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Comparative analysis of the results of an experimental study with basic equipment and a specially made one to the INSIZE ISR - C002 roughness tester

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Abstract. **The present research presents a comparative analysis between experiments conducted with basic equipment for a portable INSIZE ISR - C002 roughness tester and a specially made for the purpose attachment to the device. An analysis is made of the proposed basic device for working with a portable roughness tester INSIZE ISR - C002, and its shortcomings have been determined. In order to facilitate the operator's work with the device and obtain more accurate results, a special device is developed. It is designed using CAD/CAM products and manufactured using additive printing (3D printing). The additive printing technology used reduces its cost. The manufactured device is analyzed and its advantages and disadvantages are determined. Experiments are conducted with both devices and a comparative analysis of the obtained results is made. An analysis of the measurement system (MSA) is made, through which the results of the conducted experiments were analyzed. The comparative analysis shows a number of advantages of the new device compared to the basic one, which provide a basis for the formulated conclusions and recommendations.**

Keywords: additive printing, basic equipment, comparative analysis, experiments, fixture, measurement System Analysis (MSA), roughness tester, surface roughness.

I. Introduction

In recent years surface texture were recognized as being significant in many fields. In particular the surface roughness is an important factor in determining the satisfactory performance of the workpiece in engineering applications and the surface roughness were found useful in machinetool monitoring[1].

The performance of an engineering product depends on a number of parameters. Roughness of the surface is one of those parameters that have a significant impact on machined products. Roughness evaluation methods are divided in two basic groups: Qualitative assessment methods and Quantitative assessment methods. Quality assessment methods measure the surface roughness by comparing achieved roughness with roughness gauges. Quantitative assessment methods, in turn, are also divided into two groups: contact methods and non-contact methods. Contact methods assess the resulting roughness using devices called roughness tester, profilographs and profilometers. Non-contact measurements are carried out mainly using microscopes and laser interferometers.

There are numerous parameters for surface roughness that can be used. They correspond to the geometrical characteristics of the workpiece. These parameters are defined and can be found in many standards like SIST EN ISO 4287:2000/AC:2008[2]. The correct choice of filtering length also knows as cut-off length, lr, determines the surface roughness profile. The parameters of the roughness profile are also called surface heights. The roughness parameters can be calculated from the roughness profile after it is filtered. Figure 1 shows a well known surface roughness profile. The assessed length ln is calculated using integral multiplication method of the break length. The highest points of the evaluated profile at the most positions x could be retrieved by a general

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function that describes the surface mathematically. In general, surface profiles that were measured with a roughness tester are digitized. The discrete points (x_i, I = 1, ...n) with an increment Dx and corresponding surface roughness heights (z_i, i = 1, …n) can be used to describe the surface roughness profiles [3]. The most commonly used surface parameters are also defined below. The parameter Ra is an arithmetical average of all surface heights in the measured field, also known as center line average of the surface roughness heights (CLA), and is calculated as [3]:

$$Ra = \frac{1}{lr}\int_0^{lr} |z(x)| dx \qquad (1)$$

Rq(RMS) is calculated as the root mean square of surface roughness heights, i.e [3].

$$Rq = \sqrt{\frac{1}{lr}\int_0^{lr} |z(x)^2| dx} \qquad (2)$$

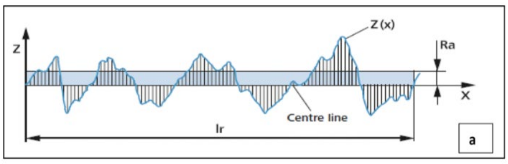

Fig 1. Method of measuring surface roughness Ra [4].

Another commonly used roughness parameter is Rz, which is also called ten-point height. This parameter is more sensitive to occasional high peaks or deep valleys than R_a. It is defined by two methods according to the definition system. The International ISO system defines this parameter as the difference in height between the average of the five highest peaks and the five lowest valleys along the assessment length of the profile [5].

It is calculated as shown on formula (3):

$$Rz = \frac{(P_1+P_2+P_3+P_4+P_5)-(V_1+V_2+V_3+V_4+V_5)}{10} \qquad (3),$$

where:

P_1 to P_5 are the highest five peaks measured on the base line,

V_1 to V_5 are the deepest five valleys measured on the base line.

Fig. 2 shows the definition of the parameter Rz.

