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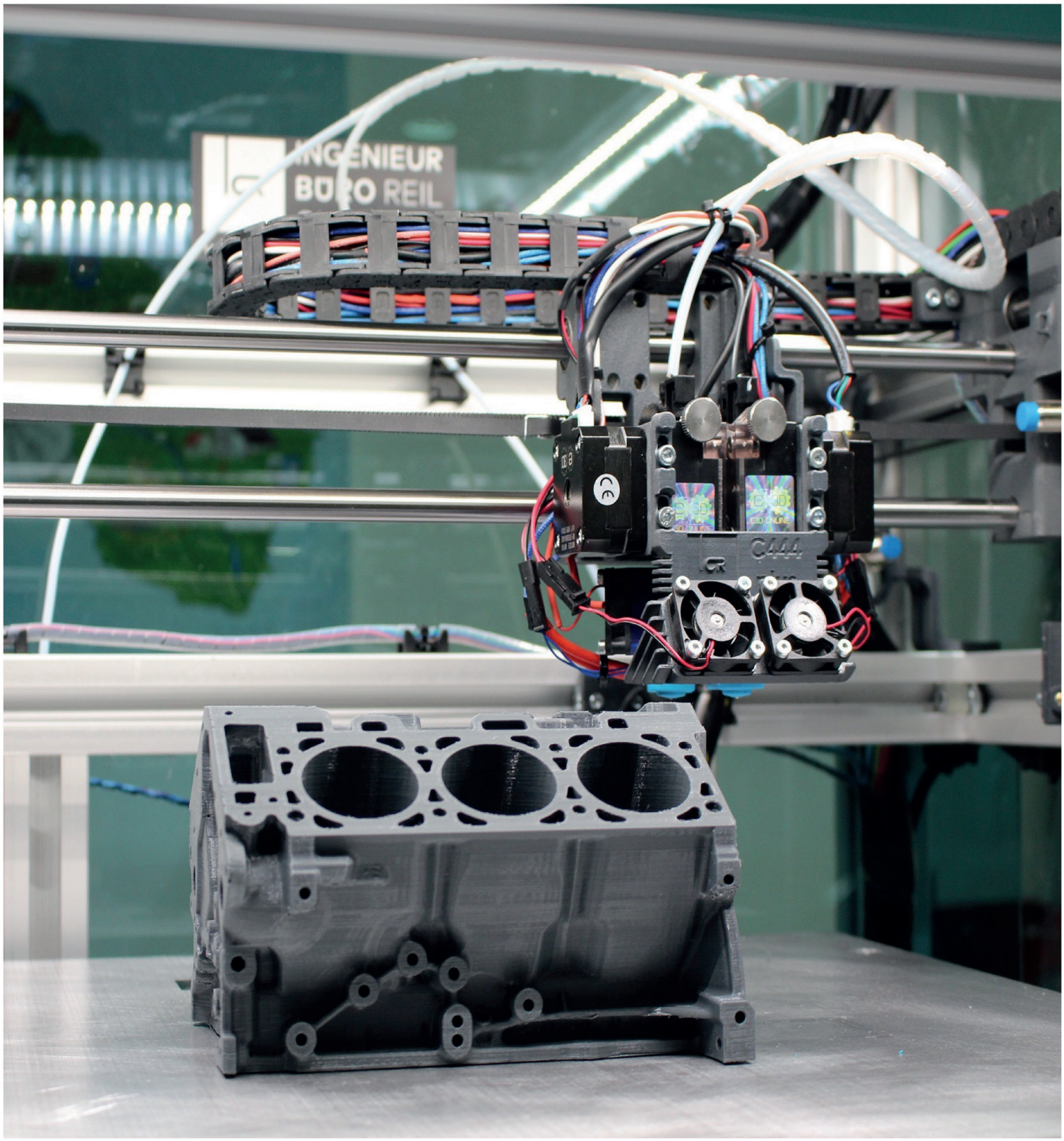

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ADRES REDAKCJI:
Kwartalnik „Technologia i Automatyzacja Montażu"
ul. Ratuszowa 11, pok. 740, 03-450 Warszawa
Tel. 22 853 81 13
e-mail: tiam@sigma-not.pl
www.tiam.pl

PRENUMERATA:
Zakład Kolportażu Wydawnictwa SIGMA-NOT Sp. z o.o.
ul. Ku Wiśle 7, 00-707 Warszawa
tel. 22 840 30 86
tel./fax: 22 827 43 65, 619 22 41 w. 215
e-mail: prenumerata@sigma-not.pl
portal: www.sigma-not.pl

REKLAMA:
Redakcja: tel. 22 853 81 13
e-mail: tiam@sigma-not.pl
Dział Reklamy i Marketingu
tel./fax: 22 827 43 65
e-mail: reklama@sigma-not.pl

SKŁAD I ŁAMANIE:
Wydawnictwo SIGMA-NOT
ul. Ratuszowa 11, 03-450 Warszawa
e-mail: sekretariat@sigma-not.pl

WYDAWCA:

Łukasiewicz
IMBiGS

Sieć Badawcza Łukasiewicz
Instytut Mechanizacji Budownictwa i Górnictwa Skalnego
ul. Racjonalizacji 6/8, 02-673 Warszawa

WYDAWNICTWO SIGMA-NOT

Wydawnictwo SIGMA-NOT
ul. Ratuszowa 11, 03-450 Warszawa

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TESTING DURABILITY OF A BROACH

Badania trwałości eksploatacyjnej przeciągacza

Magdalena BUCIOR ORCID 00000-0002-1081-5065
Rafał KLUZ ORCID 0000-0001-6745-294X
Jan JAWORSKI

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Abstract: In integrated manufacturing systems, a very important issue is the problem of ensuring the reliability of cutting tools, in particular high-speed steel broaches. To ensure the required quality of machining, the tool should be changed at specified intervals. Determining the tool replacement period and forecasting the tool's working ability is a difficult and complex issue due to the dispersion of the properties of the tool material and the workpiece. The paper presents the results of research on the dynamics of wear of HS 18-0-1 steel broaches, conducted under production conditions. Based on the analysis of the obtained results, it was shown that the scatter curves of the wear broach teeth VBalong its length and the standard deviation are in the form of a bathtub curve, which indicates uneven work of the broach teeth. In turn the teeth wear variance coefficient can be used to assess the effectiveness of its work. The research also shows that coated broaches are characterized by greater teeth wear stability and double reliable operation.
Keywords: broach, durability, HS 18-0-1 steel

Streszczenie: W zintegrowanych systemach wytwarzania bardzo ważnym zagadnieniem jest problem zapewnienia zdolności do pracy narzędzi skrawających, a w szczególności przeciągaczy ze stali szybkotnącej. Aby zapewnić wymaganą jakość obróbki należy w określonych odstępach czasu dokonać wymiany narzędzia. Wyznaczenie okresu wymiany narzędzia oraz prognozowanie zdolności do pracy narzędzia jest zagadnieniem trudnym i złożonym ze względu na rozrzut właściwości materiału narzędzia i przedmiotu obrabianego. W pracy przedstawiono wyniki badań dynamiki zużycia przeciągaczy ze stali HS 18-0-1 prowadzonych w warunkach produkcyjnych. Na podstawie analizy uzyskanych wyników wykazano, że krzywe rozrzutu zużycia zębów przeciągacza VB na całej długości i odchylenie standardowe mają postać krzywej wannowej, co wskazuje na brak identyczności pracy zębów na jego długości, natomiast do oceny efektywności jego pracy można wykorzystać współczynnik wariancji zużyci zębów. Wykazano również, że przeciągacze z pokryciem charakteryzują się większą stabilnością zużycia zębów oraz dwukrotnie większą niezawodnością pracy.
Słowa kluczowe: przeciągacz, trwałość, stal HS 18-0-1

Introduction

During the organization of the machining process in an automated manufacturing system the most complex problems arise when assessing the performance and reliability of processing. High requirements on the quality of manufactured parts determine technological failures as the main research object in the theory of technological system reliability [14, 15, 16]. During operation, the technological system is subject to mechanical and thermal effects, which cause damage and change the value of parameters of its initial state. The proper functioning of all elements of the technological system enables the implementation of the technological process, however, the quality indicators of the machined parts are mainly determined by the technological equipment, the machine tool and the tool.

Emre et al. [13] applied the thermo-mechanical process model to improve the broach design.For the simulation and optimization of complex tool geometry, they proposed an innovative method of generating intermediate teeth.They showed that in this way it is possible to optimize several geometrical features of the tool.Similar studies related to the optimization of broach design were conducted by Radhakrishnan et al. [4] for unconventional tool material. In turn, Xu and Yongfeng [6] showed that the use of anappropriate microtexture on the side surface of the broach reduces the drag force and increases the quality of the machined surface, which also affects the tool life. At optimal tool operating conditions, the dominant factors affecting the quality of the workpiece are damages caused by the wear of its cutting surfaces [1, 9]. Currently, many works are devoted to the issue of developing models of the durability of cutting tools, including broaches, required for designing and monitoring the condition of tools in automated machining systems [9, 10]. Gaddafee and Chinchanikar [11] used for this purpose classical methods based on the Weibull and Gamma distribution, Chile Louizu et al. [15] used information from the vision system.However, determining

the durability of broaches is still a current issue, the solution of which would contribute to the improvement of the tooling economy in manufacturing enterprises.

Assuring the performance quality of the tool

The cutting tool with the specified parameters of the initial state starts working under the given conditions for which it was designed. In the cutting process, with the passage of time, due to thermodynamic loads, the parameters of the initial state change their value. When the complex of geometric indicators describing the condition of the cutting part of the tool reaches its limit values, the tool is withdrawn from use [17, 18]. In order to ensure the required machining efficiency and the necessary performance, when calculating the tool wear costs at the design stage, its reliability indicators should be forecasted. Ensuring the quality of technological systems is therefore very important, and the basic feature of their quality is reliability. According to the ISO 9000 series standards, reliability is the ability of an object to fulfill its intended function under certain conditions and within a certain time. It follows that reliability is a quality feature that manifests itself in the expected lifetime. Tool life is characterized by the entire period of its use, taking into account the need for sharpening in order to ensure the state of readiness for the work performed. In calculating reliability, many quantitative indicators of the efficient operation of the tool are used. One of them is the probability of a reliable operation of the tool P (T_C), where T_C is the durability which is the probability that in the time interval ti decommissioning will not occur. Other indicators of reliability are durability, average durability, and the durability density function $f(t)$. Often, other reliability indicators are also used, such as decommissioning intensity $\lambda(T)$, γ-percentage durability or the durability variance coefficient. All quantitative indicators of reliability can be determined only as a result of the conducted experimental tests with the use of a tool with specific indicators of the initial state, as well as a result of statistical observations of the tool parameters in the process of its operation.

The current reliability theory develops in two directions [3, 5, 6, 8]:

– the physical direction deals with the description of the physical processes of the tool withdrawal models and solving tasks based on them regarding the improvement of reliability, tool diagnosis, etc.
– the mathematical or statistical direction deals with the elaboration of general mathematical models and the calculation of indicators of the reliable operation of the tool.

Thus, there are two approaches to solve reliability problems, although they are only conditional, because both directions often intertwine with each other, e.g. the creation of mathematical models is based on experiments and the physical reasons for decommissioning, and when solving physical problems, the mathematical apparatus of the probability theory is used [10].

Methodology

The study of the wear dynamics of broaches was carried out under production conditions when broaching a spline with a rectangular profile shown in Fig. 1. A 7B 510 horizontal broaching machine with a set of HS 18-0-1 steel broaches was used for the tests. The processed material was a C45 steel blank (HB = 260–320) with a length of 130 mm.

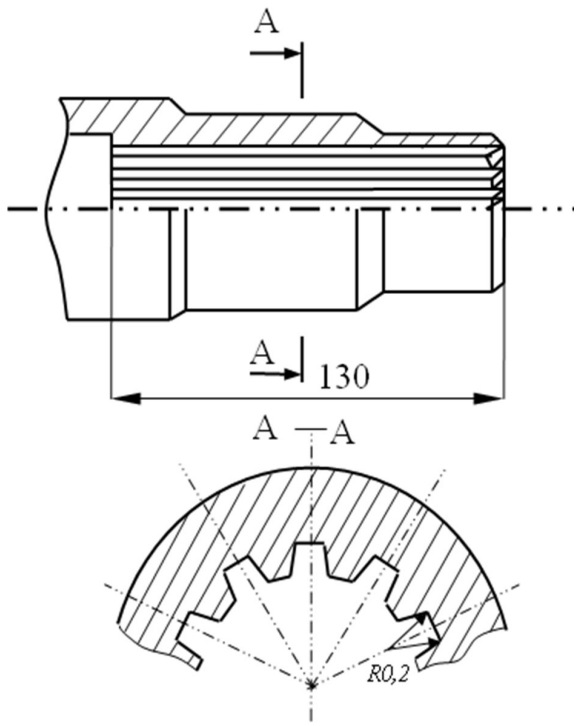

Fig.1. Workpieceests

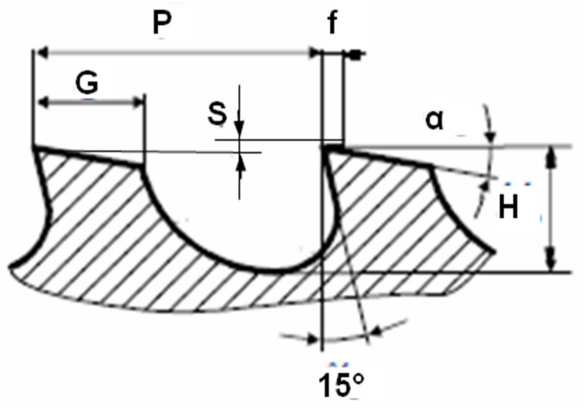

Fig. 2. The finishing broach used in the test

Table. 1. Geometric parameters of the broach

The broach tooth number	S	α	f	P	G	H	d
1-2	0.15	3°	0.05	16	5	5	33.5
3-6	0.35			22	6	7	
7-14	0.06	2°					
15	0.015						
16	0.01						
17-18	0	1°					
19-35			0.1-0.6				38,.1

Fig. 2 and Tab. 1 show the parameters of the cutting part of the finishing broach for which the tests were conducted. The study of the wear dynamics of the finishing broach was carried out at a cutting speed of *vc* = 7 m/min with the machining of 500 parts. Wear on the flank V_B = 0.4 mm was adopted as the wear criterion.

Results and analysis

The durability of a broach was determined on the basis of the number of machined parts. In order to obtain reliable wear characteristics, the obtained data was subjected to a mathematical analysis. It was established that the technological wear criterion of the broach, ensuring the required quality of the machined part, is the tool wear on the flank V_B equal to 0.4 mm. This value was adopted as the wear criterion. Based on the obtained data and its analysis, the diagrams of the teeth durability scatter and standard deviation along the broach length were developed (Fig. 3).

From the presented graphs, it can be concluded that the curves of the wear distribution of the broach teeth V_B along the entire length and the standard deviation σ have the form of a bathtub curve, which indicates the lack of identity of the teeth operation along its length.

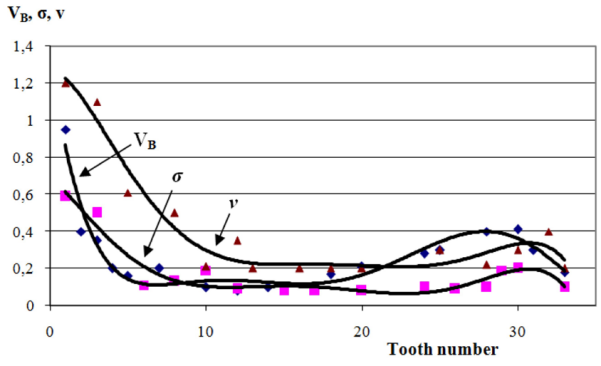

Fig. 3. Wear of a broach on the flank face V_B mm, standard wear deviation σ [mm] and wear variation coefficient *v* for individual teeth

This should be taken into account when designing and applying surface treatments. The finishing broach influences the quality of obtained parts, therefore it is subjected to increased reliability requirements. Therefore, a graphical dependence of the variance coefficient along its length was developed for it (Fig. 3).

By analyzing Fig. 3 it can be concluded that the reliability of the broach assessed by the coefficient of variation is not the same for all the teeth broach. Therefore, when determining the design and operational characteristics of the broach, especially in an automated enterprise, the criterion for its evaluation should be the coefficient of variance.

Increasing the reliability of the broach can be achieved by improving its design and manufacturing technology as well as by applying various types of surface treatments. The application of wear-resistant coatings removes surface defects of the tool material, reduces the surface roughness and the same reduces the friction force between the coating and the workpiece.

