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Metrological Comparison between Heterogeneous Surfaces and their Imprints

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This article seeks to compare the roughness characteristics of surfaces created through unconventional machining technologies, specifically utilizing plasma and laser. Cuts of different thicknesses of material were taken for this purpose. Furthermore, the article presents an evaluation of surfaces obtained from an impression material SILOFLEX®, followed by the determination of similarities between these impressions and original surfaces. In this work, we mainly aimed to statistically find and determine the differences between the evaluation of surfaces in accordance with ISO 4287, ISO 4288, and ISO 25 178. Next, investigation analysis of the machined and replicated surfaces was done utilizing the contactless profilometer and the follow-up statistical evaluation of measured data from compared surface groups.

Keywords: Surface Structure, Surface Measurement, Non-conventional Technologies, Anova.

1 Introduction

The article mainly seeks to compare surface roughness characteristics of surfaces created through unconventional machining technologies, such as those utilizing laser or plasma. During the manufacturing process, the goal is effective and economical production while holding unto the optimal quality standard. To balance those requirements, it is necessary to start even during the design phase of a given part, for which a blueprint is made in such a way so that the part will dependably fulfil its purpose. However, to perfectly replicate such a blueprint in practice is near impossible. Sizes, geometry, and surface roughness of parts all differ in some way, in real conditions, from prescribed values. Different manufacturing processes leave their imprints on the part and a goal of roughness scanning is to find out if even so, the surface is of sufficient quality for its purpose. [1,2]

Surface measurement might be problematic in some cases. High-volume parts, inaccessible surfaces, etc. might make surface evaluations impossible. [1] In these cases, the obvious solution is to use surface replicas through the utilization of impression materials. These materials have their specific requirements. They should be able to copy the relief at the level of micrometres, have sufficient toughness to prevent the alteration of the imprint, and also need to be easily shapeable and separable. [2,3]

Data evaluation is the most important analytical step as if done improperly or not at all, obtained data are of little informative value. Statistical analysis can uncover errors, find out the possible future direction and detect similarities based on measurements or observation of common events. Due to this, all presented data were tested using the hypothesis test on normal utilizing the Anderson-Darling test, where for all data the normal was not rejected. Furthermore, the Grubbs outlier test was done. After the data investigation, an F-test for homogeneity of variances was done. Every time, the sample and its imprint were compared. [4,5]

The follow-up comparison between technologies was done between the input and output part of the cut, due to their most marked differences. All data from those areas were tested fully in accordance with the ANOVA methodology, which is a method of choice for this comparison.

2 Materials and Methods

Samples were made from 1.0036 steel. It is unalloyed steel with an at max. 0.17 % of carbon, and other property-influencing elements, such as sulfur, nitrogen or phosphorus, content. It is weldable steel, suitable for different parts of machines or constructions. Samples from this steel were cut utilizing technologies of CO_2 laser and plasma cutting which are described further below in parts 2.1 and 2.2. The board thickness used for these samples was selected to be 5, 10 and 15 mm, as those are manufacturing standards, from which square samples with the size of 100 x 100 mm were cut. To achieve structural homogeneity during the application of both technologies, samples were always cut out of a single board utilizing both technologies. [6,7]

2.1 Laser machine

TruLaser 3030 machine, made by TRUMPF GmbH + Co. KG was utilized to cut parts through a laser beam. This machine has an output of up to 3200 W and the maximum processable size of the board is 1500 x 3000 mm. It can utilize two types of cutting gasses, specifically nitrogen useful for cutting aluminium and oxygen for the steel. Maximum cutting depth depends on the material, where it can cut through up to 20 mm of steel while just up to 8 mm for aluminium and its alloys. The machine is cooled by two ionized water circuits. Cut accuracy is ± 0.1 mm. The cutting speed was optimized for each experiment:

- board 5 mm – cutting power 2500 W and cutting speed 2.8 m/min
- board 10 mm – cutting power 2800 W and cutting speed 1.3 m/min
- board 15 mm – cutting power 2900 W and cutting speed 0.8 m/min