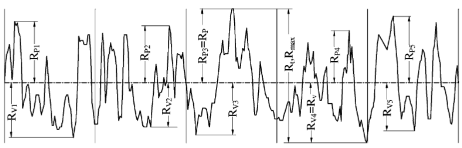

Fig 2 . Ten-point height surface roughness [5].

Measurement of the roughness and determination of the statistical properties of surfaces are significant in many fields of science and engineering. One of the most widely used techniques of surface roughness is probably the mechanical profilometer. With this instrument, the surface is lightly and directly traced by a narrow diamond stylus, which produces a time-varying voltage input proportional to the height of the surface profile. The stylus-type profilometer can surely give true information of the surface profile in the width of the stylus tip is small compared with the lateral size of the surface irregularities [6].

These are the most used surface roughness parameters. Regardless of the measurement method, roughness control devices are divided in two types: stationary and portable. In this current study a portable roughness tester INSIZE ISR - C002 is used. This roughness tester evaluates the measured roughness through the Ra parameter, but it can also show the value of the other roughness parameters. Its basic equipment was analyzed, and an additional device is developed to work as a static instrument. Portable tools for measuring surface roughness are with high accuracy, and are able work in different kind of production environments, and their basic equipment do not allow them to perform their full capacity compared to their use with static equipment. This issue complicates the and requires more preparation time to carry out the measurement and could worsens the accuracy of the results.

The paper presents a developed device which facilitates the work of the roughness tester in dynamic environment, with the use of composite materials and technology for additive (3d) printing. The researches made in a previous paper shows that there is no simular existing device for basing and adjusting to this portable profilometer, but the additive printing technologies are accessible and reliable enough for this task.

The results were evaluated using measurement system analysis (MSA). MSA is an analysis that uses measurement data to evaluate the performance of a manufacturing process. For instance, the decision for adjustment a manufacturing process is commonly based on the measurement data. The data or some of the statistic which are calculated from, are compared with the statistical control limits corresponding to the process. If the comparison indicates that the process is out of the statistical control, an adjustment is made. Otherwise, the process will be allowed to run without any adjustments [7].

The accuracy of the measurement device is defined as its ability to provide output signal close to true value. Accuracy is a more complex and significant problem. The influence of repeatability and particular operators` contribution must not be neglected. The influence of these effects on the measurement method described as R&R (Repeatability and Reproducibility). Performing R&R analysis it is necessary to consider the total nature variability that includes repeatability, reproducibility, variability of parts, and mostly the variability of one part, or the variability from allowed tolerance range [8].

The paper represents an adaptation of MSA to evaluate and compare the results between the basic equipment and the specially designed device. The above makes the study undoubtedly relevant, as there is no evidence of such a device and analysis in the sources examined.

II. MATERIALS AND METHODS

A. Materials

The experimental studies were conducted in a laboratory environment at controlled room humidity and temperature. The measured parts were shafts used in the manufacture of electric motors. The drawing of the same is shown in Fig. 3 with the indicated roughness by parameter Ra.

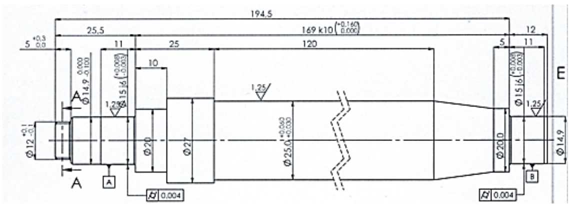

Fig 3. Measured detail

- Analysis of the roughness tester

In this chapter, an analysis of the INSIZE ISR - C002 portable roughness tester and its basic equipment is made, identifying their pros and cons. Fig. 4 illustrates the portable surface roughness tester.

The portable roughness tester “INSIZE ISR - C002” is able to measure the roughness a wide variety of parameters like: Ra, Rq, Rz, Rp, Rt, Rv, R3z, R3y, Rs, Rz (JIS), Rsk, Rp, Rsm, Rsk, Rvk, Mr1, Mr2, Rmax, Ry (JIS), the range is 160µm, the speed is 0.5mm/s, 1mm/s, Memory can save up to 100 measurement results, with weight of 400g, and dimensions of: 141x55x40mm [9].

Fig 4 . Portable roughness tester INSIZE ISR – C002 [9].