The factors influencing the durability and wear of coated tools include the destruction of the coating on the contact surface of the tool with the workpiece. The destruction of the coating occurs most intensively with the loss of the geometry of the cutting part as a result of elastic bending under loads, which leads to an increase of the dislocation density of the crystal lattice to the limit value, both in the tool material and its coating. This causes microscopic cracks which lead to the destruction of the coating. The stresses appearing in the deformation process are also a dangerous phenomenon that reduces the adhesion strength of the coating with the tool material. When designing broach, the nature of the stress in the life of the tool should also be taken into account. The amount of stress in the coating depends on various physico-mechanical and thermo-physical properties of the

coating and tool material, such as: thermal conductivity, expansion coefficient, etc. Operation of the tool with a coating having a high level of surface stresses may lead to a stochastic destruction of the coating and a sudden reduction in operational reliability of the broach.

To assess the reliability of the broach's work with the TiN coating, the wear of the broaching teeth was measured and subjected to a mathematical analysis. Based on the amount of teeth wear, the standard deviation of teeth wear was determined along the entire length of the finishing broach. As can be seen from Fig. 4, the wear of the broach teeth along its length is the same for both uncoated and coated broaches. However, greater teeth wear stability can be seen for the coated broach on both the first cutting and sizing teeth. This is due to the coating that adheres well to the tool material and is more resistant to wear.

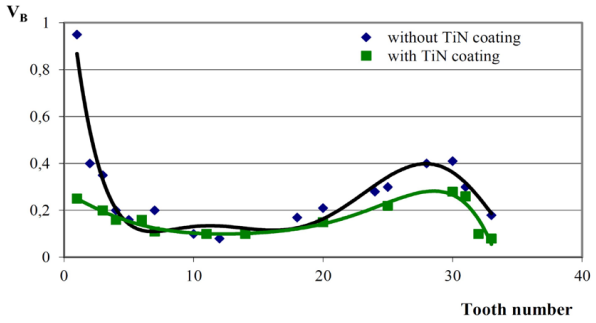

Fig. 4. Wear of the broaches on the flank surface V_B

During continuous operation of the broach, the standard deviation of wear depends on the amount of teeth wear (Fig. 5). The greater the wear on the teeth V_B, the greater the deviation value. Increasing the wear is favored by a higher value of the feed and spread of the allowance left after the previous operation. As a result, the standard deviation of the wear for the coarse broach is greater than for the finishing broach. This phenomenon is characteristic of both an uncoated and coated broach. However, for a coated broach, the difference in wear stability between rough and finish broaches is smaller.

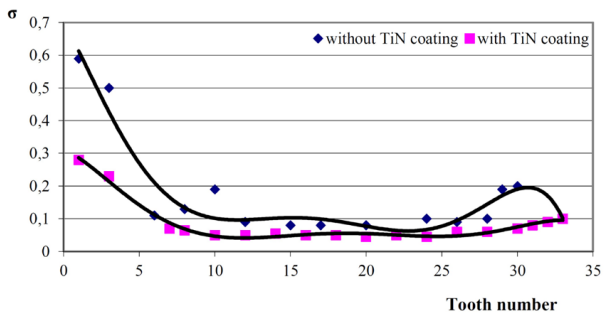

Fig. 5. Standard deviation of broach wear

During the tests, the values of the variance of the broach wear with and without the coating were compared at equal values of the average wear V_B. It allowed to notice that for broaches without coating, the value of the coefficient ranges from 0.06 to 0.16 (with an average wear value for a coarse broach of 0,88), while for a broach with coating v = 0.037. Similar results were obtained for finishing broaches. Analogically, the coated broaches had a much lower coefficient of variation than the uncoated ones. Note that by reducing the S_z feed from 0.15 to 0.05, the difference between the variance coefficient values for both coated and uncoated broaches. The mean value of the coefficient of variance for coated broaches is 0.2–0.3, while for uncoated broaches it is 0.3–0.55. For feed S_z = 0.12, the coefficient of variance for coated broaches is two times smaller than for uncoated broaches, while for feed S_z = 0.05 the difference between the coefficients is insignificant. Thus, by applying the coating to the broach, its reliability is doubled. Which, in turn, allows the use of broaches with surface treatment in an automated enterprise.

Effect of sharpening on broach work

In the process of operation, the broach is subject to repeated sharpenings. The service life of the sharpened tool ranges from 75 to 85% of the total service life of the broach. Therefore, the effectiveness of the broach work was tested throughout the entire period of its operation. Based on the statistical data obtained during the processing of C45 steel and its analysis, the dependence of the sharpening effect on the tool face on the total average wear value of the V_B teeth was developed. The tests were performed with the same number of processed parts (Fig. 6).

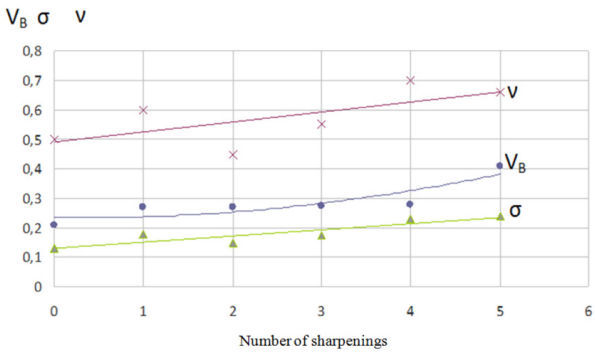

Fig. 6. Influence of the number of broaching sharpeners on the amount of wear of the teeth V_B [mm], standard deviation of wear σ [mm] and coefficient of wear variation v

The analysis of Fig. 6 shows that with the increase of the number of sharpenings, the wear of the broaching teeth and the spread of standard deviation of wear increase. As the number of sharpenings increase, the coefficient of variance also increases, which proves that the reliability of the broach's operation is reduced.

Conclusions

As a result of the research, it was concluded that:

- Scatter curves of broach teeth along its length as well as their standard deviation are in the form of a bathtub curve, which indicates uneven work of the broach teeth. This should be taken into account when designing the broach and applying surface treatments.
- When determining the design and operational features of the broach, the coefficient of variance should be used as a criterion for assessing the effectiveness of its work.
- Coated broaches are characterized by greater teeth wear stability and double reliable operation.
- The analysis of the test results shows that with the increase in the number of sharpenings, the average value of the teeth wear on the flank, the size of the standard deviation and the coefficient of variance increase, which proves the lowering of the broach's reliability.

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Dr inż. Magdalena Bucior
Rzeszow University of Technology,
Faculty of Mechanical Engineering and Aeronautics,
al. Powstańców Warszawy 8
35-959 Rzeszów, Poland
e-mail: magdabucior@prz.edu.pl

Dr inż. Rafał Kluz
Rzeszow University of Technology,
Faculty of Mechanical
Engineering and Aeronautics,
al. Powstańców Warszawy 8,
35-959 Rzeszów, Poland
e-mail: rkluz@prz.edu.pl

dr inż. Jan Jaworski
Rzeszow University of Technology
al. Powstańców Warszawy 8
35-959 Rzeszów, Poland
jjktmiop@prz.edu.pl

THE INFLUENCE OF THE BASIC CONDITIONS OF THE FORCED FEED OF ABRASIVE COMPOUND ON THE SURFACES ROUGHNESS OF FLAT CERAMIC ELEMENTS AFTER LAPPING

Wpływ podstawowych warunków wymuszonego dawkowania zawiesiny ściernej na parametry chropowatości powierzchni płaskich elementów ceramicznych po docieraniu

Adam BARYLSKI ORCID 0000-0003-1672-8445
Maciej GNIOT ORCID 0000-0002-2707-0696

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Abstract: In standard lapping, the abrasive compound is feed to the machining zone in a continuous manner – either by flooding or by droplets – which generates significant loss of the abrasive. The paper describes an innovative method of dosing and applying the abrasive compound onto the surface of a lapping disc, which eliminates this drawback. Additionally, the results of the examination of the influence of the compound feed on the selected parameters of the surface roughness of ceramic elements after lapping. In the conducted experiments the Authors examined the influence of the percentage content of grinding grains in the carrier, as well as the size of the compound dosage and viscosity of a liquid carrier on the values of particular surface roughness parameters of the lapped sealing elements.
Keywords: lapping of flat surfaces, abrasive compound, forced feed

Streszczenie: W docieraniu standardowym zawiesina ścierna dostarczana jest do strefy obróbki w sposób ciągły – zalewowo lub kroplowo, co powoduje duże straty ścierniwa. W artykule opisano innowacyjny system dozowania i nanoszenia zawiesiny ściernej na powierzchnię docieraka tarczowego, który eliminuje tą wadę. Przedstawiono wyniki badań wpływu warunków dawkowania zawiesiny na wybrane parametry chropowatości powierzchni elementów ceramicznych po docieraniu. W przeprowadzonych eksperymentach badano wpływ procentowej zawartość ziaren ściernych w nośniku oraz wielkości dawki zawiesiny i lepkości nośnika płynnego na wartości poszczególnych parametrów chropowatości powierzchni docieranych uszczelnień.
Słowa kluczowe: docieranie powierzchni płaskich, zawiesina ścierna, dawkowanie wymuszone

Introduction

Lapping process covers not only shaping of the surfaces of metal elements but also the surfaces of ceramic elements [3, 9, 11]. In practice, in case of flat surfaces, machine lapping on a single-disc machines with ring actuator system is prevailing [13, 16, 18]. Machined elements, placed in separators are being set in motion by guiding rings cooperating abrasively with the active surface of the lapping disc (Fig. 1) [4].

On the surface of the lap (1) guiding rings (5) rotate with the rate of rotation ns. Lapping disc rotates with the rate of rotation n_t driving the rings in which separators (4) are placed freely, enabling, usually negligible, additional rotary motion of the machined elements (3). Load is exerted onto the machined elements through a felt pad. The guiding ring rotates under the influence of the friction force torque and the rotations depend on the velocity of the lapping disc, friction conditions, load and location of the separator in relation to the lapping disc. Realization of the correct course of machining requires,

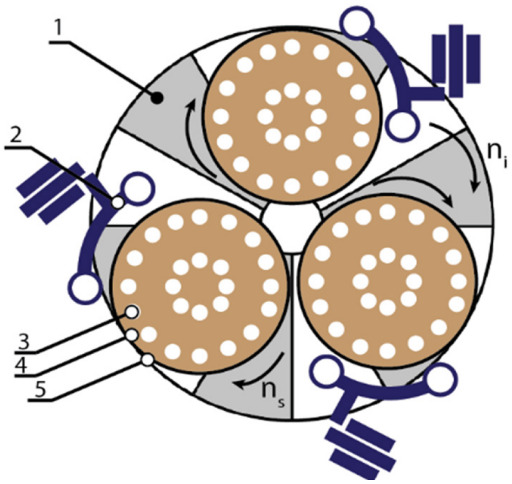

Fig. 1. Kinematic system of a single-disc lapping machine

among others, the appropriate value of unit pressure on the element and dosage of abrasive compound which is usually fed with certain excess. The outcome of lapping is influenced by a number of factors connected with the

lapping disc, components of the abrasive compound (type and size of abrasive micro-grains, concentration of the abrasive and size of the dosage), kinematic and technological conditions (mostly relative velocity and value of acceleration in the actuator system and unit pressure) [5,10]. Method and intensity of feeding the abrasive compound into the lapping zone is also of significant importance. In standard configuration the compound is fed continuously by means of flooding or droplets. This causes an excessive loss of abrasive, since some abrasive micro-grains become quickly removed from the working surface of the lapping disc by rotating guiding rings with separators and do not participate in the machining process. This significantly increases the machining costs and, indirectly, has a negative influence on the environment [7, 14]. Application of a system of forced feed of the abrasive compound on the working surface of the lapping disc eliminates these drawbacks to a large extent [1, 12].

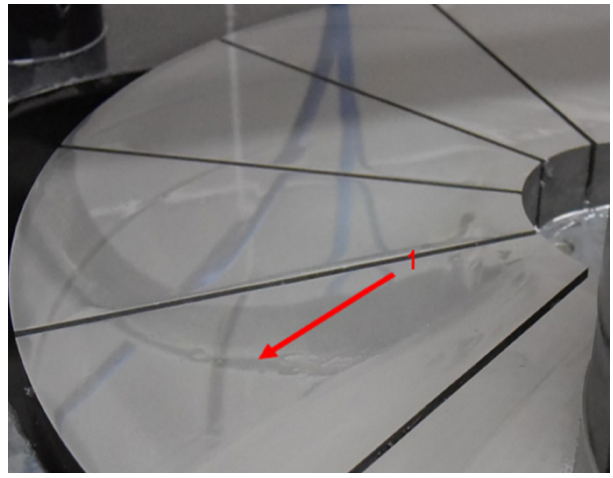

Fig. 3. Covering the surface of the lapping disc with abrasive compound after the application of the system of forced feed of the compound (1 – coruscant working surface of the lap)

Lapping station and methodology of the research

In order to conduct the research on the influence of the basic conditions of the forced feed of abrasive compound on the parameters of the geometric structure of the surface after lapping flat ceramic elements, a system of forced feed and dosage of abrasive compound was applied (Fig. 2) [6].

Application of a system of the forced feed of abrasive compound ensures an even distribution of the layer of abrasive compound, which can be seen in Fig. 3.

In experimental research a static, determined, selective, multi-factored quasi-rotable second rank plan developed by Box and Hunter with spherical distribution of information was applied. This ensures the stability of estimating the regressive function in certain surroundings of the central point of the plan *PS/DS-P*: λ [8, 15, 17]. Values of the output factors Y are variables of random character. Such an assumption allows to assume that occurring distortions U and constant conditions C constitute parameters that are seemingly constant with the assumed conditions of the research. In the paper the function of an object has been defined in multi-dimensional factor space as an equation of regression:

$$Y = f(x_1, x_2, x_3, \ldots, x_k) \quad (1)$$

where:
k – number of the analyses variables,

Determined coefficients $B = [b_1, b_2, \ldots, b_k]$ apply to the regression equation:

$$Y = b_0x_1 + b_1x_2 + b_2x_3 + b_3x_4 + b_4x_2^2 + b_5x_3^2 + b_6x_4^2 + b_7(x_1x_2) + b_7(x_2x_4) + b_7(x_3x_4) \quad (2)$$

where:
$Y = Rz$ is the value of the input factor from the model (surface roughness parameter),
while independent variables are, respectively: $x_1 = 1$, $x_2 = K$, $x_3 = V_s$, $x_4 = L_e$;
whereby:
K – percentage content of the abrasive grains in a carrier,
V_s – dosage of the abrasive compound [ml/20min],
L_e – viscosity of the carrier of abrasive grains [mPa·s].

Experimental research has been conducted while lapping sealing elements made of Al_2O_3 ceramics. Correlations between the dosage parameters for the abrasive compound and other (selected) roughness parameters: *Ra*, *Rq*, *Rt*, *Rv*, *Rz*, *Rp*, *Rku*, *Rsm* and *Rsk* of the lapped surfaces have also been analysed.

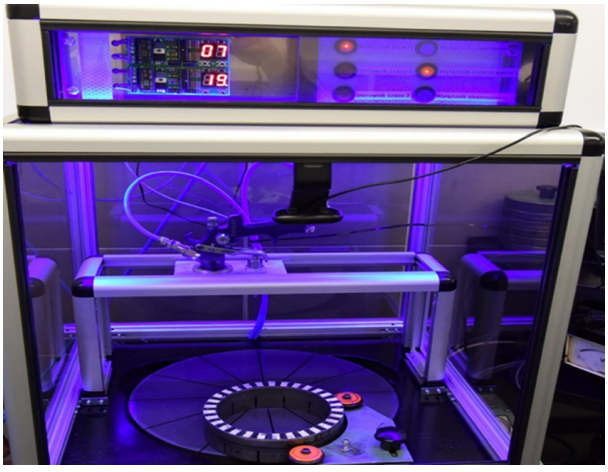

Fig. 2. System of the forced feed of abrasive compound

Results of the research

Table 1 contains the results of the experiments. Surface charts (Fig. 4–6) has been built. Several characteristic points have been marked in these graphs.