2.2 Plasma machine

Plasma cutting was performed utilizing the machine from CYBERTRONIC Robotics s.r.o. It consists of the CYBERTRONIC-made table and the ALFA – INPEGAS 101 aggregator. Same size, 1500 x 3000 mm, boards as in laser machine can be processed. This machine can be utilized to both cut and weld. Materials appropriate for cutting through this technology are steel, stainless steel, or aluminium. The machine can cut materials up to 20 mm thick and its accuracy is ± 0.6 mm. As the cutting gas, compressed air was used. Cutting conditions were also optimized according to the given experiment:

- board 5 mm – current on the aggregator 52 A and cutting speed 1.7 m/min
- board 10 mm – current on the aggregator 72 A and cutting speed 0.95 m/min
- board 15 mm – current on the aggregator 80 A and cutting speed 0.68 m/min

Table 1 shows the sample designations. This is mainly evaluated by us the parameter Ra - the mean arithmetic value of surface roughness according to ČSN EN ISO 4287. The parameter Ra is the most frequently used parameter to evaluate the quality of surfaces. It is also a parameter suitable for the statistical evaluation of data.

***Tab. 1** Sample designations*

Parameter	Technology	Thickness (mm)	Determination	Determination imprints
Ra	Laser	5	Ra_P_5	Ot_Ra_P_5
Ra	Plasma	5	Ra_L_5	Ot_Ra_L_5
Ra	Laser	10	Ra_P_10	Ot_Ra_P_10
Ra	Plasma	10	Ra_L_10	Ot_Ra_L_10
Ra	Laser	15	Ra_P_15	Ot_Ra_P_15
Ra	Plasma	15	Ra_L_15	Ot_Ra_L_15

2.3 Sample imprints

To manufacture an imprint, SILOFLEX©-made products were chosen. As a sample substrate, a silicon-based imprint material Siloflex Plus Putty was used, for the imprint itself a Siloflex Plus Light, with its high-volume stability, was chosen. As a curing catalyst a Siloflex Plus catalyst was used.

The first step in the imprint manufacturing process was to make base plates from the Siloflex Plus Putty. For easy mould release of boards, plastic base plates were chosen. Next, a certain amount of imprint material, usually enough to make 4 samples, was taken and the catalyst was added in in the prescribed ratio. They were well mixed together by hand and after the, by the manufacturer, listed minute of the processing, the matter was spread on the substrate and inserted in were wooden stakes to create the grooves for the imprint. Following this was a sample preparation for the imprint manufacturing. A to-be imprinted surface was carefully cleaned and degreased. Afterwards, the samples were spread out and secured through steel profiles and magnets so that they would not move during the imprinting and the surface structure of the imprint would not be disturbed.

2.4 Surface scanning

To scan the surface an optical profilometer NEW VIEW 8000 from ZYGO® was used. It utilizes CSI technology and can measure both transparent and non-transparent materials. [8] Due to the limited size of the sampling surface, each sample had to be scanned several times. As it is a 3D type of machine, it was necessary to make cuts on measured surfaces to obtain the required values. Each sample was measured from the top, where the beginning of contact between the cutting beam and material was, to the bottom, where the laser or plasma beam exited through the board. Preservation of top to bottom scanning methodology was important due to the changing quality and the character of the cut in relation to its thickness. Figure 1 shows the software visualization of the scanned surface. [9]

