It can change lenses with different magnification values. Based on the manufacturer's recommended values and the measured reference values of the roughness parameters from the tactile profilometer, a lens with 50x magnification was used in the study. The minimum height of deviations that a lens with that magnification can measure is 20 nanometers. Also, the minimum value of the roughness parameter *Ra* that can be measured with the 50× objective is 0.08 µm. According to the ISO 10360-8:2013 standard, the extended measurement uncertainty of the device when measuring the arithmetic mean roughness of 0.5 µm is U=0.04 µm, with a standard deviation of σ=0.002 µm. Reference values were measured with a Hommeltester T2000 tactile profilometer, using a probe with a tip radius of 5 µm, 0.375 µm lateral resolution, and 0.01 µm vertical resolution. Reference values for roughness parameters were measured at three measuring points on the workpiece. The mean value, in µm, of the obtained results was used as a reference, in Table 1.

Table 1: Reference values of roughness parameters Ra, Rz, and Rt

Ra	*Rz*	*Rt*
0.2527	1.4447	1.593

The Taguchi design of the experiment involved three factors, Table 2. The level of the vertical resolution factor was chosen based on the manufacturer's recommendation and the objective's capabilities. The manufacturer recommends that the vertical resolution value be calculated by dividing the roughness parameter *Rz* by a coefficient from 15 to 30.

Table 2: Factors and Levels in L9 Taguchi Design of Experiment

	Levels		
Brightness [ms]	5.87	7.5	12.7
Contrast	0.4	0.6	0.8
Vertical resolution [nm]	50	70	100

Figure 1 shows the hardware setup of the experiment on the InfiniteFocus SL non-contact measurement system.

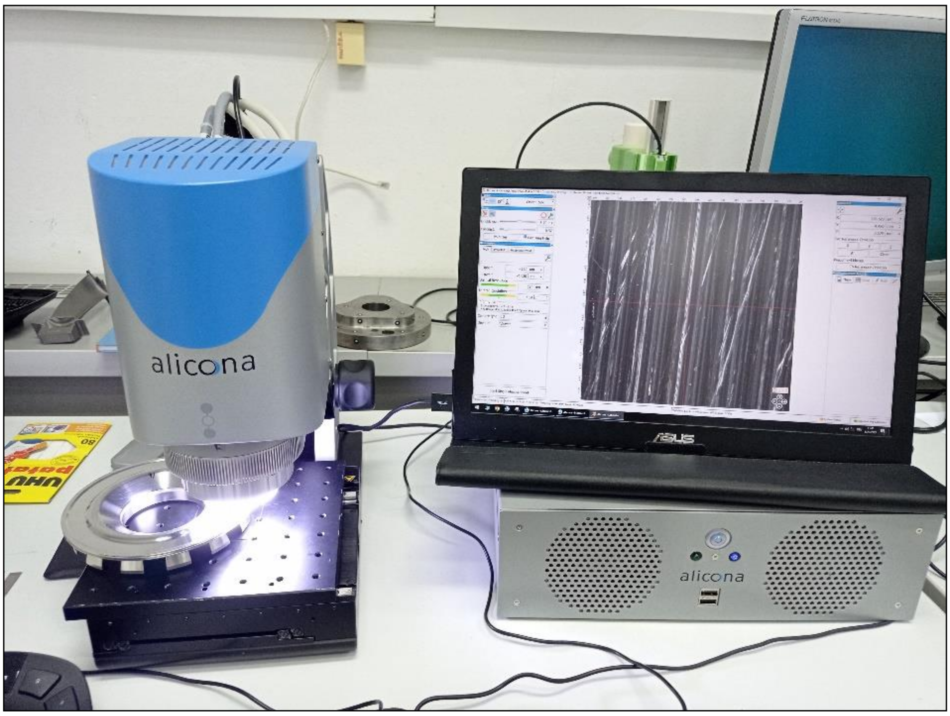

Figure 1: Measurement of workpiece roughness parameters on the InfiniteFocus SL system

3. RESULTS AND DISCUSSION

The data were analyzed using the statistical software Minitab 17. The method used to check the statistical significance of the considered factors is the Analysis of Variance (*ANOVA*). Each value obtained by non-contact measurement was subtracted from the reference value (Table 1), and the residuals were analyzed. The analysis of variance showed that for all three responses, there is not enough data to sufficiently conclude statistical significance at 95% confidence, for chosen factors. It is interesting that the model error for all three parameters is not statistically significant, but that the adequacy of the model is unsatisfactory for all three parameters. The reason for this phenomenon may be the presence of outliers in the collected data, which was determined by the later analysis of the box-plot diagram.
When analyzing the Taguchi design of the experiment, the optimization condition "smaller is better" was chosen, because the residuals of the measured values from the non-contact system were analyzed. The most influential factor for the signal-to-noise ratio is the brightness, followed by the vertical resolution factor, and the least influential factor is contrast. The most influential factor for the Means is brightness, followed by contrast, and the least influential factor is vertical resolution. The main effects plot for mean values and signal-to-noise ratio is shown in Figure 2.