Table 1. Conditions of the forced feed of abrasive compound and results of the measurement of roughness parameter *Rz* (mean values of 3 measurements have been listed)

	K [%]	V_s [ml/20min]	L_e [mPa·s]	Rz [µm]
1	15	10	23	5.4954
2	15	50	23	5.2069
3	15	50	23	5.2567
4	15	50	23	5.225
5	15	50	23	5.2269
6	15	50	23	5.2869
7	15	50	23	5.2673
8	15	90	23	6.0191
9	5	50	23	6.5775
10	25	50	23	6.064
11	21	74	29.5	6.1754
12	21	26	29.5	6.1458
13	9	74	29.5	6.7796
14	9	26	29.5	6.1509
15	15	50	34	5.8279
16	15	50	10.3	5.8783
17	21	74	16.5	6.0677
18	21	26	16.5	5.9464
19	9	74	16.5	6.3593
20	9	26	16.5	5.3033

Necessary calculations and spatial graphs showing the influence of the input factors (K, V_s and L_e), on surface roughness parameter *Rz* were conducted in Statistica software.

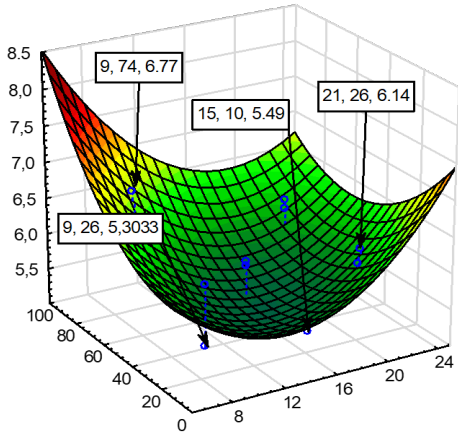

Fig. 4. Surface chart of the height of *Rz* surface roughness parameter in relation with the input factors K and V_s

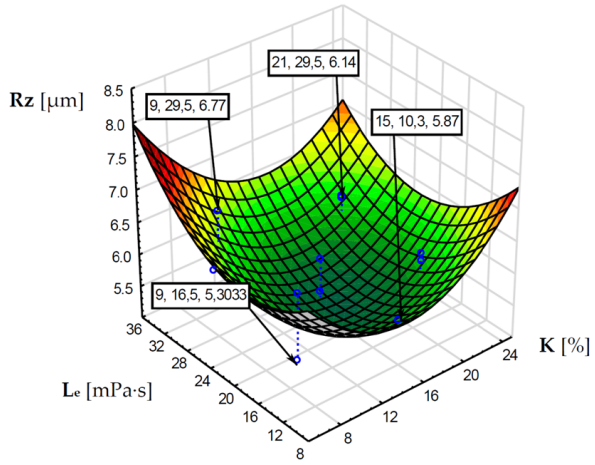

Fig. 5. Surface chart of the height of *Rz* surface roughness parameter in relation with the input factors K and L_e

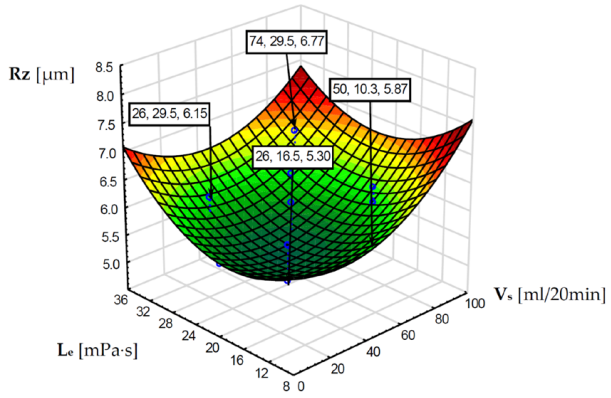

Fig. 6. Surface chart of the height of *Rz* surface roughness parameter in relation with the input factors V_s and L_e

Processing the results of research

The obtained results confirm the efficiency of the operation of a forced dosing system. Values of the roughness parameter *Rz* recorded in the research are close to the values of *Rz* parameter for elements lapped with the conventional method of dosing the abrasive compound [2].

Rz_{min} = 5.21 µm obtained for: K= 15%, V_s = 50 ml/20 min and L_e = 23 mPa·s

as well as Rz_{max} = 6.78 µm for: K = 9%, V_s =74 ml/20 min and L_e = 29.5 mPa·s

A statistical analysis of the obtained results has also been conducted. SS test for model (2) has been conducted on the basis of data contained in Tab. 1. Multiple correlation factor and determination factor (Tab. 2) have been determined.

Next, unidimensional formula significance tests were performed for $Rz = f(K, V_s, L_e)$ (Tab. 3).

For the analysed regression equation, the value of F coefficient was 20.40820. This value corresponds with the significance level p-value = 0.000059. Low value of

Table 2. Model analysis results

Dependent variable	SS Test for a complete model										
	Multiple R	Multiple R^2	Corrected R^2	Model SS	Model df	Model MS	Rest SS	Rest df	Rest MS	F	P
Rz	0.9763	0.9532	0.9065	4,3843	9	0.4871	9	0.0238	0.0233	20.4082	0.00005

Table 3. Unidimensional test of regression formula significance

Effect	Unidimensional significance tests for *Rz* Parametrization with sigma-limitations Decomposition of effective hypotheses; Standard error of the assessment: 0.1545				
	SS	Degrees of freedom	*MS*	*F*	*p*
Absolute term	1.8450	1	1.8450	77.2947	0.00001
K	0.4388	1	0.4388	18.3867	0.0020
K^2	2.2961	1	2.2961	96.1924	0.000004
V_s	0.0002	1	0.0002	0.0094	0.9246
V_s^2	0.5926	1	0.5922	24.8118	0.0007
L_e	0.2044	1	0.2044	8.5635	0.0168
L_e^2	0.8478	1	0.8478	35.5205	0.0002
$K \cdot V_s$	0.2257	1	0.2257	9.4581	0.01323
$K \cdot L_e$	0.0781	1	0.0781	3.2743	0.1038
$V_s \cdot L_e$	0.212	1	0.0212	0.8918	0.3696
Error	0.2148	9	0.2338		

Table 4. Values of the regression coefficients and their level of significance

Effect	Assessment of parameters Parametrization with sigma-limitations									
	Rz	*Rz* Stat. Error	*Rz* t	*Rz* p	-95.00% Confidence boundary	+95.00% Confidence boundary	*Rz* Beta (β)	*Rz* Stat. Error (β)	-95.00% Confidence boundary	+95.00% Confidence boundary
Absolute term	8.2241	0.9354	8.7917	0.00001	6.1080	10.3403				
K	-0.2213	0.0516	-4.2879	0.0020	-0.3381	-0.1045	-2.1899	0.5107	-3.3452	-0.0346
K^2	0.0114	0.0016	9.8077	0.00004	0.0088	0.0140	3.4561	0.3523	2.6559	4.2533
V_s	0.0012	0.0122	0.0973	0.9246	-0.0267	0.0291	0.0476	0.4894	-1.0595	1.1547
V_s^2	0.0003	0.00007	4.9811	0.0007	0.0001	0.0005	1.4752	0.2961	0.8052	2.1452
Le	-0.1467	0.0501	-2.9263	0.0168	-0.2601	-0.0333	-1.6432	0.5615	-0.9135	-0.3729
L_e^2	0.0050	0.0008	5.9599	0.0002	0.0031	0.0069	2.5617	0.4298	1.5894	3.5341
KV_s	-0.0013	0.0004	-3.0754	0.0132	-0.0023	-0.0003	-0.9975	0.3243	-1.7312	-0.2637
KL_e	-0.0029	0.0016	-1.8095	0.1038	-0.0066	0.0007	-0.8841	0.4886	-1.9894	0.2211
$V_s L_e$	-0.0003	0.0004	-0.9443	0.3696	-0.0013	0.0005	-0.,4365	0.4622	-1.4822	0.6091

the significance level indicates a high significance of the constructed regression equation. Standard error of the test assessment is 0.1545, which indicates that all the parameters of the model were estimated with sufficient precision. The model was assessed as positive. The analysis of the regression equation was extended with testing the significance of the equation's coefficients (Tab. 4).

On this basis, a mathematical mode was obtained, being a quadratic polynomial with three input variables (K, V_s, L_e):

$$Rz = 8.2241 - 0.2213K + 0.0114K^2 + 0.0012V_s + 0.0003V_s^2 - 0.1467L_e + 0.0050\mathrm{L_e}^2 - 0.0013\mathrm{KV_s} - 0.0029\mathrm{KL_e} - 0.0003V_sL_e \quad (3)$$

Comparison of the real results of *Rz* parameter and predicted *Rzt* (from a model) parameter is presented in (Tab. 5).

Utility function parameter notion has also been introduced (Tab. 6). The maximum value of the parameter obtained as a result of optimization was *Rzt* = 6.81 μm, while $Rzu_{żyt}$ = 1, in case when *Rzt* = 4.79, $Rzu_{żyt}$ = 0.

List of the replies regarding the predicted value of the roughness parameter *Rz* is presented in Tab. 7.

Profiles of the approximated and theoretical values (in the function of input coefficients K_t, V_{st}, L_{et}) have been presented in Fig. 7. In this case, the dependent variable is $Rzt = Rz_{użyt}$, while predicators are K_t, V_{st} and L_{et}. Fig. 8–10 present the surface charts $Rz_{użyt} = f(K_t, Vst, L_{et})$.

Table 5. Comparison of *Rz* values (observed vs anticipated)

No.	Observed, anticipated and rest values Parametrization with sigma-limitations		
	Observed *Rz*	**Predicted *Rz***	**Rest *Rz***
1	5.4954	5.4892	0.0061
2	5.2069	5.2361	-0.0292
3	5.2567	5.2361	0.0205
4	5.2250	5.2361	-0.0111
5	5.2269	5.2361	-0.0092
6	5.2869	5.2361	0.0507
7	5.2673	5.2361	0.0311
8	6.019	6.1462	-0.1271
9	6.5775	6.5226	0.0548
10	6.0640	6.2397	-0.1757
11	6.1754	5.9397	0.2356
12	6.1458	6.0588	0.0870
13	6.7796	6.7331	0.0464
14	6.1509	6.0628	0.0839
15	5.8279	6.0628	-0.2349
16	5.8783	5.7900	0.0882
17	5.8783	5.7900	0.0882
18	5.9464	5.908	0.0375
19	6.3593	6.3623	-0.0030
20	5.3033	5.4549	-0.1516

Table 6. Parameters of the utility function of the roughness parameter *Rz*

Variable	Utility function parameters Settings of the utility function for each dependent variable							
	Low value	**Useful value**	**Intermediate value**	**Useful value**	**High value**	**Useful value**	**s Parameter**	**t Parameter**
Rz	4.7886	0.00	5.7996	0.5000	6.8105	1.0000	1.0000	1.0000

Table 7. List of the replies regarding the predicted value of the roughness parameter *Rz*

Coefficient	Levels of the coefficient and predicted replies Predicted replies for all the levels of each coefficient with set values of all the other coefficients				
	Level of the coefficient	Predicted *Rz*	Useful value	-95% P *Rz*	+95% P *Rz*
K	4.6830	6.5865	0.8891	6.1354	7.0376
K	9.6836	5.6255	0.4139	5.2460	6.0050
K	14.6842	5.2371	0.2218	4.8598	5.6144
K	19.6848	5.4214	0.3129	5.0422	5.8007
K	24.6853	6.1784	0.6873	5.7331	6.6237
V_s	8.7321	5.5137	0.3586	5.0626	5.9648
V_s	28.7345	5.2300	0.2183	4.8505	5.6095
V_s	48.7368	5.2371	0.2218	4.8598	5.6144
V_s	68.7391	5.5351	0.3692	5.1559	5.9143
V_s	88.7415	6.1239	0.6604	5.6786	6.5692
L_e	11.9308	5.6079	0.4052	5.1792	6.0366
L_e	17.5917	5.2619	0.2341	4.8825	5.6414
L_e	23.2526	5.2371	0.2218	4.8598	5.6144
L_e	28.9135	5.5335	0.3684	5.1528	5.9142
L_e	34.5744	6.1511	0.6738	5.6962	6.6059

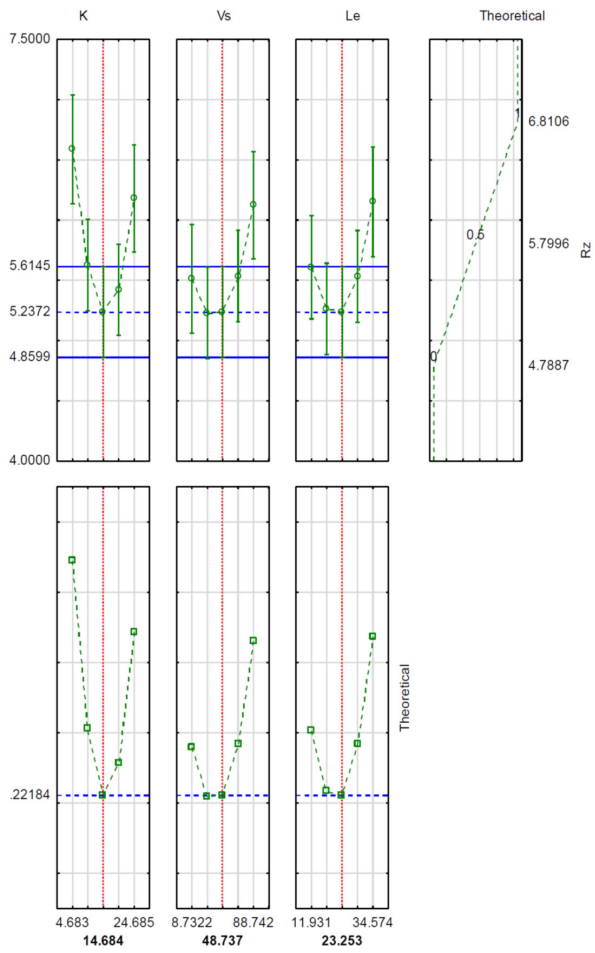

Fig. 7. Profiles of the approximated and useful values of the examined coefficients *K*, V_s and L_e, influencing the value of the surface roughness parameter *Rz*

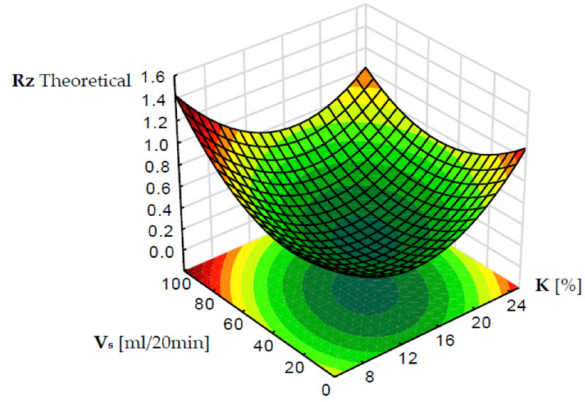

Fig. 8. Surface chart of the predicted value of roughness parameter *Rz* in relation to *K* and V_s coefficients

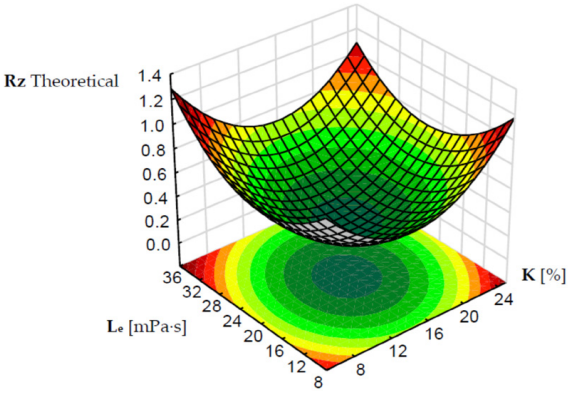

Fig. 9. Surface chart of the predicted value of roughness parameter *Rz* in relation to *K* and L_e coefficients

Analysing the graphs presented above, it is possible to see the influence exerted by predicators on the explicated variable. With this method it is possible to predict replies regarding the roughness parameter *Rz* in the function of input coefficients.

In the experimental research, roughness parameter *Rz* assumed the following values: i:
Rz_{min} = 5.225 μm for input parameters K = 15%, V_s = 50 ml/20 min and L_e = 23 mPa·s and
Rz_{max} = 6.777 μm for input parameters K = 9%, V_s = 74 ml/20 min, L_e = 29.5 mPa·s.

Conducting the optimization of the predicted replies, it was determined that the roughness parameter Rzt_{min} = 5.237 μm corresponds with input parameters: K = 14.6%, V_s = 48.7 ml/20 min i L_e= 23.2 mPa·s.

On this basis it can be stated, that after the optimization the following values were corrected: *Rz*- by 0%, K – conservation of the abrasive grains by 2,7%, V_s – conservation of the dosage by 2,6%.