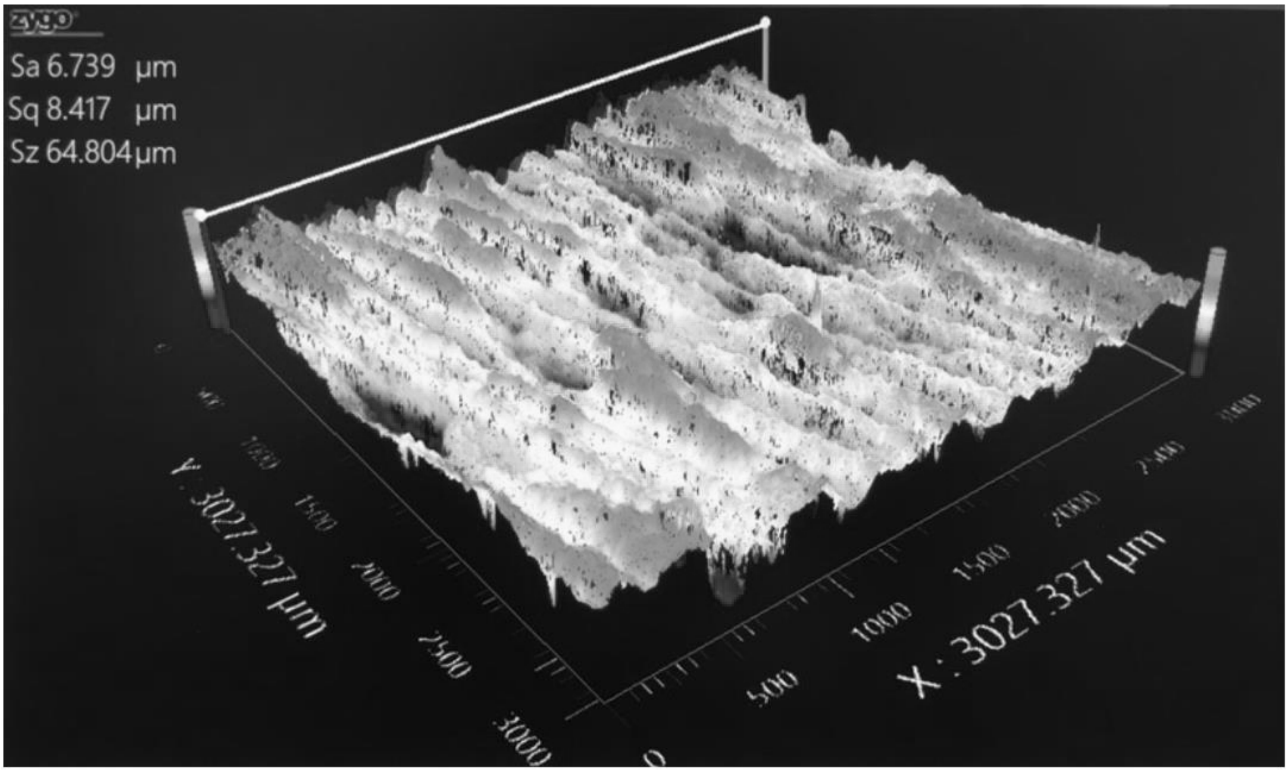

Fig. 1 *3D software visualization of the scanned surface*

2.5 Qualitative evaluation of results

Data were first evaluated qualitatively before their statistical evaluation. For this purpose, the digital microscope of the Leica brand was utilized at 50x magnification. The reason for qualitative evaluation was the surface defect control according to ISO 4287 and the evaluation of visual characteristics of the cut.