Fig. 5 shows the roughness tester with his basic equipment while measuring. The basic equipment includes front mount (1) and back mount (2), which are used to adjust the height and the level of the sensor on the measured detail. The bolts on the from mount are quite loose, as a result adjusting the level and the height of the sensor takes a lot of time and it is not as accurate as it should be.

Fig 5 . Basic setup

The advantages:

- Ergonomic form;
- Easy to use;
- Fast and accurate measurements;
- Easy connections to computer;
- Build in memory up to one hundred measurements;

The disadvantages:

- Basic equipment is making the device hard to use as static roughness tester;
- The additional device for static use is expensive;

The development of a device for mounting the profilemeter would lead to easy positioning, and will increase the ability to measure. Such a device would improve the results and will facilitate the work of the operator.

- Design of the device

The newly developed device must meet all the following requirements:

- Not to obstruct the operations during measurement;
- To be easily mounted on different surfaces;
- To be suitable for additive printing;
- To allow the adjustment of the device and its better stability;
- To ensure better accuracy;

The 3D model of the device designed using SolidWorks is shown at fig. 6. The tool is designed according to the geometry of the roughness tester and its features, and it facilitates the basing and brings the profilometer to ready for measurement. The device an assembly of: a base (1) that holds the roughness tester is, a block that is used for fastening the device to a magnetic stand (2), locking bolts (4) and a bolt with an adjusting nut (3). The base of the produced device is to ensure the stillness without restricting the movements of the sensor. The block (2) is used to mount the device to the magnetic stand.

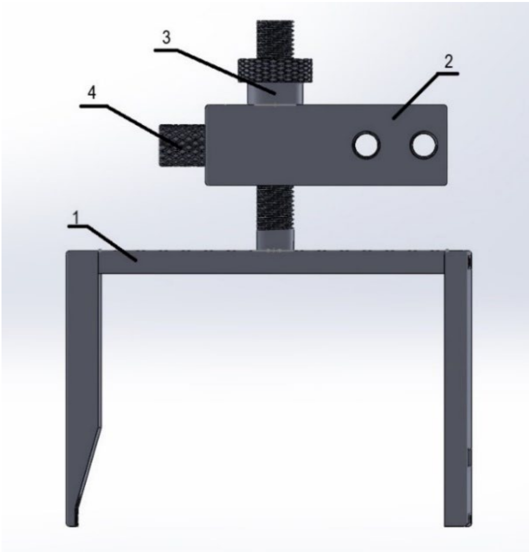

Fig 6 . 3D model of the designed equipment

The development of the technology in the recent decades allows us to use additive (3d) printing technologies. This technology allows us to develop prototypes and devices with different types, shapes, and sizes, easy, and cheap. There is a great variety of materials that can be used in these technologies, and they allow the selection of a suitable material that meets the characteristics and requirements of the 3d model. The developed device is shown on fig.5, and is made by using FDM (fusion deposition modeling), a technology that builds the model layer by layer. Fusion Deposition Modeling (FDM) is one of the most investigated 3d printing methods, because of its ease of use, the low-cost, and because it is applicable for the processing of thermoplastic polymers like: PLA, PETG, PS, Nylon, ABS, and others [10].

The material chosen to produce the device is PLA. PLA is a biodegradable polymer, which is attracting more and more interest in several fields thanks to its good mechanical properties and optical transparency [9].

B. Methods

To evaluate the quality of the measurement process, the Measurement System Analysis (MSA) methodology is used.

The specifics of the comparative analysis between basic equipment and a specially designed device for surface tester INSIZE ISR – C002 requires adaptation of the MSA to obtain the most comprehensive measurement process information. Fig. 7 shows the Measurement System Variability Cause and Effect Diagram.

Compared to the standard application of MSA in which Workpiece (Part), Instrument (Gage) and Person (Appraiser) are considered through their variations: Part variation (PV), Equipment variation (EV), which is basically Repeatability, Appraiser variation (AP), which is basically Reproducibility. GRR is the variance of the internal and external disturbances for the system represented by the combined variance of repeatability and reproducibility [11].