It is also advised to slightly change the viscosity of the compound from 23 to 23.2 mPa·s.

He assessment of the influence of the parameters of forced dosing on the quality of the surface should be conducted in conjunction with the efficiency of machining. An optimum solution consists in obtaining high efficiency of machining while maintaining a high quality of the surface. This is a complex issue, since it is difficult to have a simultaneous influence on a number of roughness parameters. Concentration on a single parameter can cause the deterioration of other parameters, such as, for example, surface bearing capacity. The most important roughness parameters should result from the relationship between specific 2D parameters (such as location of the tips) in mutually perpendicular directions, due to the fact that the shape and location of the contact areas of contacting surfaces are of particular importance. To assess the influence of the conditions of forced dosing on selected 2D roughness parameters, their measurements were conducted. The results of the measurements have been presented in Tab. 8.

Next, analysis of the correlation of the influence of examined (variable) coefficients on selected roughness parameters (Tab. 9).

Table 8. List of the parameters determined for P2D(i) outline

No.	K [%]	V_s [ml/20min]	L_e [mPa·s]	*Ra*	*Rq*	*Rt*	*Rv*	*Rz*	*Rp*	*Rku*	*Rsm*	*Rsk*
1	15	10	23	0.9171	1.4636	6.5887	3.4616	5.4954	2.0363	4.0670	48.0559	-0.5857
2	15	50	23	0.6329	0.9371	7.0647	3.0876	5.2069	2.1886	4.3347	36.0138	-0.4355
3	15	50	23	0.6361	0.9372	7.0124	3.0851	5.2567	2.1841	4.3110	36.0850	-0.4386
4	15	50	23	0.6361	0.9333	7.0321	3.0967	5.2250	2.1833	4.3387	36.0429	-0.4366
5	15	50	23	0.6255	0.9353	7.0345	3.0303	5.2269	2.1815	4.3550	36.0934	-0.4375
6	15	50	23	0.6381	0.9329	7.0579	3.0716	5.2869	2.1852	4.3110	36.0811	-0.4357
7	15	50	23	0.6328	0.9381	7.0078	3.0786	5.2673	2.1887	4.3013	36.0246	-0.4350
8	15	90	23	0.8107	1.0716	8.8133	3.8043	6.0191	2.2154	9.5737	39.6956	-1.3440
9	5	50	23	0.6868	0.9582	10.0875	4.2833	6.5775	2.2943	9.7350	35.1398	-1.5710
10	25	50	23	0.7956	1.0345	7.3878	3.7032	6.0640	2.3608	4.1340	42.5203	-0.4247
11	21	74	29.5	0.7429	0.9713	7.7281	3.5886	6.1754	2.5869	3.9137	43.4665	-0.3703
12	21	26	29.5	0.7431	0.9649	7.8105	3.9819	6.1458	2.1639	4.5010	41.2469	-0.7273
13	9	74	29.5	0.7034	0.9077	8.8420	4.2404	6.7796	2.5391	5.4597	6.0630	-0.7630
14	9	26	29.5	0.7697	0.9941	7.7722	4.0603	6.1509	2.0906	4.5857	6.0630	-0.8240
15	15	50	34	0.7391	0.9583	7.4016	3.3392	5.8279	2.4887	3.6740	6.0630	-0.3223
16	15	50	10.3	0.6884	0.9023	7.1104	3.4198	5.8783	2.4585	3.6877	41.7411	-0.3997
17	21	74	16.5	0.6876	0.9030	8.0437	3.7786	6.0677	2.2891	5.3783	40.5722	-0.8247
18	21	26	16.5	0.7438	0.9833	7.3874	3.6503	5.9464	2.2960	4.4053	41.1710	-0.5543
19	9	74	16.5	0.7796	1.0073	8.1021	4.0598	6.3593	2.2995	4.3187	45.3597	-0.7023
20	9	26	16.5	0.6444	0.8546	6.2794	3.5118	5.3033	1.7916	4.8453	36.4907	-0.8787

Table 9. Levels of significance for the significance tests of correlation coefficients between the following variables: *K*, V_s, L_e, Ra, *Rq*, *Rt*, *Rv*, *Rz*, *Rp*, *Rku*, *Rsm*, *Rsk* (red is indicated for statistically significant dependencies)

Variable	Marker correlation coefficients are significan with p < 0.05000 N = 20 (lack of data mitigated with specific cases)											
	K	***Vs***	***Le***	***Ra***	***Rq***	***Rt***	***Rv***	***Rz***	***Rp***	***Rku***	***Rsm***	***Rsk***
K	1.0000 p= ...	.0000 p=1.00	.0000 p=1.00	.1624 p=.494	.0934 p=.169	-.3196 p=.196	-.2753 p=.240	-.1400 p=.556	.2478 p=.292	-.3831 p=.095	.4137 p=.070	.4936 p=.027
V_s	.0000 p=1.00	1.0000 p= ...	.0000 p=1.00	-.1327 p=.577	-.3321 p=.153	.5067 p=.023	.1548 p=.515	.3405 p=.142	.5705 p=.009	.3670 p=.111	-.1783 p=.452	-.1783 p=.452
L_e	.0000 p=1.00	.0000 p=1.00	1.0000 p= ...	.1516 p=.524	.0989 p=.678	.2006 p=.396	.1111 p=.641	.1779 p=.453	.2301 p=.329	-.0068 p=.977	-.6051 p=.005	.0624 p=.794
Ra	.1624 p=.494	-.1327 p=.577	.1516 p=.524	1.0000 p= ...	.8141 p=.000	.1694 p=.475	.4820 p=.031	.4467 p=.048	.0888 p=.710	.0974 p=.683	.1080 p=.650	-.1955 p=.409
Rq	.0934 p=.169	-.3321 p=.153	.0989 p=.678	.8141 p=.000	1.0000 p= ...	-.0955 p=.689	.0673 p=.778	-.0048 p=.984	-.1729 p=.466	.0187 p=.938	.2716 p=.247	-.0491 p=.837
Rt	-.3196 p=.196	.5067 p=.023	.2006 p=.396	.1694 p=.475	-.0955 p=.689	1.0000 p= ...	.7651 p=.000	.8085 p=.000	.4334 p=.056	.7807 p=.000	.2067 p=.382	-.7498 p=.000
Rv	-.2753 p=.240	.1548 p=.515	.1111 p=.641	.4820 p=.031	.0673 p=.778	.7651 p=.000	1.0000 p= ...	.9318 p=.000	.2194 p=.353	.4897 p=.028	-.2072 p=.381	-.6820 p=.001
Rz	-.1400 p=.556	.3405 p=.142	.1779 p=.453	.4467 p=.048	-.0048 p=.984	.8085 p=.000	.9318 p=.000	1.0000 p= ...	.5563 p=.011	.3976 p=.083	-.2514 p=.285	-.5023 p=.024
Rp	.2478 p=.292	.5705 p=.009	.2301 p=.329	.0888 p=.710	-.1729 p=.466	.4334 p=.056	.2194 p=.353	.5563 p=.011	1.0000 p= ...	-.0464 p=.846	-.2060 p=.383	.2086 p=.378
Rku	-.3831 p=.095	.3670 p=.111	-.0068 p=.977	.0974 p=.683	.0187 p=.938	.7807 p=.000	.4897 p=.028	.3976 p=.083	-.0464 p=.846	1.0000 p= ...	.0130 p=.956	-.9242 p=.000
Rsm	.4137 p=.070	-.0168 p=.944	-.6051 p=.005	.1080 p=.650	.2716 p=.247	.2067 p=.382	-.2072 p=.381	-.2514 p=.285	-.2060 p=.383	.0130 p=.956	1.0000 p= ...	.0210 p=.930
Rsk	.4936 p=.027	-.1783 p=.452	.0624 p=.794	-.1955 p=.409	-.0491 p=.837	-.7498 p=.000	-.6820 p=.001	-.5023 p=.024	.2086 p=.378	-.9242 p=.000	.0210 p=.930	1.0000 p= ...

Analysing the influence of the conditions of forced dosing (*K*, V_s and L_e) on correlation with surface roughness parameters (*Ra*, *Rq*, *Rt*, *Rv*, *Rz*, *Rp*, *Rku*, *Rsm* and *Rsk*) it was determined that dosing conditions influence only certain parameters of roughness. Statistically significant correlations of the examined coefficients occur for the following pairs: *K* - *Rsk* (Fig. 11), V_s - *Rt* (Fig. 12), V_s - *Rp* (Fig. 13) and L_e - *Rsm* (Fig. 14).

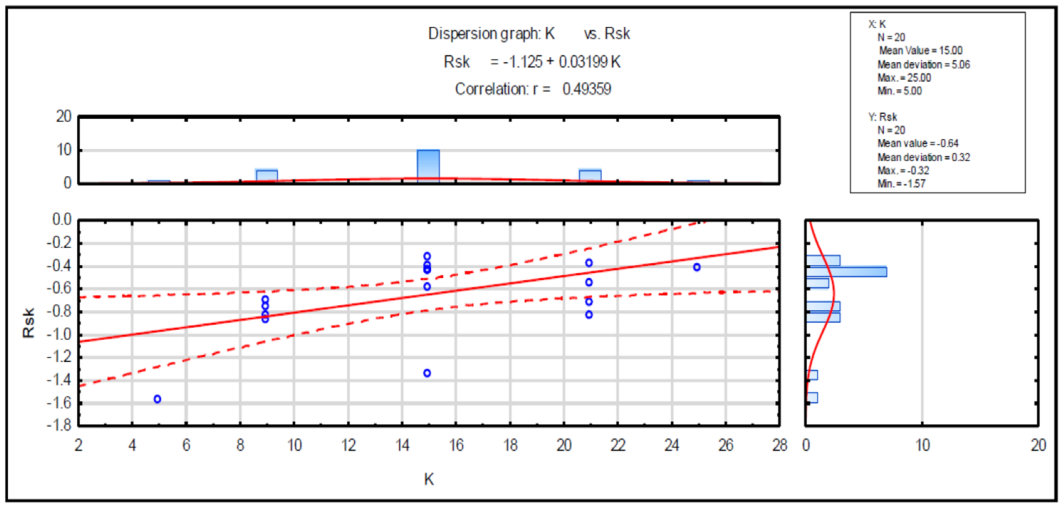

Fig. 11. Correlation of the input coefficient *K* and roughness parameter *Rsk*

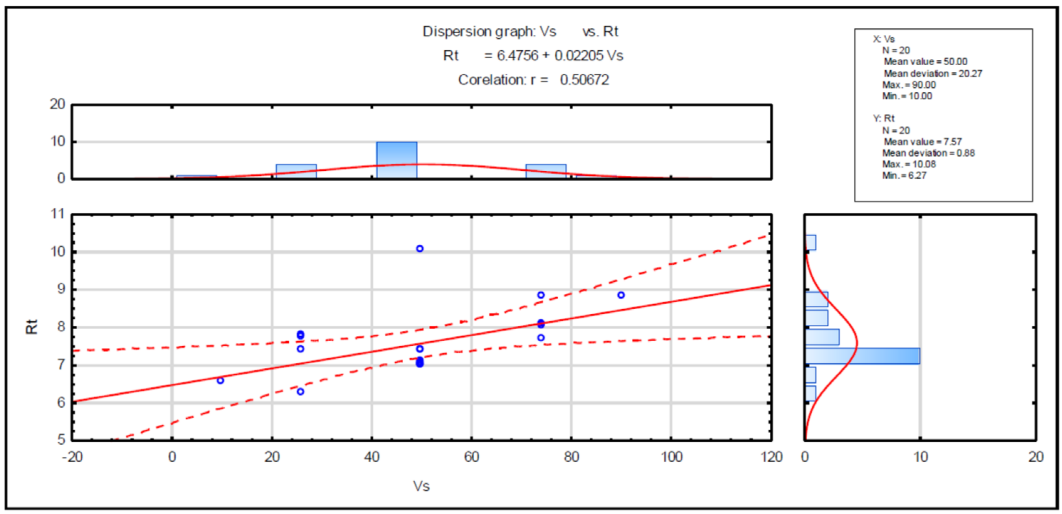

Fig.12. Correlation between input coefficient *K* and roughness parameter *Rt*

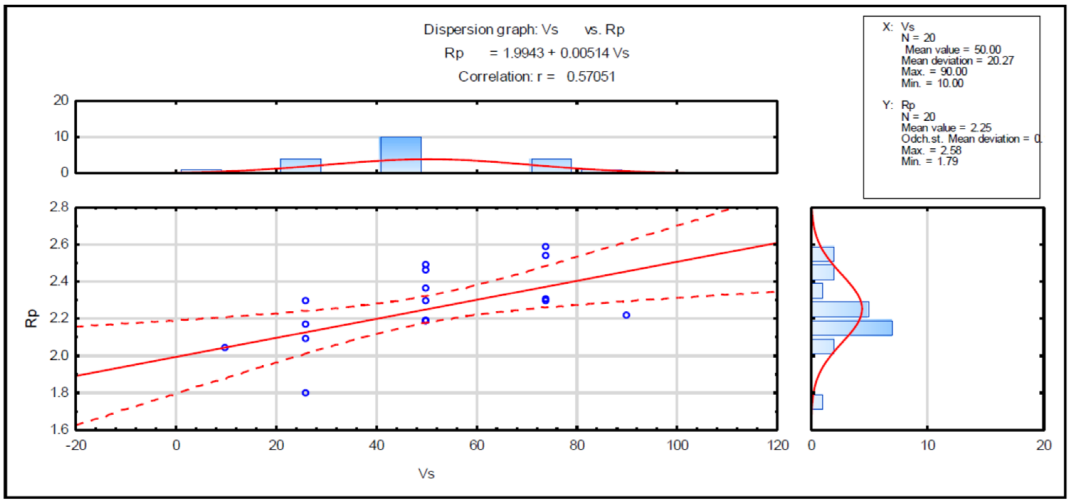

Fig. 13. Correlation of the input coefficient *K* and roughness parameter *Rp*

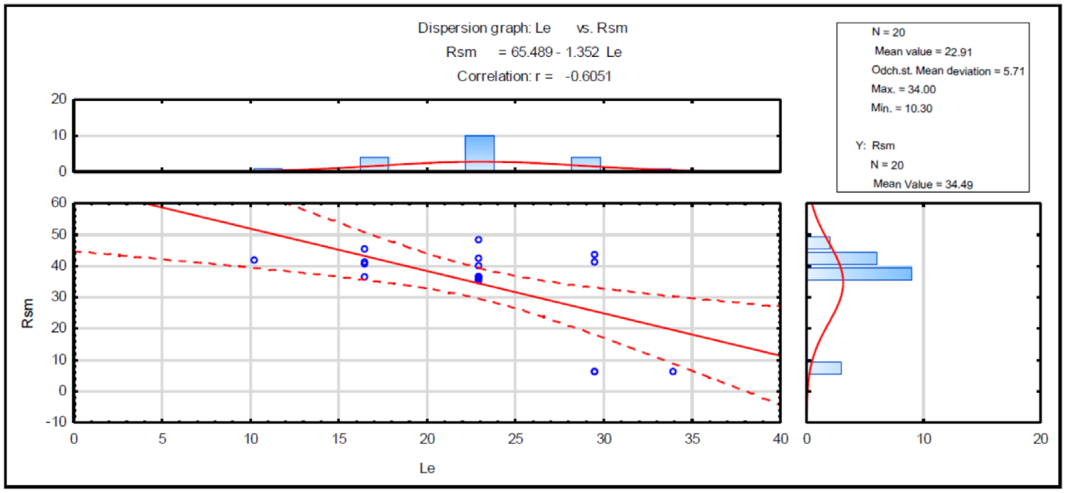

Fig. 14. Correlation of the input coefficient *K* and roughness parameter *Rsm*

Final conclusions

On the basis of the conducted research and analyses, the following general conclusions can be formulated:

- Developed and constructed innovative system of dosing the abrasive compound onto a disc lap brings significant savings in terms of the level of wear of micro-grains, thereby reducing the tool costs of this process of highly-precise machining,
- Analysed conditions of forced dosing, such as percentage content of the abrasive grains in the compound *K*, dosage of the compound V_s and viscosity of the liquid components of the compound have a significant influence on the basic parameters of the surface roughness of the machined technical ceramics,
- Regression equation developed in the result of the conducted research allows predicting the surface roughness parameter *Rz* for lapped sealing elements made of Al_2O_3 ceramics.