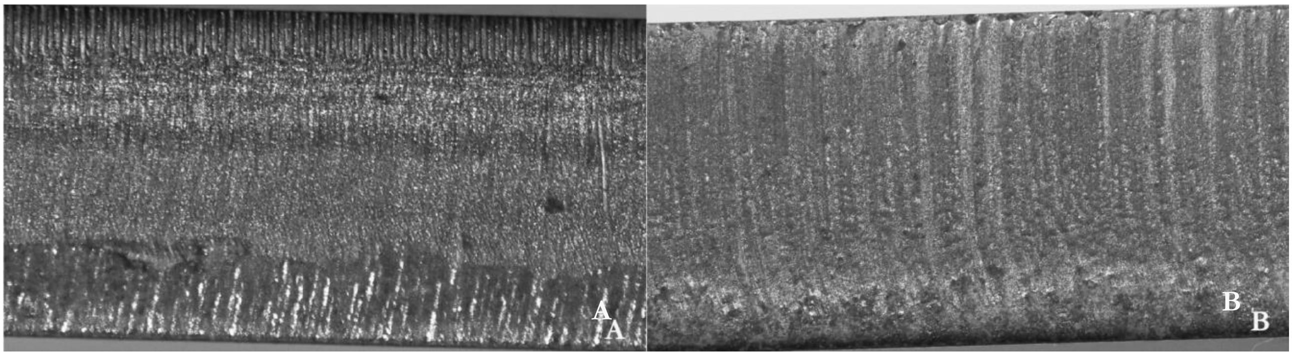

Fig. 2 *Surface of the 10 mm thick sample A) laser-cut B) plasma cut*

In Figure 2 cuts on 10 mm thick samples made by both technologies can be seen. Noticeable for laser cutting are the grooves on the top side of the material, where the beam started to penetrate the material, perpendicular to the cutting direction. They however apparently disappear in the middle and reappear again only at the exit. Entrance grooves are most likely caused by the bad focus of the laser beam. The cut is relatively rough due to this; however, it is not noticeably tilted. Comparatively, plasma left traces of its passing in the full bulk of the cut surface. On the other hand, traces are not so deep, and the surface is smoother compared to a laser cut. The cut is however quite tilted, which is caused by the conical shape of the plasma beam. This tilt is significantly affected by the depth of the cut, where the thinner sample is less affected than the thicker ones.

2.6 Exploratory data analysis EDA

Before similarities between technologies could be analysed, measured data of the samples and imprints had to be examined to find out what type of distribution they exhibit, if they contain gross errors and if the match of variances will be not rejected. During the analysis, it was necessary to investigate each sample file separately. Since for steel samples, two technologies and three samples of different thicknesses are compared, it was necessary to analyse each sample file on normality and absence of gross errors, so that later an ANOVA method, which requires fulfilment of those criteria, could be used.

First, an Anderson-Darling normality test was used, on which baser the hypothesis theory determines if we reject or not reject the standard distribution. The hypothesis setup for the normality test is:

- H0: the set comes from the normal distribution
- Ha: the set comes from other than the normal distribution
- these hypotheses are tested at the confidence interval 1- α = 0.95

As can be seen in Tab. 2., we present a set of values necessary for further investigation of the data. Averages, standard deviation (St. dev.), and p-values here serve to evaluate the normality of sample files. N is the number of measurements.

Tab. 2 *Results of the normality test for steel samples*

Sample	N	Average (μm)	St.dev	p-value	Normality
Ra_P_5	10	8.03	2.75	0.21	Not rejected
Ra_P_10	10	8.53	1.52	0.48	Not rejected
Ra_P_15	10	9.58	1.63	0.21	Not rejected
Ra_L_5	10	6.78	2.98	0.32	Not rejected
Ra_L_10	10	6.04	1.92	0.90	Not rejected
Ra_L_15	10	12.40	4.69	0.11	Not rejected

Tab. 3 *Results of the normality test for imprints*

Sample	N	Average (μm)	St.dev	p-value	Normality
Ot_Ra_P_5	10	8.46	1.82	0.22	Not rejected
Ot_Ra_P_10	10	8.21	1.98	0.92	Not rejected
Ot_Ra_P_15	10	9.06	1.80	0.13	Not rejected
Ot_Ra_L_5	10	6.56	1.78	0.15	Not rejected
Ot_Ra_L_10	10	7.67	1.79	0.72	Not rejected
Ot_Ra_L_15	10	11.64	4.73	0.06	Not rejected

Based on measurements for each sample, the p-value results were >0.05 in the confidence interval 1 - α = 0.95. Therefore, it is not possible to reject the null hypothesis that selected values Ra come from the standard distribution for all steel samples.

2.7 Outliers tests

Before the start of conformity of samples with imprints testing, it is necessary to test, if sample files do not contain gross errors. For this, the Grubbs outlier test, which thanks to the hypothesis theory determines if the outliers are only extremes or gross errors, was used. The hypothesis setup for the outliers test is:

- H0: lowest and highest values are only extremes, they are not outliers
- Ha: lowest or highest value is an outlier or a gross error
- these hypotheses are tested at the confidence interval 1- α = 0.95

In Tab 4. and 5. we can observe the results of the Grubbs outlier test for both steel samples and their imprints. Both minimum and maximum values are presented there. Considering that no p-value was smaller than 0.05, the null hypotheses were confirmed, and minimum and maximum values are in all cases just extremes and not gross errors.