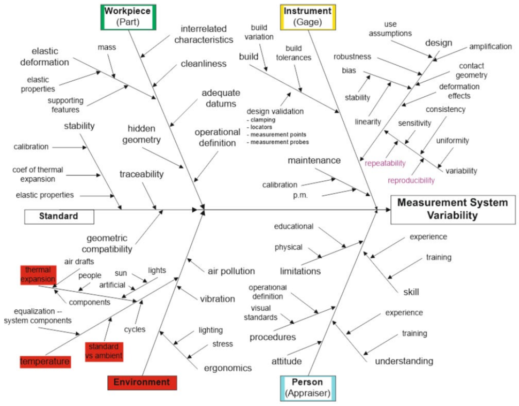

Fig.7 Measurement System Variability Cause and Effect Diagram [11]

Based on these data, we perform MSA using the GRR method according to the Reference Manual, 4th Edition [8], and obtain the following values:

Repeatability is equal to Equipment Variation:

$$EV = \bar{R} * K_1 \qquad (4)$$

(where all the coefficients are chosen from table according to Measurement systems analysis, Reference Manual [8])

Equipment Variation could be presented as %EV=100(EV/ Tolerance), where Tolerance is equal to difference between Upper Tolerance Limit (UTL) and Lower Tolerance Limit (LTL))

Reproducibility is equal to Appraiser Variation (AV)[8]:

$$AV = \sqrt{(\bar{X}_{DIFF} * K_2) - \frac{EV^2}{nr}} \qquad (5)$$

(where all the coefficients are chosen from table according to Measurement systems analysis, Reference Manual [8])

Appraiser Variation could be presented as %AV=100(AV/Tol). The influence of the operator can be disregarded because it has an insignificant impact on the outcome if he performs his duties conscientiously.

Gage Repeatability & Reproducibility [8]:

$$GRR = \sqrt{EV^2 + AV^2} \qquad (6)$$

and

$$\%GRR = 100(GRR/Tol) \qquad (7)$$

Part Variation:

$$PV = R_p * K_3 \qquad (8)$$

(where all the coefficients are chosen from table according to Measurement systems analysis, Reference Manual [8])

Result could be presented as [8]:

$$\%PV = 100(PV/Tol) \qquad (9)$$

All abbreviations used in the current paper are consistent with the Reference Manual, 4th Edition [8].

An adaptation of the MSA is used to analyze the results obtained in this report. The modification consists in using the same measurement system, but with different fixtures for basing the INSIZE ISR - C002 roughness instrument. In this situation all measurements were carried out by the same operator and the same measuring instrument. The purpose of this adaptation is to investigate the influence of the fixtures used on the results obtained.

III. RESULTS AND DISSCUSSION

The experiments were conducted with ten parts, each of which is measured three times. One set of measurements is made by one operator with the basic standard equipment. With the custom-made one, two series of measurements were carried out with two operators. Classical MSA was used to check the condition of the measurement system with both operators. An adapted MSA is then applied with only one operator and the influence of the fixtures on the measurement system is investigated. The experimental setup of the experiments performed with the baseline fixture is shown in Fig. 4. Due to the specificity of the controlled workpiece in the measurement, it is based in a prism, evident from Fig. 4. In order to realize this measurement, flat-parallel end measures were additionally used. Any additional interference in the measurement setup can contribute to more errors in the measurement results.

The experimental setup of the measurement with the developed new device is shown in Fig. 8, where (1) is a prism for basing the shafts, (2) is the newly designed device, (3) is the magnetic stand, (4) – roughness tester and (5) is the testing probe. The fixture allows quick and easy positioning and adjustment of the instrument relative to the workpiece being measured.

All laboratory measurements were conducted on sufficiently stable base equipment that made vibrations in the measurement system negligible. In addition, both fixtures have locking devices that are used in the presetting. The positioning accuracy of the device relative to the workpiece is controlled by the sensitive sensor positioning scale built into the device. To reduce the influence of the operator the measurements were carried out by having the instrument controlled remotely via software installed on an accompanying PC.

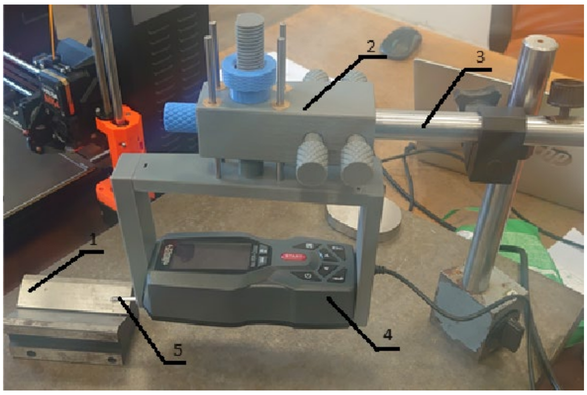

Fig.8 Experimental setup with the designed device

In Fig. 9, the experimental results of the measurements are presented, where operator A and B are understood to be the two measurement operators. Based on these, a standard MSA analysis is performed with two operators using the specially developed attachment to the INSIZE ISR - C002 roughness tester. Fig. 10 shows the results of the analysis performed.