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prof. dr hab. inż. Adam Barylski - Politechnika Gdańska, Wydział Inżynierii Mechanicznej i Okrętownictwa, ul. G. Narutowicza 11/12, 80-233 Gdańsk
e-mail: abarylsk@pg.edu.pl

mgr inż. Maciej Gniot - Uniwersytet Technologiczno – Przyrodniczy, Wydział Inżynierii Mechanicznej, Al. prof. S. Kaliskiego 7, 85-796 Bydgoszcz
e-mail: maciej.gniot@utp.edu.pl

EFFECT OF THE SURFACE TREATMENT ON THE STRENGTH OF THE SINGLE-LAP ADHESIVE JOINTS

Wpływ obróbki powierzchniowej na wytrzymałość jednozakładkowych połączeń klejowych

Elżbieta DOLUK ORCID 0000-0003-2605-1394
Anna RUDAWSKA ORCID 0000-0003-3592-8047
Dana STANČEKOVÁ ORCID 0000-0003-0713-8750

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Abstract: The paper analyzed the shear strength of the single-lap adhesive joints made of zinc galvanized coat of steel sheet. Mechanical treatment of the samples was carried out using P120, P180, P220, P400 and P600 abrasive papers. In the experiment were used two variants of surface treatment: with a degreaser and without a degreaser.A two-component epoxy adhesive Epidian 53/IDA/100:40 was used to make the joints.The strength tests were carried out on a Zwick/Roell Z150 testing machine, PN-EN 1465 standard. The article contains also the results of the maximum force and the values of the surface roughness parameters (*Ra*, *Rz*, *Rq*) of the samples prepared without a degreaser. The measurements of surface roughness parameters (*Ra*, *Rz*, *Rq*) were made using a HOMMEL TESTER T1000 profilometer, according to PN-EN ISO 4287. The maximum value of the shear strength (2.70 MPa) was obtained for the samples prepared with P220 abrasive paper using a degreaser and the lowest (1.02 MPa) for the samples prepared with P180 abrasive paper using a degreaser.
Keywords: adhesive joint, shear strength, surface treatment, surface roughness

Streszczenie: W artykule przeanalizowano wytrzymałość na ścinanie jednozakładkowych połączeń klejowych wykonanych z ocynkowanej powłoki blachy stalowej. Obróbkę mechaniczną próbek przeprowadzono przy użyciu papierów ściernych P120, P180, P220, P400 i P600. W eksperymencie zastosowano dwa warianty obróbki powierzchni: z odtłuszczaczem i bez odtłuszczacza. Do wykonania połączeń użyto dwuskładnikowego kleju epoksydowego Epidian 53/IDA/100:40. Badania wytrzymałościowe przeprowadzono na maszynie wytrzymałościowej Zwick/Roell Z150, norma PN-EN 1465. W artykule zamieszczono również wyniki pomiaru siły maksymalnej oraz wartości parametrów chropowatości powierzchni (*Ra*, *Rz*, *Rq*) próbek przygotowanych bez odtłuszczacza. Pomiary parametrów chropowatości powierzchni (*Ra*, *Rz*, *Rq*) wykonano przy użyciu profilometru HOMMEL TESTER T1000, zgodnie z normą PN-EN ISO 4287. Maksymalną wartość wytrzymałości na ścinanie (2,70 MPa) uzyskano dla próbek przygotowanych papierem ściernym P220 z użyciem odtłuszczacza, a najmniejszą (1,02 MPa) dla próbek przygotowanych papierem ściernym P180 z użyciem odtłuszczacza.
Słowa kluczowe: spoina klejowa, wytrzymałość na ścinanie, obróbka powierzchniowa, chropowatość powierzchni

Introduction

Due to the growing demand for lightweight constructions, it is necessary to modify the methods used for joining materials. Bonding is one of the alternatives to traditional joining techniques such as mechanical fasteners or welded and solders connections [4, 8, 25]. The increasing use of adhesive joints in industry is associated with a number of advantages of this type of joint, like: ability to join different materials, reduction of the weight of the structure, corrosion resistance. One of the main disadvantages of the adhesive joint is the formation of stress concentrations in the adhesive layer [9, 16, 26]. It is so important to properly design the adhesive joint, which can occur in several configurations. The most common configurations are single-lap, double-lap and scarf joints [1, 9-11].

The first stage of bonding process is surface treatment of adherends [1, 2, 6, 17-20].The process has a significant influence on the strength and durability of the future adhesive bond. The surface treatment step should be carefully carried out to ensure the strongest adhesive joints are obtained and involves geometrical surface development and removal of impurities and surface layers of oxides from them [8, 13, 19-22].Knowledge of the type, structure and properties of the materials to be joined determines the choice of the appropriate surface treatment method [3, 4, 15, 22, 26].

Bonding of galvanized steel sheets is associated with many difficulties. Commonly used methods of joining these types of materials are often the cause damage near the joint. Therefore, additional processing is necessary which protects against possible crack propagation [7, 10].The industry often uses hot-dip galvanized and

electro-galvanized steel sheets, which are joined with adhesive. The treatment of galvanized steel sheets for the bonding process usually involves degreasing of joined surfaces, machining with abrasive tools, re-degreasing and etching. The use of agents with acetone for degreasing surfaces of hot-dip galvanized sheets results in increased strength of the adhesive joints 13, 19, 24].

The study was intended to determine the effect of the surface treatment (degreasing) and granulation of abrasive paper on the strength of adhesive joints made of hot-dip galvanized steel sheet.

Materials and methods

• *Adherend*

The subject of the study was a single-lap adhesive joint. DX51D Z275(PN-EN 10327) hot-dip galvanized steel sheets (1.0035 structural steel) were used in the test as the adherends. The weight of the zinc coating was 275 g/m^2. Selected mechanical properties are following (EN10346): (i) the tensile strength *Rm* is 270-500 MPa, and (ii) elongation A80 is 22% (min).The adhesive joint specimens are shown in Fig. 1.

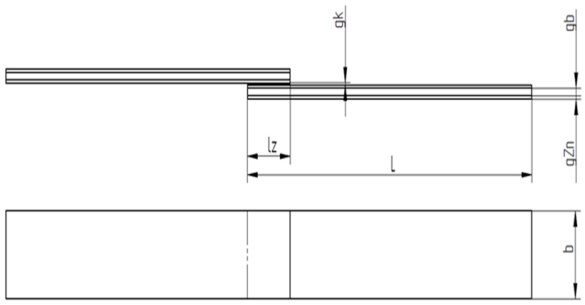

Fig. 1.Tested adhesive joints

The dimensions of the specimen were: length l=100±0,4 mm, width

b = 20 ± 0.4 mm, overlap length *lz*=15 mm, adherend thickness *gb*= 0.7±0.04 mm, adhesive layer thickness gk= 0.1 ± 0.02 mm, zinc coating thickness *gZn* = 0.018 mm.

• *Surface treatment method*

As a method of the surface treatment of hot-dip galvanized sheets, mechanical treatment with abrasive coating tools in the form of abrasive paper was used. Five abrasive paper of different gradation in the form of an A4 sheet were used for surface treatment: P120, P180, P220, P400, P600 (RS Components, Warsaw, Poland).The machining was performed using mentioned abrasive paper with 30 circular movements on each sample.

Two types of surface treatment variants were used in the experiment: with degreasing and without degreasing (Tab. 1).

Half of the samples were subjected to degreasing using acetone (PIKKO, Dragon Poland, Kraków, Poland) wiping off the wet surfaces with dust-free pads to remove impurities, as degreasing agent in 2 repetitions. In the case of degreasing, the rubbing method was used. After the second degreaser deposition, the acetone was left on the surfaces of the samples for complete evaporation (about 1 minute). The surface treatment of the second batch of samples consisted of an analogous mechanical treatment omitting the degreasing stage. The degreasing was carried out at a temperature of 25 ± 1°C and air humidity of 22 ± 1%.

• *Adhesive*

The samples were joined with a two-component epoxy adhesive consists of modified epoxy resin (Epidian 53, trade name) and amine curing agent (IDA, trade name). For epoxy resin with an epoxy number of 0,41 mol/100 g and amide curing agent with an amine number between 200 and 350 mg KOH/g, the range of this ratio is 40: 100 (amount of curing agent per 100 g of resin). The designation of epoxy adhesive is Epidian 53/IDA/100:40. The resin and amine curing agent are produced by CIECH Resins manufacturer, Nowa Sarzyna, Poland. The characteristic the epoxy adhesive components were presented in [23].The definite amount of the epoxy resin and amine curing agent were batched with an electronic scale (OX-8100 type, FAWAG S.A, Lublin, Poland, measurement accuracy 0.1 g, ISO 9001) in a polymer container. Then the epoxy adhesive components were mechanically mixed using an anchor stirrer at a speed of 460 RPM for 2 minutes on a mechanical mixing station and after that the epoxy compound was kept under vacuum for 2 minutes. The batching and mixing processes were made at temperature of 25 ± 1°C and humidity of 22 ± 1%.

The epoxy adhesive was applied on one of the surfaces to be bonded immediately after mixing. The adhesive joints were one step cold-cured for 10 days under

Table 1.Surface treatment variants–designations

Surface treatment variants	Abrasive paper				
	P120	P180	P220	P400	P600
Variant M (mechanical treatment)	MP120	MP180	MP220	MP400	MP600
Variant MD (mechanical treatment and degreasing)	MDP120	MDP180	MDP220	MDP400	MDP600

pressure of 0.09 MPa. The bonding was carried out at a temperature of 25 ± 1°C and air humidity of 22 ± 1%.

• *Tests*

The measurements of surface roughness parameters (Ra, Rz, Rq) were made using a HOMMEL TESTER T1000 profilometer for samples prepared with each type of abrasive paper in a variant without a degreaser (3 samples for each type of abrasive paper) according to PN-EN ISO 4287. The shear strength tests were carried out in accordance with the recommendations of PN-EN 1465standard on a Zwick/Roell Z150 testing machine (Zwick Roell GmbH & Co. KG, Ulm, Germany) assuming an initial force value of 5 N and a traverse speed of 5 mm/min.

Results

• *Surface roughness parameters*

The results of the measured surface roughness parameters of the single-lap adhesive joints prepared without adegreasing – Variant M (Table 1) are shown in Fig. 2.

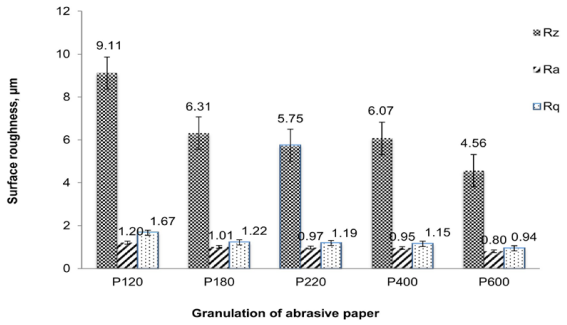

Fig. 2. Surface roughness results

Analyzing the test results presented in Fig. 2, it can be seen that for all measured surface roughness parameters, the maximum values (*Rz* = 9,11 µm, *Ra* = 1,20 µm, *Rq* = 1,67µm) were obtained for the samples treated with P120 abrasive paper and the minimum values (*Rz* = 4,56 µm, *Ra* = 0,80 µm, *Rq* = 0,94 µm) after processing with P600 abrasive paper. The differences between the extremes of individual parameters were respectively: *Rz* – 50%, *Ra* – 34% and *Rq*– 78%. For most samples, an increase in the abrasive paper grain size resulted in a decrease in the surface roughness parameters. The exception were the samples prepared using P400 abrasive paper, for which the value of *Ra* increased by almost 5% compared to the value of this parameter obtained using a lower granulation of abrasive paper, i.e. P220.

•Shear strength

The strength results of adhesive joints for both surface treatments variants are presented in Fig. 3.

The highest value of the shear strength of samples subjected to degreasing (2,70 MPa) was recorded after processing with P220 abrasive paper (MDP220). The lowest value for this variant (1,02 MPa) was observed for samples prepared with P180 abrasive paper. The difference between the extremes of variant with a degreaser was about 62%. For variant without a degreaser the highest value of the shear strength (2,53 MPa) was recorded for machining with P400 abrasive paper and the lowest (1,16 MPa) using P120 abrasive paper. These values differed by almost 54%. The difference between the maximum values of both variants was nearly 6%.

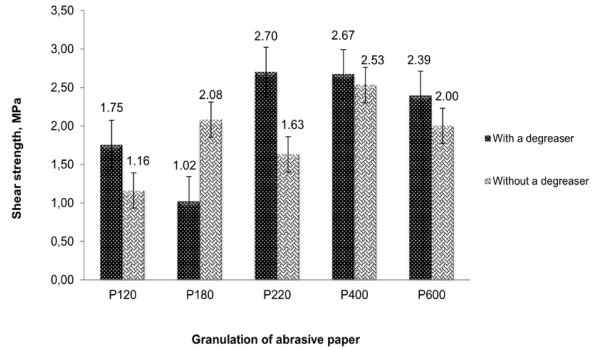

Fig. 3. Shear strength resultss

The strength results of samples treated with P120, P220, P400 and P600 abrasive papers for the variant using a degreaser were higher than for the samples prepared with the same abrasive papers without the use of a degreaser. These differences were as follows: P120 – 33 %, P220 – 40 %, P400 – 5 %, P600 – 16 %.The exceptions were the samples prepared with P180 abrasive paper without using a degreasing agent (MP180). The shear strength of samples prepared in this variant was about 50% higher than the shear strength of samples prepared with abrasive paper of the same granulation but with the use of a degreaser.

•Basic statistic analysis

The influence of the granulation of abrasive paper, surface treatment and their interaction on the shear strength was analyzed using ANOVA. It was stated that the all tested factors are not statistically significant for the shear strength ($p < 0.05$) at the 95% confidence interval (Tab. 2).

To determine the relation between the tested factors, the Pearson linear correlation coefficient r was calculated (Tab. 3).

The value of this coefficient for the granulation of abrasive paper is 0.45, which proves a moderate correlation between the shear strength and the granulation of abrasive paper. The coefficient of determination (r^2) is 0.20, which means the variability of the shear strength is in 20% explained by the variability of the granulation of abrasive paper. For the surface treatment, the *r* value is about -0.16, which indicates a weak correlation between

Table 2. ANOVA for the shear strength

Source	Sum of Squares	df	Mean Square	F-Ratio	p-Value
Variant M	6.45	4	1.61	2.68	0.05
Variant MD	0.62	1	0.62	1.03	0.32
Variant M Vs. Variant MD	4.29	4	1.07	1.78	0.16
Total error	17.45	29	0.60		
Total (corrected)	28.81	38			

Table 3. Correlations of tested factors

Correlation: shear strength vs	Mean	Standard deviation	*r*	r^2	p-Value
Variant M	103.56	1.77	0.45	0.20	<0.05
Variant MD	101.49	0.51	-0.16	0.02	0.34

the shear strength and the presence of the degreaser. The variation in the shear strength could be explained in 2% by variation in the presence of the degreaser (r^2 = 0.02).

Discussion

The strength of the adhesive joint is influenced by many factors. One of them is surface treatment. Prolongo and Ureña [15] noticed that pre-treatment effect depends on the adhesive nature, the order of the epoxy adhesive studied, as a function of its bonding strength remains constant. They also underlined that it scarcely depends on the applied pre-treatment. The article presents the effect of the degreasing and the surface roughing on the strength of adhesive joints made of hot-dip galvanized steel sheet. Based on the obtained results it can be stated degreasing usually allowed to obtain higher strength of the adhesive joint. Rudawska et al. [22] underlined that the strength results reveal that thesurface treatment method of galvanized metal sheets for adhesive bonding should take into account not only the type of degreasing agent but also the degreasing method, as the results reveal that these two factors have a significant effect on the strength of the tested adhesive joints. The maximum value of the shear strength in the variant with degreasing was obtained for P220 abrasive paper (MDP220) and without degreasing for P400 abrasive paper (MP400). The use of a degreasing agent is associated with the possibility of using a lower granulation of abrasive paper. In work [18] it was observed that the most advantageous method of surface preparation of structural steel C45, aluminium alloy EN AW-1050A and stainless steel 1,4401 is treatment using P220 grit abrasive paper. Analyzing the results it can be notice that the surface roughness is reasonable up to certain values. Rudawska et al. [17] also indicated that both surface roughness and adhesive properties are more affected by the type of abrasive material used rather than by variations in pressure. In addition in work [20] it was noted that with increasing roughness, the strength of the joints also increases, which confirms the influence of surface treatment on strength of adhesive joints. Optimum surface roughness is essential to obtain the maximum strength of adhesive joint [3, 11, 13] and depends on the adherends.