Tab. 4 *Results of the Grubbs outlier test for steel samples*

Sample	Min (μm)	Max (μm)	p-value	Excluded values
Ra_P_5	4.12	10.5	0.43	no
Ra_P_10	5.93	10.59	0.57	no
Ra_P_15	7.4	11.37	0.89	no
Ra_L_5	4.54	9.22	0.17	no
Ra_L_10	3.33	9.56	0.34	no
Ra_L_15	8.04	20.72	0.45	no

Tab. 5 *Results of the Grubbs outlier test for imprints*

Sample	Min (μm)	Max (μm)	p-value	Excluded values
Ot_Ra_P_5	5.13	10.41	0.10	no
Ot_Ra_P_10	5.53	11.14	0.71	no
Ot_Ra_P_15	6.51	10.89	0.96	no
Ot_Ra_L_5	4.92	9.82	0.13	no
Ot_Ra_L_10	4.55	10.21	0.52	no
Ot_Ra_L_15	7.26	20.11	0.43	no

After the performed exploratory data analysis, we can state, that all data come from standard distribution and do not contain any gross errors. It is now possible to do an f-test and t-test in order to compare each sample with its imprint.

2.8 F-test

This test shows if the deviation of Ra values of the surface of sample and imprint differs statistically significantly or insignificantly. The hypothesis setup for the F-test is:

- H0: variance of variables differs statistically insignificantly: $\sigma Ra\ 2\ \_P\_x = \sigma Ra\ 2\ \_L\_x$
- Ha: variance of selections differs statistically significantly: $\sigma R2a\_P\_x \neq \sigma Ra\ 2\ \_L\_x$
- these hypotheses are tested at the confidence interval 1- α = 0.95

Tab. 6 *Results of the F-test for the match between steel parts and imprints*

Samples	St. dev Steel	St. dev Imprint	Bartlet's test p-value	Levene's test p-value	Agreement
Ra_P_5 – Ot_Ra_P_5	2.75	1.82	0.55	0.27	Yes
Ra_P_10 – Ot_Ra_P_10	1.52	1.98	0.64	0.65	Yes
Ra_P_15 – Ot_Ra_P_15	1.63	1.80	0.71	0.85	Yes
Ra_L_5 – Ot_Ra_L_5	2.98	1.78	0.29	0.13	Yes
Ra_L_10 – Ot_Ra_L_10	1.92	1.79	0.83	0.78	Yes
Ra_L_15 – Ot_Ra_L_15	4.69	4.73	0.98	0.91	Yes

Bartlet's test, which is used for data with standard distribution was used here. In accordance with confirmed normality, we can consider the result valid. The second test is Levene's test, which is not so sensitive to compliance with normalcy as Bartlet's, therefore in the case where normality was mistakenly accepted somewhere, it would be conclusive instead. As can be seen in Tab. 6., the p-value for comparison between samples and their imprints was higher than 0.05 in all cases and both tests. We can therefore conclude that difference in standard deviations is statistically insignificant.

2.9 t-test

After performing F-tests, which in all cases confirmed equality of variances of Ra value for imprints and samples, the t-test, which evaluates if averages of compared samples differ significantly or insignificantly, can be performed. The hypothesis setup for the t-test is:

- H0: set averages differ statistically insignificantly: $\mu Ra\ 2\ \_P\_x = \mu Ra\ 2\ \_L\_x$
- Ha: set averages differ statistically significantly: $\mu Ra\ 2\ \_P\_x \neq \mu Ra\ 2\ \_L\_x$
- these hypotheses are tested at the confidence interval 1- α = 0.95