APPRAISER/ TRIAL #		PART 1	2	3	4	5	6	7	8	9	10	AVERAGE	
1. A	1	2.023	2.076	2.114	2.077	1.996	2.059	2.072	2.061	2.061	2.063		2.060
2.	2	2.051	2.063	2.049	2.064	2.018	2.055	2.012	2.043	2.054	2.068		2.048
3.	3	2.068	2.083	2.109	2.106	2.019	2.046	2.021	2.037	2.049	2.007		2.055
4.	AVE	2.05	2.07	2.09	2.08	2.01	2.05	2.04	2.05	2.05	2.05	X_a=	2.054
5.	R	0.04	0.02	0.06	0.04	0.02	0.01	0.06	0.02	0.01	0.06	r_a=	0.037
6. B	1	2.034	2.086	2.123	2.082	2.005	2.069	2.083	2.075	2.085	2.073		2.072
7.	2	2.063	2.073	2.061	2.075	2.025	2.068	2.023	2.052	2.065	2.085		2.059
8.	3	2.078	2.095	2.121	2.128	2.028	2.056	2.035	2.052	2.066	2.025		2.068
9.	AVE	2.06	2.08	2.10	2.10	2.02	2.06	2.05	2.06	2.07	2.06	X_b=	2.066
10.	R	0.04	0.02	0.06	0.05	0.02	0.01	0.06	0.02	0.02	0.06	r_b=	0.038
11. C	1												
12.	2												
13.	3												
14.	AVE											X_c=	
15.	R											r_c=	
16. PART AVERAGE		2.05	2.08	2.10	2.09	2.02	2.06	2.04	2.05	2.06	2.05	X= / R_p=	2.060 / 0.081
17.	$(r_a + r_b + r_c)$ / (# OF APPRAISERS) =											R=	0.037
18.	x_{DIFF} = (Max X - Min X) =											X_{DIFF}=	0.012
19.	* UCL_R = R x D_4 =											UCL_R=	0.096

Fig.9 Measurement data, two appraisers, new device

Measurement Unit Analysis					% Tolerance (Tol)		
Repeatability - Equipment Variation (EV)							
EV	=	R x K_1	**Trials**	**K_1**	% EV	=	100 (EV/Tol)
	=	0.037 x 0.5908	2	0.8862		=	100(0.022/0.133)
	=	0.022	3	0.5908		=	16.51
Reproducibility - Appraiser Variation (AV)							
AV	=	$\{(X_{DIFF} \times K_2)^2 - (EV^2/nr)\}^{1/2}$			% AV	=	100 (AV/Tol)
	=	{(0.012 x 0.7071)^2 - (0.022 ^2/(10 x 3))}^1/2				=	100(0.008/0.133)
	=	0.008				=	5.71
		Appraisers	**2**	**3**			
n = parts	r = trials	**K_2**	0.7071	0.5231			
Repeatability & Reproducibility (GRR)					% GRR	=	100 (GRR/Tol)
GRR	=	$\{(EV^2 + AV^2)\}^{1/2}$	**Parts**	**K_3**		=	100(0.023/0.133)
	=	{(0.022^2 + 0.008^2)}^1/2	2	0.7071		=	17.46
	=	0.023	3	0.5231	*Gage system may be acceptable*		
Part Variation (PV)			4	0.4467			
PV	=	R_P x K_3	5	0.4030	% PV	=	100 (PV/Tol)
	=	0.081 x 0.3146	6	0.3742		=	100(0.025/0.133)
	=	0.025	7	0.3534		=	19.11
Tolerance (Tol)			8	0.3375			
Tol	=	Upper - Lower / 6	9	0.3249	ndc	=	1.41(PV/GRR)
	=	(2.4 - 1.6) / 6	10	0.3146		=	1.41(0.025/0.023)
	=	0.133				=	1
					Gage discrimination low		
For information on the theory and constants used in the form see *MSA Reference Manual*, Fourth edition.							