Conclusions

The analysis of the results allows the formulation of the following conclusions:

- the use of a degreasing during the samples treatment allowed to obtain the highest shear strength of the single-lap adhesive joints;
- the granularity of abrasive paper used for the surface treatment affects the strength of the adhesive joint;
- the maximum value of the shear strength (2,70 MPa) was obtained for the variant with a degreaser and using P220 abrasive paper;
- the minimum value of the shear strength (1,02 MPa) was obtained for the variant with a degreaser and using P180 abrasive paper;
- in most of the tested samples the surface roughness parameters *Rz*, *Ra*, *Rq* decreased with increasing granularity of abrasive papers.

The experimental results demonstrate that adhesive joint strength greatly depends on the applied degreasing process. In addition, adhesive joint strength is affected by the granularity of abrasive paper used for the surface treatment, too.

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mgr inż. Elżbieta Doluk (corresponding author)
Lublin University of Technology, Mechanical Engineering Faculty, Nadbystrzycka 36, 20-618 Lublin, Poland,
e-mail: e.doluk@pollub.pl

dr hab. inż. Anna Rudawska, prof. PL
Lublin University of Technology, Mechanical Engineering Faculty Nadbystrzycka 36, 20-618 Lublin, Poland
e-mail: a.rudawska@pollub.pl

Dana Stančeková3
University of Žilina, Faculty of Mechanical Engineering, Univerzitna 1, 010 26, Žilina, Slowak Republic,
e-mail: dana.stancekova@fstroj.uniza.sk

ANALYSIS OF THE ANGULARITY OF THE SURFACE IN THE AXIAL SECTION OF THE WORM WHEEL OBTAINED BY COMPUTER SIMULATION OF MACHINING

Analiza graniastości powierzchni w przekroju osiowym ślimacznicy uzyskanej metodą komputerowej symulacji obróbki

Łukasz RĘBISZ ORCID 0000-0001-8424-3736

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Abstract: Obtaining an accurate worm wheel requires a wheel model with the appropriate accuracy. This model can be obtained by computation, however, this is a complex and labor-intensive issue. In the CAD environment, there is a possibility of simple and quick modeling of the dentition, which is an alternative to mathematical calculations. It consists in creating micro surfaces and their approximation. The paper presents a comparative analysis of two methods of approximation of a discrete surface and the influence of modeling accuracy on the deviation of the profile of a wormwheel tooth was determined. It has been shown that the use of 30 surfaces allows to obtain the required accuracy of the outline.
Keywords: worm wheel, machining, CAD/CAM

Streszczenie: Uzyskanie dokładnej ślimacznicy wymaga modelu koła o odpowiedniej dokładności. Model ten można uzyskać na drodze obliczeń. Jest to jednak zagadnienie złożone i pracochłonne. W środowisku CAD istnieje jednakże możliwość prostego i szybkiego zamodelowania uzębienia stanowiąca alternatywę do przeprowadzania obliczeń matematycznych. Polega ona na utworzeniu mikropowierzchni oraz ich aproksymacji. W pracy dokonano analizy porównawczej dwóch metod aproksymacji powierzchni dyskretnej oraz określano wpływu dokładności modelowania na odchyłkę zarysu zęba ślimacznicy. Wykazano, że zastosowanie 30 powierzchni umożlia uzyskanie wymaganej dokładności zarysu.
Słowa kluczowe: koło ślimakowe, obróbka, CAD/CAM

Introduction

Obtaining the correct geometry of the worm gear wheels and the correct trace of their contact is a difficult process. The methods of obtaining the correct geometry of the screw have been described, inter alia, in articles [2, 7, 8, 12]. In the case of a worm wheel, usually in industrial practice only a simplified outline is obtained. Unfortunately, this has negative consequences for the proper cooperation and durability of the gear. In order to obtain the correct contact pattern of the gears, give the gears to the wheel lapping process. However, it should be remembered that this process has its limitations and disadvantages. These limitations are especially important when we want to use a worm wheel that would be able to withstand a greater load with less susceptibility to wear. In such cases, it would be advisable to obtain a more accurate worm wheel.

For a more accurate worm wheel, a sufficiently accurate wheel model is required. This model can be obtained by calculations resulting from the kinematics of the gear operation. For such calculations, we try to determine the correct geometry based on the required contact trace. The principle of operation of this type of methods and their possible application to the analysis of the operation and strength of the transmission are presented in articles [4, 5, 6].

An alternative to mathematical calculations may be the appropriate adaptation of the machining simulation method to create a worm wheel model [11]. On its basis, the created micro-surfaces are approximated. The smoothing process is necessary to obtain a better surface quality. However, the literature on the subject does not state the accuracy of this method. Therefore, the aim of the article is to determine the influence of modeling accuracy on the deviation of the contour of a worm wheel tooth.

Materials and methods

The machining simulation method is based on simulating the contact of the tool with the workpiece. When cutting the worm wheel, the worm becomes a tool. The model of the worm wheel shell was adopted as the workpiece. The method requires the determination of the kinematics of cooperation. For the considered

Table 1. Systems defining kinematics on the work of the worm gear and worm wheel

Case No.	Type of worm movement	Type of worm wheel movement
1	Rotation	Rotation
2	Translation	Translation
3	Rotation	Translation
4	Translation	Rotation
5	Translation and rotation	No movement
6	No movement	Translation and rotation

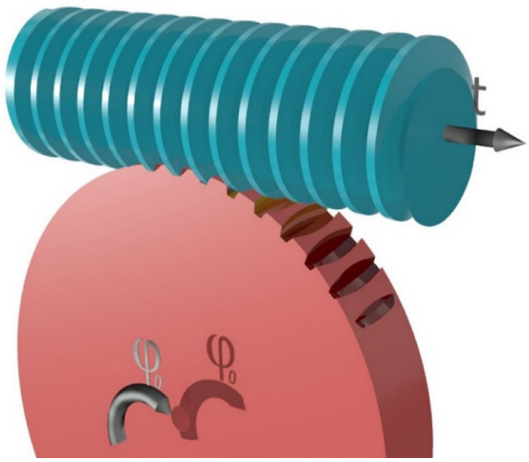

Fig. 1. Scheme of the system adopted for simulation (variant 4 from Tab. 1)

transmission, 6 systems defining the kinematics are available (Tab. 1).

System No. 1 is usually the first choice as direct transmission adaptation. Unfortunately, due the way CAD software works, does not always give the best results [9, 10]. The principle of operation of this method according to the layout No. 4 is shown in Fig. 1.

The practical application of the method is based on the execution of a task loop which consists of:

– snail translation,
– rotation of the worm wheel,
– performing the "pain" algebra operation (difference: we subtract the snail from the envelope; the snail remains available).

These operations are repeated until the entire interdental notch is obtained. In order to automate this process, Visual Basic Language [1, 3] was used in the CAD software.

It is important for the process that the result is a set of micro surfaces, not a single surface. This means that in the axial plane and other planes perpendicular to the axis of the worm wheel, we will not obtain the curve forming the outline directly. We only get a certain number of episodes. The necessity to approximate these elements causes the contour mapping error. Therefore, in the further part of the work, the focus was on determining the inaccuracy of the method for the adopted simulation parameters.

The choice of the approximation method

There are few studies in the literature on the influence of the approximation method on the accuracy of the worm wheel modeling [9, 10, 11]. For this reason, it was decided to test two simple-to-implement methods of discrete surface approximation for the selected simulation step. Fig. 2 shows a comparison of both methods. One of the methods (Fig. 2) is based on drawing the curve (red line) through the points of intersection of the surface edge with the axial plane. The second method is to draw a curve (green line) through the centers of the segments built at the edges of the intersection of the surfaces. Other methods can also be used, however, this involves a significant complexity of the process. As shown later in the article, the accuracy of the results obtained with the chosen method seems to be sufficient for the considered element.

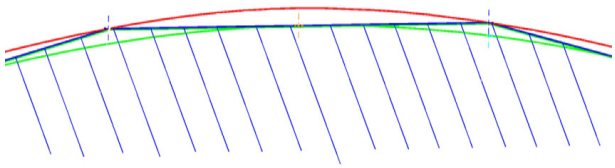

Fig. 2. Comparison of discrete surface approximation methods

Table 2. Parameters adopted for the simulatio

No. simulation	Rotation angle (°)	Offset value (mm)	Number of simulation steps	Number of surfaces obtained
1	6	6.283185307	6	6
2	4	4.188790205	8	8
3	3	3.141592654	11	11
4	2.4	2.513274123	14	14
5	2.142857143	2.243994753	15	15
6	2	2.094395102	16	16
7	1.875	1.963495408	17	17
8	1.5	1.570796327	20	20
9	1.25	1.308996939	25	26
10	1	1.047197551	30	32
11	0.5	0.523598776	59	64

The values of the deviations determined for individual methods were shown in Tab. 3. The comparison of these methods shows that the absolute value of the deviation is very similar. Unfortunately, the first method is not suitable for further analyzes because, due to the direction of the deviation, it may lead to incorrect contact of the gears and the effect of the system jamming. Tab. 2 presents the parameters adopted for the simulation.

The simulation No. 5 was deliberately carried out with an irrational angle of rotation and displacement in order to check how important the error resulting from the lower accuracy of the program regarding the angular dimensions would be for the size of the tooth deviation.

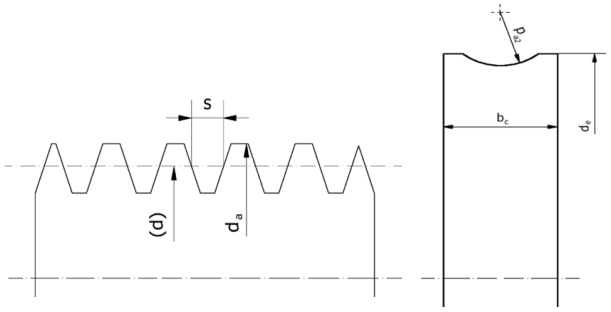

Fig. 3. Modified dimensions of the worm wheel

Purification before brazing process

The produced and checked resonator, being positively admitted to further assembling, obtains its individual number with the assigned table of mechanical size measurements. A positive reaching of all expected parameters allows chemical preparing of the structure's elements to the process of their mechanical and permanent joining by brazing. Purity of the materials before soldering of the cavities is very important [2, 3]. Dirt and the oxides, generated during the treatment have a negative effect on electric conductivity and decrease the wettability of the solder. The cavities are washed in ultrasonic scrubber in the mixture of petrol and acetone and then, they are rinsed with distilled water. After the mentioned treatment, they are subjected to the electro-polishing. The completion of purification process puts extremely difficult requirements concerning hygiene regime before the operators, implementing the successive stage of the structure production.

Modification of the worm and worm wheel

When creating a worm wheel, the problems resulting from the modeling techniques used, and problems with a different treatment method than usual should also be taken into account. Fig. 3 shows the dimensions of the model that have been intentionally modified to prevent certain phenomena.

Fig. 3. Modified dimensions of the worm wheel.

Two modifications were made on the cochlea. Both were related to the necessity to take into account the lateral clearance values. In the case of, for example, all-round technology, the lateral play is an automatically generated element. This is due to the behavior of the tool and shell during machining. However, when using the machining simulation method, a discrete surface is obtained that does not take into account the clearance value. It follows from this that it is necessary to introduce the value of the slack on the component (worm) which is the tool cutting the worm wheel in order to obtain the discrete surface transformed by the value of the slack in the appropriate direction. That is why the outer diameter of the worm d_a was increased and the thickness of the tooth s in the axial section was reduced by the value of the lateral play.

Three elements were modified in the worm wheel. The outer diameter d_e is increased, the concavity radius p_{a2} is decreased, and the worm wheel width b_c is increased. These modifications were necessary due to the use of a "spline" curve as an element approximating a discrete surface. The introduction of these modifications made it possible to generate additional points that allow to determine the tangency of the curve for the end points. This allowed for a smaller deviation of the profile of the worm wheel tooth.

Results and discussion

Conducted simulations and analyzes allowed to assess the impact of modeling accuracy on the deviation of the worm wheel tooth profile (rys. 4, 5). Table 3 presents the most important input data for individual simulations and information on the number of surfaces under consideration. All simulations were performed for the same kinematic system. The variable element was the number of simulation steps. Note that the number of surfaces forming the contour of a worm wheel tooth is not always the same as the number of simulation steps. The inaccuracy regarding the ratio of the number of points measured to the number of surfaces forming the side of the tooth of the generated worm wheel results from the type of envelope adopted and the measurements limited to the axial plane. Not all of the generated surfaces are necessary for axial measurements. However, their number is important if we would like to conduct further research.

Table 3 shows examples of the deviation values along the tooth height obtained by simulating the surfaces 6, 8 and 11. The deviation values given in the table are absolute values. Relationship (1) allows you to relate the value of the deviation in relation to the axis of the screw.

$$d_{zi} = \frac{a - r_{ki}}{2} \tag{1}$$

Fig. 3. Deviation values

6 surfaces			8 surfaces			11 surfaces		
No.	Deviation value (µm)	Worm diameter (mm)	No.	Deviation value (µm)	Worm diameter (mm)	No.	Deviation value (µm)	Worm diameter (mm)
1	8.292887	115.0733617	1	3.948354	114.6690336	1	1.739283	114.4846455
2	26.062451	117.9739879	2	9.18649	116.3489535	2	4.82334	115.6477044
3	30.599552	121.9579928	3	10.836457	118.5296151	3	5.055735	117.0974698
4	22.075501	126.9223807	4	12.94157	121.1839893	4	6.611305	118.823448
			5	17.690217	124.2817277	5	7.262665	120.8138014
			6	5.478508	127.7905919	6	8.57126	123.0557023
						7	9.089895	125.5356745

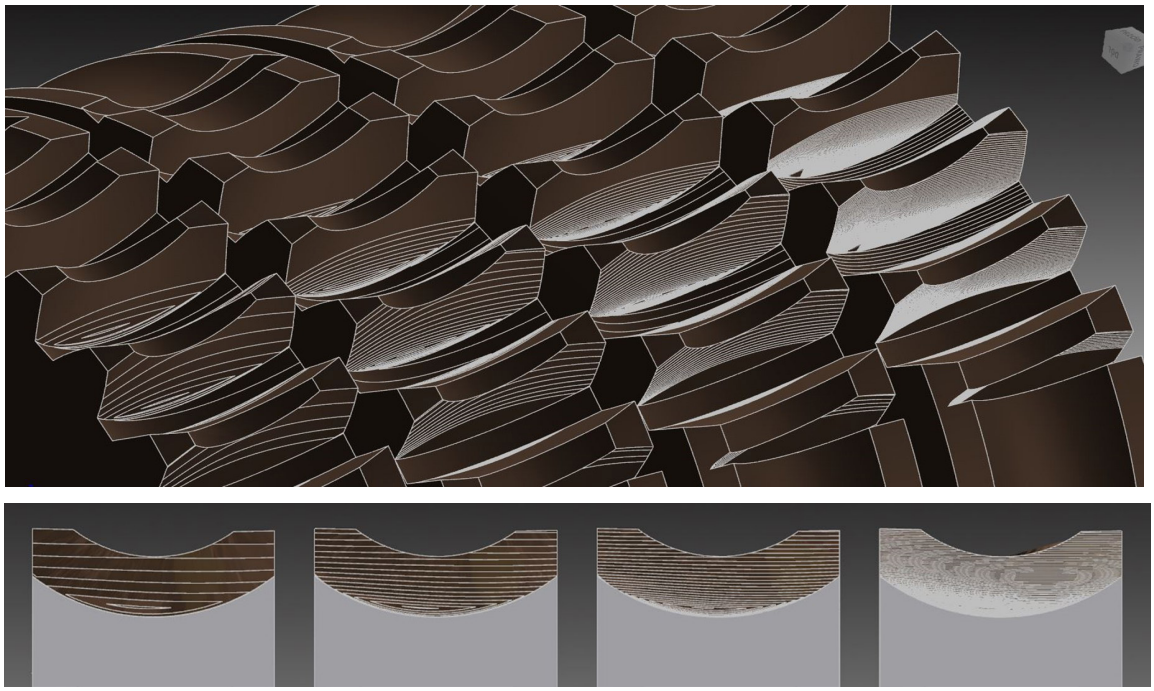

Fig. 4. Surfaces obtained as a result of the simulation

where:
d_{zi} – the conversion value of the diameter in relation to the worm axis (mm),
a – gear axis distance (mm),
r_{ki} – value of the radius of the worm wheel on which the measurement was made (mm).

Based on the simulation, the influence of the number of surfaces on the outline deviation was determined (Fig. 6). The analysis of Fig. 4 shows that the use of 30 surfaces makes it possible to obtain the required accuracy of the outline. Further increasing the amount of space seems to be pointless, as it does not contribute to a significant improvement in the accuracy of the simulation with a significant increase in its labor consumption.