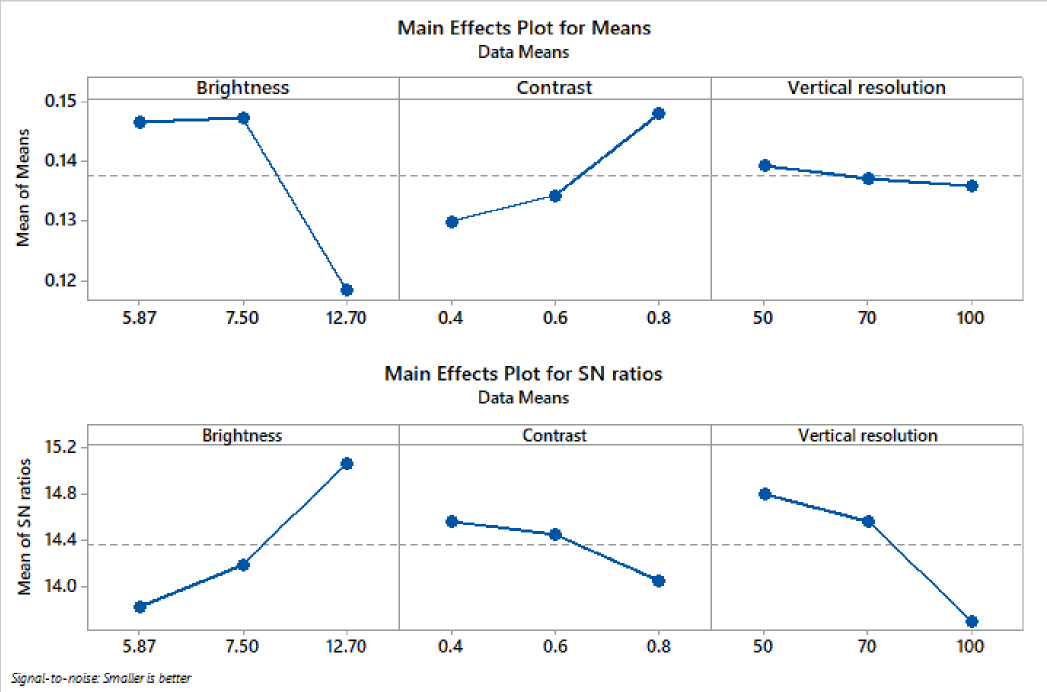

Figure 2: Main effects plot for mean values and signal-to-noise ratio

According to the diagram of the main effects, the optimal combination of factor levels for the S/N ratio is: for brightness choose the highest level (12.7), for contrast choose the lowest level (0.4), for the vertical resolution value choose 50 nm. The optimal combination of factor levels for mean values is as follows: for brightness, choose the highest level (12.7), for contrast, choose the lowest level (0.4), for the vertical resolution value, choose 100 nm.

Factors such as brightness and contrast are highly dependent, and an interaction is expected. This is also confirmed by the interaction diagram, where for all three observed roughness parameters *Ra*, *Rz* and *Rt*, i.e. their residuals appear as intersecting lines on the diagram. Due to limited space, Figure 3 shows the interaction diagram for the *Ra* and *Rz* parameter.

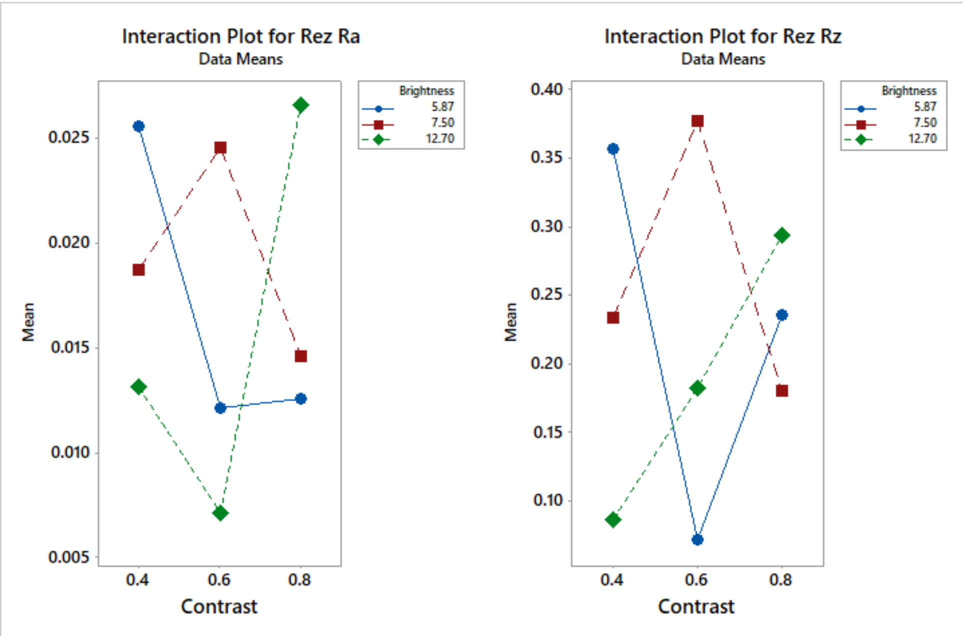

Figure 3: Diagram of interactions of brightness and contrast factors on the roughness parameter Ra and Rz

4. CONCLUSION

In addition to meeting the requirements for dimensional accuracy and geometric tolerances, satisfactory values of roughness parameters are an essential factor for the correct functioning of each product. The focus variation method with the possibility of measuring macro and micro geometrical irregularities on workpieces proved to be an excellent choice when measuring surfaces with submicron values of roughness parameters, with certain advantages over tactile profilometry such as the speed and amount of collected data. In the paper, the Taguchi design of the experiment was carried out, and through the analysis of variance, the main influence diagram, and the interaction diagram, the effects of certain factors on the quality characteristics were shown. For certain values of surface roughness, optimal levels of brightness, contrast, and vertical resolution are given.
Currently, in the industry, the standard for finding optimal parameters is the trial-and-error method (Gauder et al., 2021). This approach is not optimal, and we should strive for the formulation of a global optimization model. Through the possibility of including more factors such as the influence of different ring light settings, polarization, and lateral resolution, it is possible to provide a more comprehensive optimization model, which will be the direction of future research.

5. ACKNOWLEDGMENTS

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6. LITERATURE

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