Fig.10 MSA results.

The analysis shows the variation of the results in terms of instrument EV (Equipment variation) and operator AV (Appraiser variation). = 5.71%. The value of EV = 16.51% indicates the influence of equipment versus meter variance of the results. The value of AV = 5.71%, indicates a slight influence of the operator relative to the results obtained. Based on these results, an adapted MSA is performed in which the measurements were carried out by a single operator and the influence of the fixtures against the obtained results is investigated. The value of GRR (Gage Repeatability & Reproducibility) = 17.46% indicates that the results of the measurement system can be accepted as the GRR value < 30%.

Fig. 11 shows the measurement data with the two fixtures, due to the specificity of the adapted MSA, operator A is understood to be the baseline fixture and operator B is assumed to be the newly designed fixture.

APPRAISER/ TRIAL #		PART 1	2	3	4	5	6	7	8	9	10	AVERAGE	
1. A	1	2.104	2.077	2.148	2.088	2.032	2.066	2.076	2.04	2.114	2.08		2.083
2.	2	2.063	2.078	2.105	2.068	2.023	2.058	2.029	2.081	2.073	2.131		2.071
3.	3	2.15	2.092	2.12	2.214	2.025	2.048	2.085	2.116	2.104	2.075		2.103
4.	AVE	2.11	2.08	2.12	2.12	2.03	2.06	2.06	2.08	2.10	2.10	X_a=	2.085
5.	R	0.09	0.02	0.04	0.15	0.01	0.02	0.06	0.08	0.04	0.06	r_a=	0.055
6. B	1	2.023	2.076	2.114	2.077	1.996	2.059	2.072	2.06	2.06	2.063		2.060
7.	2	2.051	2.063	2.049	2.064	2.018	2.055	2.012	2.043	2.054	2.068		2.048
8.	3	2.068	2.083	2.109	2.106	2.019	2.046	2.021	2.037	2.049	2.007		2.055
9.	AVE	2.05	2.07	2.09	2.08	2.01	2.05	2.04	2.05	2.05	2.05	X_b=	2.054
10.	R	0.04	0.02	0.06	0.04	0.02	0.01	0.06	0.02	0.01	0.06	r_b=	0.036
11. C	1												
12.	2												
13.	3												
14.	AVE											X_c=	
15.	R											r_c=	
16. PART AVERAGE		2.08	2.08	2.11	2.10	2.02	2.06	2.05	2.06	2.08	2.07	X= / R_p=	2.070 / 0.089
17.	(r_a + r_b + r_c) / (# OF APPRAISERS) =											R=	0.046
18.	x_{DIFF} = (Max X - Min X) =											X_{DIFF}=	0.031
19.	* UCL_R = R x D_4 =	APPRAISER		A				OUT OF CONTROL				UCL_R=	0.117

Fig.11 Measurement data from adapted MSA

Measurement Unit Analysis						% Tolerance (Tol)		
Repeatability - Equipment Variation (EV)								
EV	=	R x K_1		**Trials**	**K_1**	% EV	=	100 (EV/Tol)
	=	0.046 x 0.5908		2	0.8862		=	100(0.027/0.133)
	=	0.027		3	0.5908		=	20.16
Reproducibility - Device Variation (DV)								
AV	=	$\{(X_{DIFF} \times K_2)^2 - (EV^2/nr)\}^{1/2}$				% DV	=	100 (AV/Tol)
	=	{(0.031 x 0.7071)^2 - (0.027 ^2/(10 x 3))}^1/2					=	100(0.022/0.133)
	=	0.022					=	16.22
			Appraisers	2	3			
n = parts		r = trials	**K_2**	0.7071	0.5231			
Repeatability & Reproducibility (GRR)						% GRR	=	100 (GRR/Tol)
GRR	=	$\{(EV^2 + AV^2)\}^{1/2}$		**Parts**	**K_3**		=	100(0.035/0.133)
	=	{(0.027^2 + 0.022^2)}^1/2		2	0.7071		=	25.88
	=	0.035		3	0.5231	*Gage system may be acceptable*		
Part Variation (PV)				4	0.4467			
PV	=	R_P x K_3		5	0.4030	% PV	=	100 (PV/Tol)
	=	0.089 x 0.3146		6	0.3742		=	100(0.028/0.133)
	=	0.028		7	0.3534		=	20.92
Tolerance (Tol)				8	0.3375			
Tol	=	Upper - Lower / 6		9	0.3249	ndc	=	1.41(PV/GRR)
	=	(2.4 - 1.6) / 6		10	0.3146		=	1.41(0.028/0.035)
	=	0.133					=	1
						Gage discrimination low		
For information on the theory and constants used in the form see *MSA Reference Manual*, Fourth edition.								