Fig. 6. The influence of the number of surfaces on the deviation of the outline (in the axial section).

The maximum value of the deviation depending on the number of surfaces, disregarding the results of simulation No. 5 conducted with an irrational angle of rotation and shift, can be determined on the basis of the relationship (2):

$$y = 1205.3x^{-2.025} \quad (2)$$

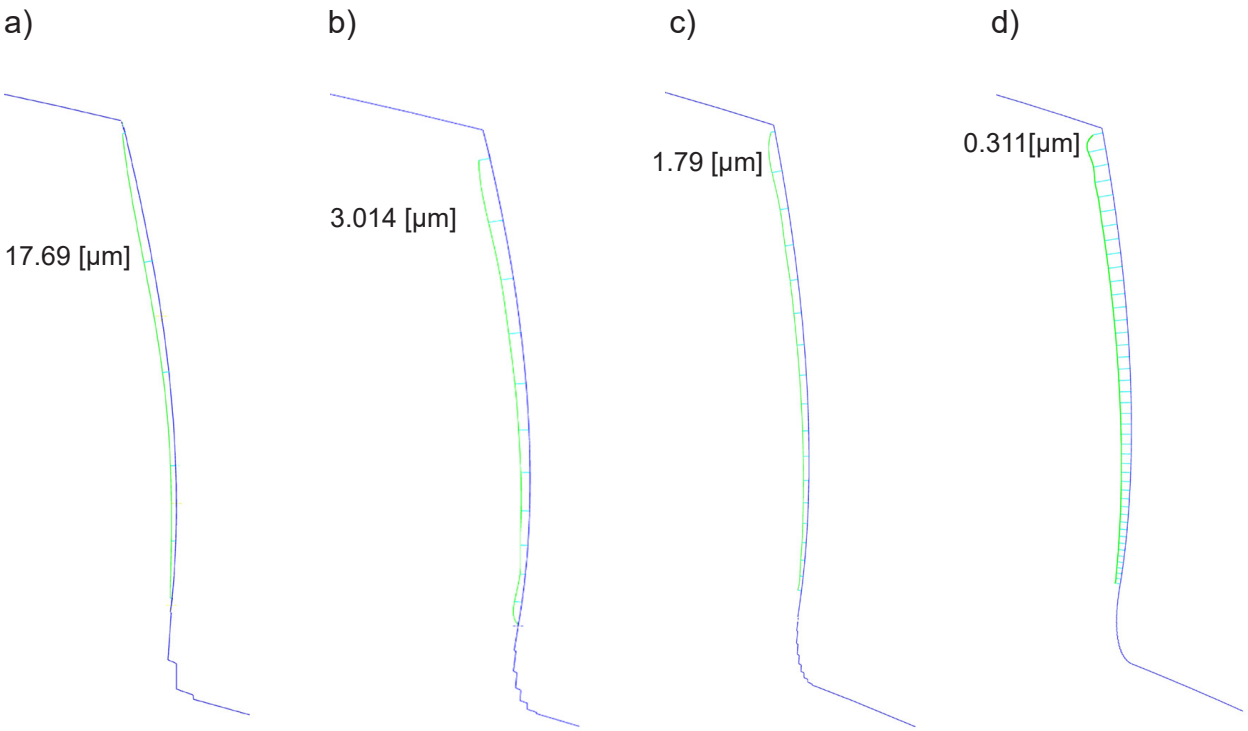

Fig. 5. Distribution of deviations for selected simulations and the maximum values for: a) 8 surfaces. b) 17 surfaces. c) 26 surfaces. d) 59 surfaces

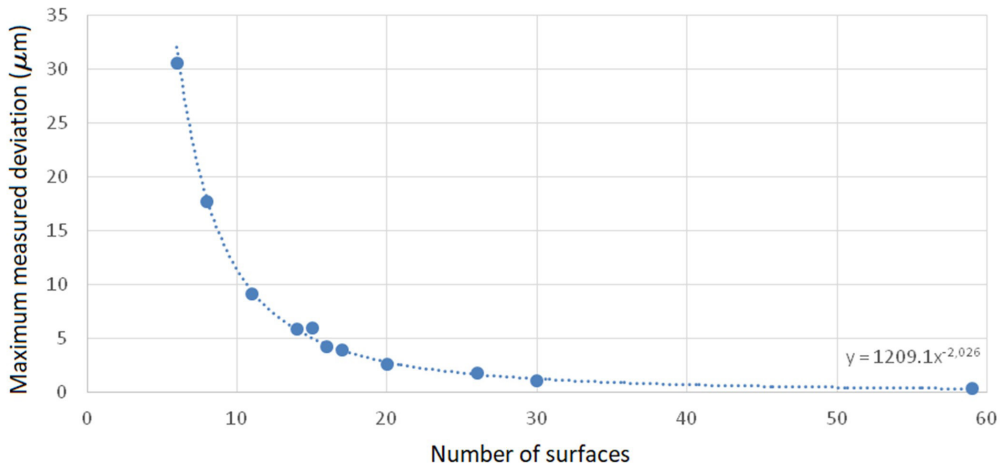

Fig. 6. The influence of the number of surfaces on the deviation of the outline (in the axial section)

while taking into account the results of simulation No. 5 based on the dependence (3):

$$y = 1209.1x^{-2.026} \quad (3)$$

This allows for the exact selection of the number of surfaces depending on the required accuracy of the outline.

Conclusions

Modern CAD/CAM software provides new possibilities both at the stage of design and technology of gear teeth machining. Development of the worm gear teeth model directly in the CAD environment is not an easy task. This is due to the fact that the tooth contour is different in each cross-section.

Creating a worm wheel by simulating machining allows to obtain a virtual model of the worm wheel. This can be useful for e.g. examining the gear contact pattern, or it can be used as a template for CAM programs using manufacturing techniques other than envelope machining. In addition, the method allows you to generate a worm wheel model for any contour without the need to produce a cutter with a special contour. Thanks to the machining simulation method, it is possible to obtain a virtual

model of the worm wheel with an accuracy sufficient for simulation errors to have a negligible impact on the part being made.

The simulations carried out in the work allowed to assess the influence of the modeling accuracy on the deviation of the worm wheel tooth profile. On their basis, it has been shown that to obtain the required accuracy of the outline, it is necessary to generate about 30 surfaces forming the outline of a worm wheel tooth. The use of a larger surface area does not significantly affect the accuracy of the contour of the worm wheel.

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mgr inż. Łukasz Rębisz
Rzeszow University of Technology
al. Powstańców Warszawy 8
Rzeszów 35-959, Poland
lr_ktmiop@prz.edu.pl

AUTOMATIC COMPENSATION OF ERRORS OF MULTI-TASK MACHINES IN THE PRODUCTION OF AERO ENGINE CASES

Automatyczna kompensacja błędów obrabiarek wielozadaniowych w produkcji kadłubów silnika lotniczego w warunkach produkcyjnych

Grzegorz SZYSZKA
Daniel KWIATANOWSKI
Jarosław SĘP ORCID 0000-0003-2544-2211
Katarzyna ANTOSZ ORCID 0000-0001-6048-5220

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Abstract: The article presents a procedure which has been developed for rapid machine tools geometry selected errors compensation without machining process interruption, during long-term machining in the industrial shop floor conditions with the use of touch probe. The method presented in the article aim to increase quality of large machining components (DIA > 1000 [mm]) and a significant difference of the part height for aerospace industry, with machined on the same production line, to achieve zero non-conformances and minimize the effort of manufacturing engineers of process control. The article presents results of tests and implementation methodology results for large, sheet metal engine cases production on 5-axis multitasking machines. Presented method is directly connected with specific engine components manufacturer needs however it gives an opportunity for other industry areas implementation.
Keywords: CNC, part probing, 5-axis machining, machine accuracy, aviation industry

Streszczenie: W artykule przedstawiono procedurę, która została opracowana w celu szybkiej kompensacji wybranych błędów geometrii obrabiarek bez przerywania procesu obróbki, podczas długotrwałej obróbki w warunkach hali przemysłowej z wykorzystaniem sondy dotykowej. Przedstawiona w artykule metoda ma na celu podniesienie jakości dużych elementów obróbczych (DIA> 1000 [mm]) oraz znaczną różnicę wysokości części dla przemysłu lotniczego, obrabianego na tej samej linii produkcyjnej, aby uzyskać zerowe niezgodności i zminimalizować wysiłek inżynierów wytwarzania kontroli procesu. W artykule przedstawiono wyniki badań i metodyki wdrożeniowej do produkcji dużych blaszanych obudów silników na maszynach wielozadaniowych 5-osiowych. Przedstawiona metoda jest bezpośrednio związana z konkretnymi potrzebami producentów podzespołów silnika, jednak daje możliwość wdrożenia w innych obszarach przemysłu.
Słowa kluczowe: CNC, sondowanie detali, obróbka 5-osiowa, dokładność maszyn, przemysł lotniczy

Introduction

The use of 5-axis machine tools in production processes is currently a common phenomenon in practically every branch of industry and especially in the aviation industry, due to the possibility of complex manufacturing of geometrically complex objects [1]. The production of advanced components for aircraft engines is usually characterized by a small number of pieces in production batch, variability of the products made and a long production time. A key aspect in aviation production is the quality of manufactured elements, and new designs of aircraft engines place ever higher demands on the accuracy and repeatability of machining processes.

The accuracy of the part is significantly influenced by the machine tool error, which can generally be defined as the difference between the actual and programmed position of the tool in relation to the machined assembly. This difference is causing among others by errors forced by the production process and changing production environment [2]. The most common errors which occursin the implementation of production processes are [3]: geometric errors, kinematic errors, thermal errors, errors in drives and measurement systems, errors caused by the machining process, errors in product measurement systems, errors due to natural wear and tear or history of use.

A particularly important parameter, influencing the stability of the machine tool operation, is the variability of the ambient temperature in the production environment combined with the temperature influence of the machine tool units. Large gradients of the daily temperature change cause the formation of thermal errors in the machine tool, significantly affecting the correctness of its geometry, which directly affects the quality of the workpiece and may be a decisive factor for the dimensional and shape compliance of its performance [2].

In the case of the aviation industry, 5-axis multi-task machining centers are particularly useful machines that enable the implementation of complete machining in one

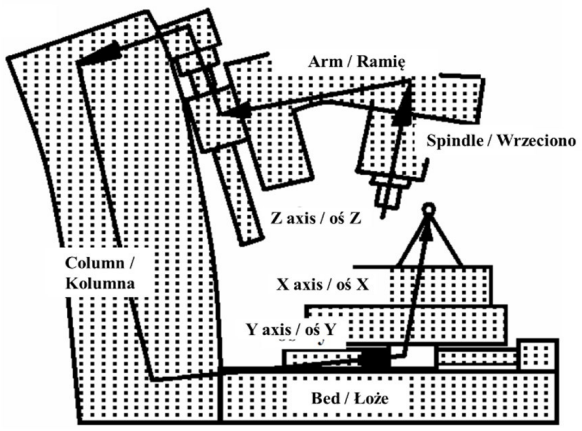


Fig. 1. The nature of changes in the geometry of the machine tool under the influence of thermal deformations [2, 4]

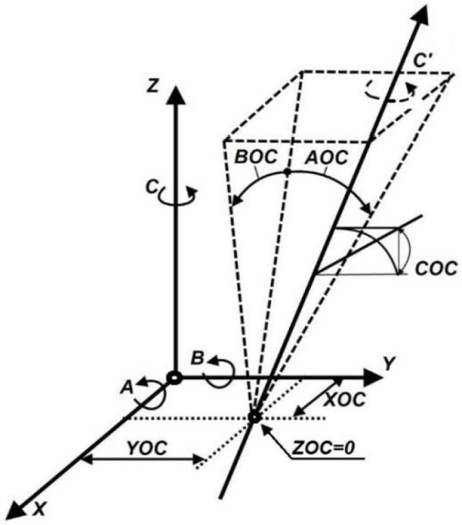


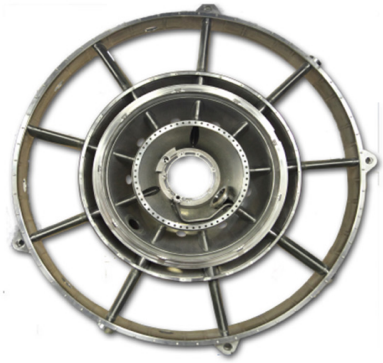
Fig. 2. Displacement of the kinematic center of the rotary axis, where [6]:
- X, Y, Z are numerically controlled linear axes, intersected in the initial position,
- A, B, C - are rotaryin the initial position,
- axesXOC, YOC, ZOC - shifts of the kinematic center of rotation of the axis,
- AOC, BOC, COC - angles of rotation of individually numerically controlled axes,
- C'- new position of the center of rotation of the C axis.

clamping, thanks to the possibility of a comprehensive combination of many types of machining, from turning, through drilling, milling, boring, threading to grinding, which allows for obtaining geometrically complex elements maintaining the required dimensional and geometric tolerances subjects [5]. Due to their design, large, 5-axis, vertical multi-task machine tools with a tilting head are particularly exposed to the impact of the above-described thermal errors that have a destructive effect on their geometry, and additionally, due to the design of the tilting head, they are exposed to deformations resulting from component forces from the process turning, which increase the geometric and kinematic errors of the machine tool. This is of particular importance in complete machining processes, where deformations of the geometry, after the turning part of the process, negatively affect the quality of the milling and drilling part of the process, especially the conditions of the position of the holes.

The above-described errors directly affect the position of the center of the kinematic rotation of the rotary axes, the errors of the rotary axes influence each other and, as a result, affect the quality of the machined parts. The displacement of the kinematic center of rotation of the -C- axis (intersections of the XYZ controlled axes) can cause errors in the produced parts both for 5-axis simultaneousmachining [1] and indexed. Fig. 2 shows the positioning errors of the rotary axis center of rotation -C-. The shift of the kinematic center of the C axis is described as XOC, YOC, ZOC and the individual torsion angles about numerically controlled axes denoted as AOC, BOC, COC where -X-, -Y-, -Z- are linear axes and the axes -A-, - B- and -C- are rotary axes. -C'- is the new point of actual rotation of the -C- axis [6].

This issue is of particular importance in the production of large cases for aircraft turbine engines (part ø> ø 1000 [mm]), which due to their design characteristics require a significant number of holes in the flanges or external and internal surfaces (Fig. 3a and 3b), using the index of the machine table, usually within tight tolerances of

a)



b)

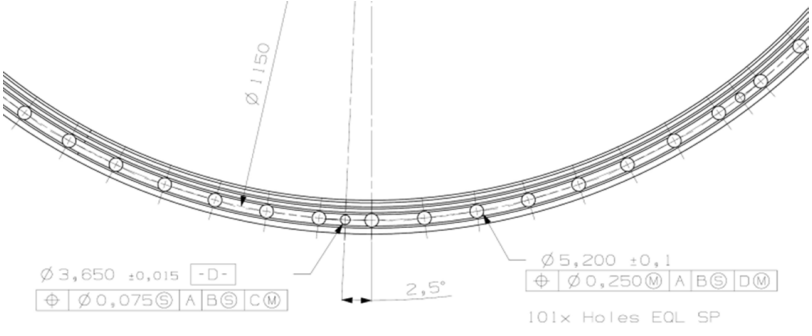


Fig. 3. Parts of the fuselage type of an aircraft turbine engine:
a) general view,
b) example requirements of the construction drawing, tolerance of the position of the holes in the fuselage flange.

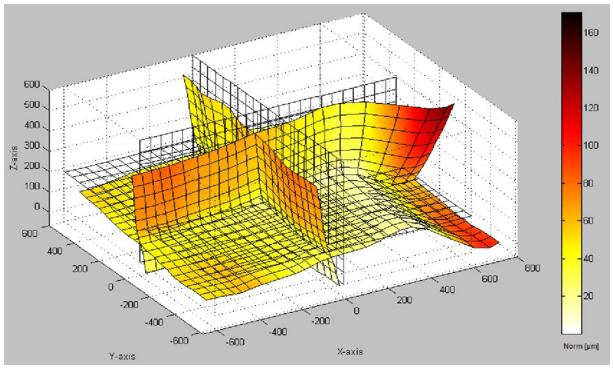


Fig. 4. Visualization of the value distribution of the vector field of spatial positioning error for tool reach Z = -400 [mm], measurement of the analyzed machine tool made with the use of the EtalonLaserTracer-MT tracking interferometer.

the condition of the position of the holes, in relation to the construction bases parts, which in particular requires minimizing the position error of the center of rotation of the -C- axis with respect to the machine spindle axis in the -XYZ- plane. The necessity to use the axis of rotation, instead of the movement with linear axes, usually results from the design limitations of the machine tool, where the travel behind the axis of rotation is from 5 [mm] to several hundred mm.