Tab. 7 *Results of the t-test for comparison between steel samples and imprints*

Samples	Average Steel (μm)	Average Imprint (μm)	Difference of Averages (μm)	p-value	Agreement
Ra_P_5 – Ot_Ra_P_5	8.03	8.46	0.43	0.74	Yes
Ra_P_10 – Ot_Ra_P_10	8.53	8.21	0.45	0.57	Yes
Ra_P_15 – Ot_Ra_P_15	9.58	9.06	0.52	0.53	Yes
Ra_L_5 – Ot_Ra_L_5	6.78	6.56	0.22	0.88	Yes
Ra_L_10 – Ot_Ra_L_10	6.04	7.67	0.40	0.08	Yes
Ra_L_15 – Ot_Ra_L_15	12.40	11.64	0.76	0.74	Yes

Results of the t-test for compared steel part and its imprint can be seen in Tab 7. Although all averages were different, on basis of p-values, which are higher than 0.05, we can conclude that with the probability of 1 - α = 0.95 Ra values of imprints and original parts are comparable.

2.10 Cluster analysis

Even though it was proven that differences between parts and their imprints are statistically insignificant it is possible to confirm this agreement using the cluster analysis. This analysis can evaluate data compliance and evaluate their similarities. If previous conclusions are correct and imprints are similar, cluster analysis should then correctly assign an imprint to the part from which it was taken and determine their percentual degree of the match. As was assumed, the cluster analysis correctly sorted out part-imprint pairs in accordance with thickness and the technology used, as can be seen in Figure 3. This confirms the conclusion that imprints credibly copied the original surface and are therefore appropriate for imprinting the surface roughness. In Figure 3 we can see other possible groups, which cluster analysis provided, these however have no statistical significance and are only random similarities between data sets.

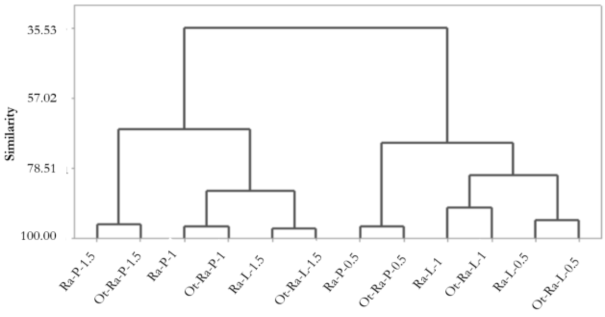

Fig. 3 *Cluster analysis*

2.11 ANOVA

During the qualitative evaluation, it became apparent that the biggest difference between technologies is in the area of entrance and exit of the beam. The following evaluation will therefore compare those places in-between technologies to find out if this supposition will be confirmed by the statistical analysis. Samples have been compared based on their thickness, as with thickness increases also visible differences between samples. For comparison, the one-way ANOVA methodology will be utilized. For evaluation, 10 values on the surface 3 mm from the edge of the cut were measured. The hypothesis setup for the ANOVA is:

- H0: effect of the technological factor is null, its influence over the Ra parameter at the entrance part of the cut is statistically insignificant
- Ha: effect of the technological factor is non-zero, its influence over the Ra parameter at the entrance part of the cut is statistically significant
- These hypotheses are tested at the confidence interval level of 1- α = 0.95

Tab. 8 *Results of the ANOVA methodology for the difference between technologies at the entrance part of the cut*

Thickness	Sample	N	Average (μm)	St. dev	95 % CI	p-value
15 mm	Z_Ra_P_15	10	9.95	1.80	(8.351; 13.220)	0.54
	Z_Ra_L_15	10	10.79	1.19	(7.520; 12.390)	
10 mm	Z_Ra_P_10	10	7.93	1.84	(5.499; 10.622)	0.93
	Z_Ra_L_10	10	8.06	1.31	(5.370; 10.490)	
5 mm	Z_Ra_P_5	10	8.07	0.45	(5.478; 9.379)	0.06
	Z_Ra_L_5	10	7.42	1.56	(8.117; 12.018)	

Tab. 8 presents the results of the ANOVA methodology, which was done independently for each thickness of the sample. N is the number of measurements. As can be seen, the p-value > 0.05, therefore, we do not the reject null hypothesis – at the entrance part of the cut is the influence of technology on a Ra parameter statistically insignificant.