Fig.12 Adapted MSA results

The results of the adapted MSA (Fig. 12) analysis show a value of EV = 20.16%, the value obtained is close to the value from the classical MSA. The value of DV (Device Variation) = 16.22% is significantly higher than that of the standard MSA. GRR = 25.88%, the obtained value is less than 30%, accordingly the measurement system can be accepted.

Looking at the data obtained from the two MSAs, the high EV values are striking. Both analyses show similar EV values around 20%, which means that the equipment influences the measurement results, but this influence is not particularly high. The values obtained for the AV and DV coefficient (in the adapted MSA), differ significantly for the two analyses. In the first analysis, the coefficient AV = 5.71%, indicates the insignificant influence of the operator on the results of the studies. The second MSA shows a significantly higher value of DV = 16.22%, indicating a significant influence of the operator relative to the measurement results. In this situation, since the operators are replaced by fixtures therefore, the influence of the fixtures on the obtained results are significant. It can be seen from the presented results (Fig. 11) that operator A (the base fixture) degrades the results.

IV. CONCLUSIONS

1) The MSA results indicate that the results obtained from both analyses are acceptable because the GRRs (Gage Repeatability & Reproducibility) < 30%.
2) The data from the MSA analysis shows that the results obtained with the new device are significantly better.
3) MSA can not only be used to compare operators and instrumentation, but can also be adapted to study the influence of other experimental equipment.
4) The newly designed instrument fixture INSIZE ISR - C002 facilitates instrument operation, reduces measurement preparation time and reduces basing error.

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REFERENCES

[1] Whitehouse, D. J. (1997). Surface metrology. Measurement science and technology, 8(9), 955.

[2] G. Eason, B. Noble, and I. N. Sneddon, “On certain integrals of Lipschitz-Hankel type involving products of Bessel functions,” Phil. Trans. Roy. Soc. London, vol. A247, pp. 529–551, April 1955.

[3] J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.

[4] Hamed, M., Zedan, Y., Samuel, A. M., Doty, H. W., & Samuel, F. H. (2019). Milling parameters of Al-Cu and Al-Si cast alloys. The International Journal of Advanced Manufacturing Technology, 104, 3731-3743.

[5] Gadelmawla, E. S., Koura, M. M., Maksoud, T. M., Elewa, I. M., & Soliman, H. H. (2002). Roughness parameters. Journal of materials processing Technology, 123(1), 133-145.

[6] Asakura, T. (1978). Surface roughness measurement. Speckle metrology, 11-49.

[7] Measurement systems analysis (MSA), Reference Manual, Fourth Edition, Copyright 2010 Chrysler Group LLC, Ford Motor Company, General Motors Corporation, ISBN#: 978-1-60-534211-5

[8] Dian, M., & Hodinář, L. (2018). The GRR a Fundamental Tool for Dealing with Measurement System Variability. Manufacturing Technology, 18(1), 29-34.

[9] Portable roughness tester INSIZE ISR – C002, available at: https://www.grainger.com/product/INSIZE-Handheld-Surface-Roughness-463L43, 15.02.2024.

[10] Coppola, B., Cappetti, N., Di Maio, L., Scarfato, P., & Incarnato, L. (2018). 3D printing of PLA/clay nanocomposites: Influence of printing temperature on printed samples properties. Materials, 11(10), 1947.

[11] Hristov, M. H. (2023, September). SPC as an Instrument for Implementation and MSA as an Instrument for Evaluation of Non-Linear Object Based Temperature Compensation into Shop Floor CMM. In 2023 15th Electrical Engineering Faculty Conference (BulEF) (pp. 1-9). IEEE.

[12] Qiu P., Introduction to Statistical Process Control, 2014 by Taylor & Francis Group, LLC, ISBN-13: 978-1-4822-2041-4 (eBook - PDF)

[13] https://www.aiag.org/