Tab. 9 *Results of the ANOVA methodology for the difference between technologies at the exit part of the cut*

Thickness	Sample	N	Average (μm)	St. dev	95% CI	p-value
15 mm	K_Ra_L_15	10	10.72	0.80	(12.81; 23.91)	0.04
	K_Ra_P_15	10	18.09	3.02	(4.63; 15.73)	
10 mm	K_Ra_L_10	10	5.98	0.69	(5.06; 8.44)	0.02
	K_Ra_P_10	10	9.82	1.07	(8.25; 11.63)	
5 mm	K_Ra_L_5	10	5.13	1.63	(3.07; 8.91)	0.74
	K_Ra_P_5	10	5.98	2.01	(3.36; 7.38)	

In Tab. 9. are presented results of the ANOVA methodology done separately for each thickness. As can be seen, the p-value in 15- and 10-mm thick samples is lower than 0.05, we can therefore reject the zero hypothesis in favour of an alternative one. This means that for these samples, the used technology has a statistically significant effect on the Ra parameter. For 5-mm samples the p-value > 0.05, it is therefore not possible to reject the null hypothesis that says that the influence of technology on the Ra parameter is statistically insignificant. This would mean that the technology does not affect the Ra parameter.

3 Conclusion

This article focuses on the comparison between surface roughness of different surfaces created through unconventional machining technologies, specifically plasma and laser.

Samples include six steel parts and six imprints. Steel parts were cut out using plasma and laser beams from sheets 5, 10 and 15 mm thick. Imprints were created using the imprinting material SILOFLEX and scanned afterwards. For this, a contactless profilometer ZYGO NEWVIEW 8000, which scanned the surface of the sample in the 3 x 3 mm area, was utilized. Obtained scans had characteristics of the 3D map of the scanned surface on which, in certain spots, cuts were created to obtain the required Ra parameter. After securing the data an evaluation of results followed. First, steel samples were compared using magnified photos, where welds on the surface became apparent. Plasma cut samples were smoother, but with the increase in thickness, tilt rose too. Laser-cut samples had significant grooves on their surfaces, created due to the bad focus. Next, surface profiles were compared and significant differences between the entrance and exit parts of the beam could be observed. At the entrance part, there appeared a higher number of profile elements with a smaller difference in size. On the contrary, at the exit, the profile was more monolithic but with higher differences.

Statistical evaluation of data followed. First, samples and their imprints were compared. All data sets were tested on normality using the Anderson-Darling test, where for all data, normalcy was not rejected. Next, the Grubbs outlier test was done, where the assertion that outliers are only the extremes, and not gross errors, was accepted. After data investigation, the F-test was performed to find out similarities between variances. Compared was always part and its imprint. In all cases, it was not rejected, that variances differ statistically insignificantly. After finding that variances match, the t-test, evaluating the statistical significance of the difference between averages, was performed. Here in all cases were the differences between averages of parts and imprints evaluated as statistically insignificant. The assertion about the match between parts and their imprints was finally confirmed by the cluster analysis, which recognized similarities between data sets and sorted them out correctly. A follow-up comparison between technologies was done between the entrance and exit parts of the cut as it was here where the difference between values was most noticeable. All data from those areas were tested fully in compliance with the ANOVA methodology, which was the method of choice for this comparison.

Parts were compared through the one-way ANOVA methodology according to sample thickness. At the entrance part of the cut was the difference in Ra parameter evaluated as statistically insignificant for all thicknesses, which was afterwards confirmed by two-way ANOVA methodology, which evaluated both factors of thickness and technology as statistically insignificant. On the contrary, for the exit part of the surface was the surface quality for the 10- and 15-mm samples evaluated as different between technologies. Surfaces of 5 mm samples were evaluated as similar; the effect of technology was therefore statistically insignificant. Follow-up two-way ANOVA confirmed that the factor of thickness is statistically significant in this case, however, the effect of technology was evaluated as insignificant, which was likely caused by similarities between 5 mm samples. The main goal of the two-way ANOVA was however the combination of both factors, which was evaluated as statistically significant. We can therefore assert, that for thicker samples, it is necessary to choose technology based on quality requirements as both provided different quality of the cuts.

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