The use of the axis of rotation of the C axis also allows for higher accuracy of hole positions for large-size products, which results from the usually highest accuracy of the machine tool in its central part when setting and compensating the machine tool without using volumetric compensation. Machining of holes with the use of cycles allows you to reduce the movements of the machine tool only to the rotation of the table (C axis) and spindle movement (Z axis). Fig. 4 shows an example of the results of the measurement of the machine tool geometry in the entire machining space, where in the extreme positions of the linear axes, the machine tool geometry is burdened with the greatest error. The smallest error is in the center and at the level of the machine table.

Problem description

Currently, modern CNC machine tools used in in the aviation industry, the vast majority of them are equipped with systems that enable testing and compensation of the position of the kinematic center of the rotary axes based on the measurements of the standards with the use of the object probe. Product measurement probes are nowadays an indispensable equipment of a machine tool and are used not only to accurately determine the position of the product, process adaptation, or measurement of characteristics after the end of the process, but also to control and compensate machine tool errors. Machine tool compensation systems using product measurement probes can be divided into:

- dedicated, built into the CNC system, prepared by the manufacturer, e.g. Mazacheck (Mazak), 5-axis Auto Tuning System (Okuma), 3D-Quick Set (DMG), etc.
- universal, e.g., Cycle 996 (Sinumerik), AxiSet (Renishaw), MSP NC Checker (MSP) [6].

In the production company where the tests were carried out, the Mazak Integrex e-1600V machine tools used in the production process (Yamazaki Mazak Corporation, Oguchu-cho, Japan) are equipped with a dedicated error compensation system "Intelligent Mazachek" to correct the kinematic center of rotation of the C axis (table) and the B axis (tilting head). This system allows for the compensation of machine tool errors with the use of the object probe and standards in the form of calibration balls and a length standard mounted in the machine tool spindle. The system is widely used in production practice at Pratt & Whitney Rzeszów SA (PWR).

Fig. 5 shows the machine areas that are compensated by the „Intelligent Mazacheck” function.

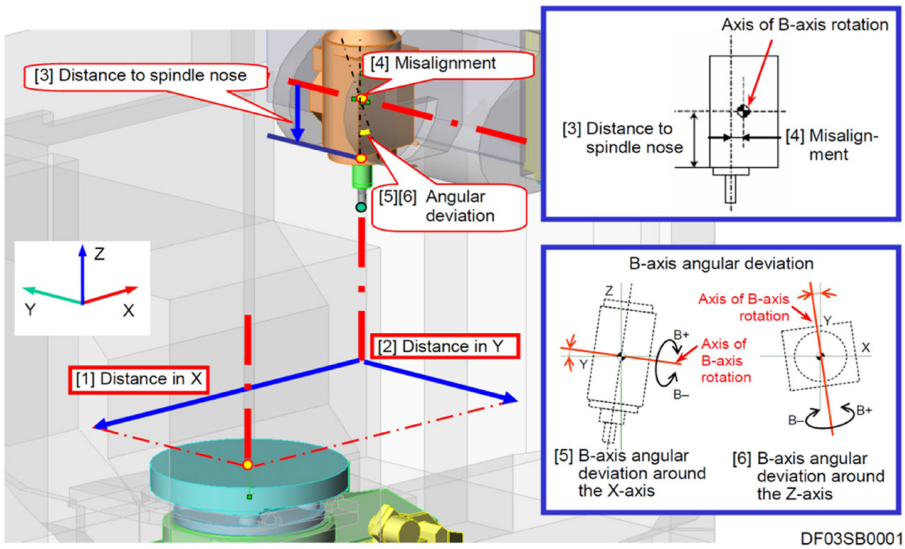


Fig. 5. Dimensions essential for maintaining high accuracy of 5-axis machining, compensated by the "Intelligent Mazacheck" function for a vertical machine tool with a tilting head [7]

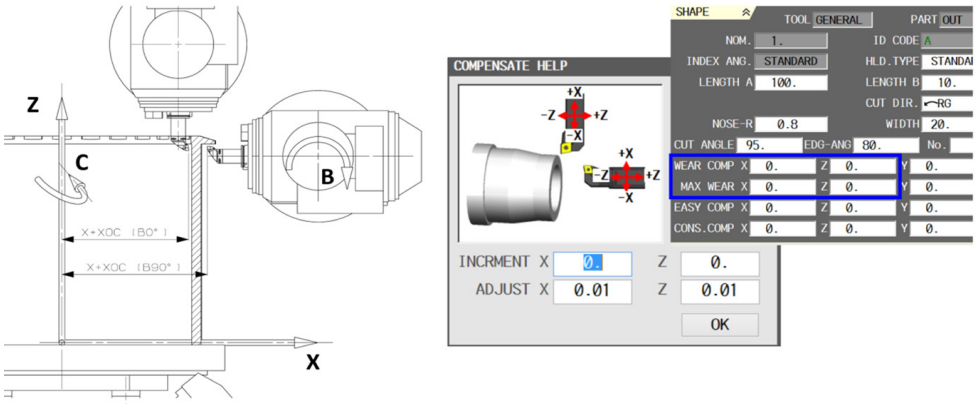


Fig. 6. Influence of XOC error a) diagram for a machine tool system with a tilting head in the B axis, b) definition, correction and control table of a turning tool (CNC MazatrolSmoothX) - allocation of XOC error in the case of lack of its compensation [9]

Despite the high efficiency of the compensation implemented by the above-described system, in production conditions there were such problems as:

1) How to compensate the error of changing the position of the center of rotation in a dynamic manner, during long-term operation of the machine tool, without interrupting the machining process, in periods of high daily temperature variation (no air conditioning)?
2) How to compensate for the error of changing the position of the center of rotation for products with variable height in order to minimize the error increase with the increase of the distance of the machining place in the Z axis from the machine tool table?
3) How to compensate the programmable center of rotation error with the real axis of rotation in turning operations?

The compliance of the software center of rotation with the actual product rotation axis is also important in turning operations. The value of the XOC error, the position of the kinematic center of rotation in the X axis (for the Mazak e-1600V machine tool system), directly affects the value of the measurement result with object probes equipped with styluses of a special shape, working in hard-to-reach areas (e.g. measuring internal / external channels), which is usually due to the possibility of using only a single point measurement along the X axis (eg Renishaw Inspection Plus, cycle O9611, O9811) [8], and also affects the value of tool wear correctors. The minimization of tool correction variability allows not only for more repeatable process performance, but also for more accurate process security in the form of the imposition of control gates with tight tolerance, both on the value of the machined diameter and on the value of the correction of the dimensions of the turning tool.

Fig. 6 a) and b) shows the influence of the XOC error on the tool value correction, for a 5-axis multi-task machine with a tilting head, for different head positions (B0 ° and B90 °) for external and internal turning.

In response to the above-described issues, research was undertaken to improve the error compensation process, and thus minimize the impact of the machine tool on the final product quality

Goal and scope of research

The aim of this article is to present the developed methodology of effective compensation of the kinematic center of rotation of the table, for the Mazak e-1600V machine tool, during product processing, for long-term processes in changing environmental conditions

and machine tool loading, without the need to interrupt the process, in an automatic cycle

with using the available technological equipment and equipment of the analyzed machine tool.

The method presented in this article has been developed and implemented in order to minimize the risk of manufacturing non-compliant aircraft turbine engine cases, stabilize the machining process, reduce maintenance costs and production downtime.

The main goals of the development of the active compensation methodology are:

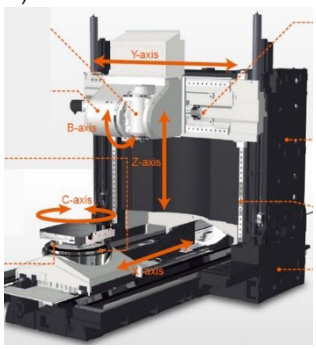
- minimization of XOC and YOC displacements (Fig. 1) of the kinematic center of rotation of the table in long-term processes in order to minimize the effect of machine tool drift with a change in the environment,
- compensation of column non-perpendicularity in the XZ and YZ plane with the increase of the workpiece height workpiece up to the maximum travel range of the Z axis,
- stabilization of the variability of the correctors of turning tools performing machining in the XZ plane (Fig. 6) by minimizing the correction of the position of the kinematic center of rotation in relation to the programmable distance in the X axis,
- minimizing the measurement errors with the standard and special probe of the machined diameters in turning process.

Characteristics of the test stand

The research and tests were carried out on a 5-axis multi-task machine Mazak Integrex e-1600V (Fig. 7) installed in a production line used for machining large sheet metal cases of a turbine engine. The general characteristics of the stand are given in Table 1.

a)

b)



c)

Fig.7. Mazak Integrex e-1600V 5-axis multi-task machining center:
a) General view of the machine tool [10].
b) View of the working elements of the machine tool with a description of the numerically controlled axis system and their interconnection from the machining tool towards workpiece: tool, B axis, Y axis, Z axis, X axis, C axis, workpiece [10].
c) Renishaw RMP600 strain gauge

Table 1. Basic parameters of the test stand [10]

Mazak e-1600V/10 2PC			
Capability	Max. workpiece size	ø2050x1600	[mm]
	Max. pallet load	3750	[kg]
Axis stroke	X - axis	2315	[mm]
	Y - axis	1600	[mm]
	Z - axis	1345	[mm]
	B - axis	-30 do +120	[°]
	C - axis	360	[°]
CNC Controller	Mazatrol	SmoothX	
Touch probe type	Renishaw	4xRMP600 & 3xRMP60M	
Software	Renishaw	Inspection Plus Special for PWR	

Preliminary tests

Preliminary tests were carried out on Mazak Integrex e-1600V machine tools. The data was collected for 3 machines of this type working on one production line in similar environmental conditions, over a long period of time, at least one full year.

Significant variability of the compensation parameter resulted from several conditions, the most important of which are: a

- large range of machine tool operation in the X axis, which translates into a greater variability ΔL_L of the machine bed length under variable temperature conditions, a
- high range of machine operation in the Z axis, which also translates into on the increased variability ΔL_K of the column height and the natural tendency of the column to deviate from the vertical in the Z axis, and thus the deterioration of the perpendicularity in the XZ system, as schematically shown in Fig. 1,
- the influence of radial and axial forces from the turning process directly affecting the head tilting machine tool (Fig. 6a).

The above-described factors made it necessary to look for a solution enabling the machining of large cases, engine units with the highest possible geometric accuracy, with a significant amount of machining of holes with tight position conditions, especially in the case of machining cycles with table rotation by indexing the C axis (Fig. 3b).

In connection with the periodic deterioration of the results of the conditions of the position of the holes for the machined units, measures were taken to increase

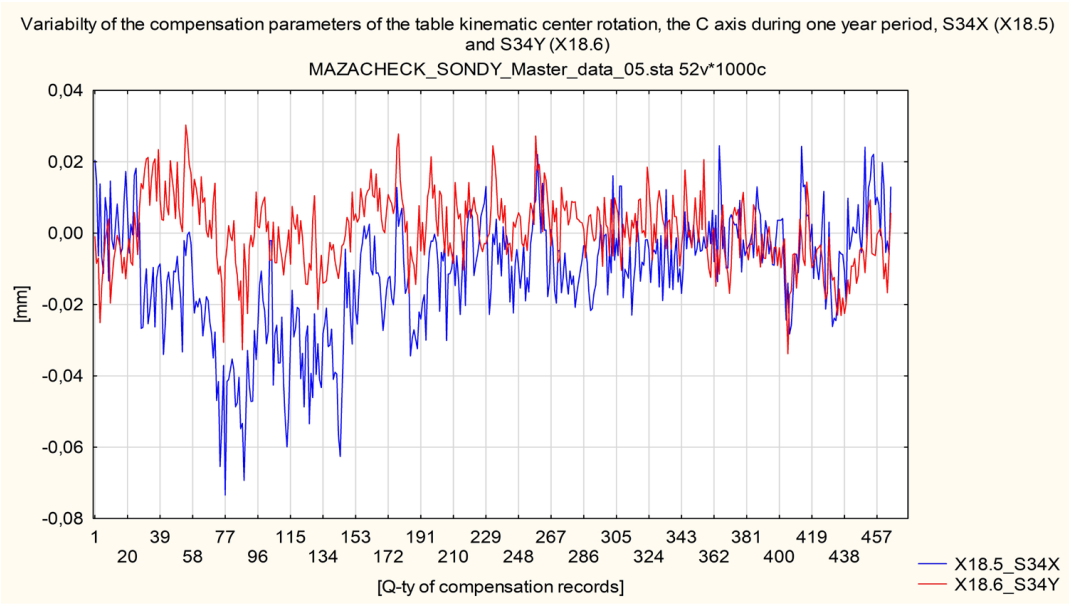


Fig 8. Analysis of the variability of the compensation parameters of the kinematic center of rotation of the table, the C axis during the 1st year, parameters S34X (X18.5) and S34Y (X18.6)

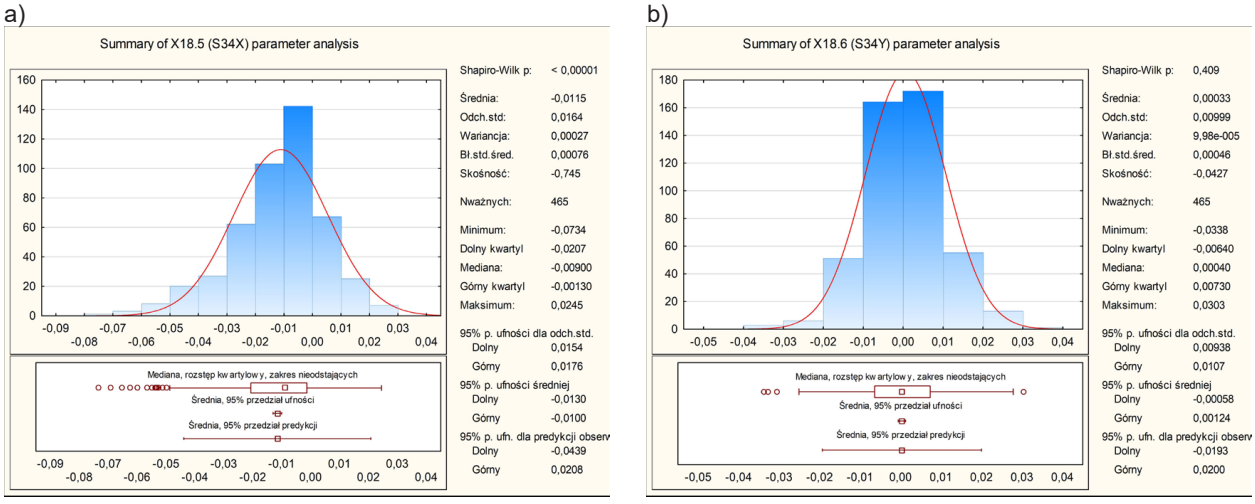


Fig 9. Analysis of the nature of the variability of the compensation parameters S34X (X18.5) and S34Y (X18.6) in the 1-year range

the frequency of machine tool compensation using the Mazacheck system with simultaneous data acquisition for a long-term (at least 1 year) analysis of the range of variability of the parameters of the position of the center of rotation of the table (S34X, S34Y), the position of the C axis relative to the programmable center in the XY system. An example of a long-term analysis is presented in the graphs Fig. 8 and 9.

Methodology of determining the position of the kinematicof thecenterrotary axis

The „Intelligent Mazacheck" software, through the G600 cycles built into the control system, corrects the position of the kinematic center of rotation of the C axis in relation to the XYZ system by updating the machine parameters of the CNC, S34X and S34Y system in real time (Table 2).

Table 2. Compensation parameters for the kinematic center of rotation of the C axis with respect to the XY system [7]

Parameters	Unit	Description
S34 (X)	0.0001 mm	Correction value (on the X axis) for the data, external correction of machine coordinates
S34(Y)	0.0001 mm	Correction value (on the Y axis) for the data, external correction of machine coordinates

Thanks to many years of cooperation with the machine tool supplier, direct access to the S34X and S34Y parameters was obtained through the # variables, thanks to which it is possible to update the parameters of the kinematic center of rotation of the C axis, and the work undertaken allowed for the development of an active error compensation methodology, the diagram of which is shown in Fig. 10 and Fig. 11.

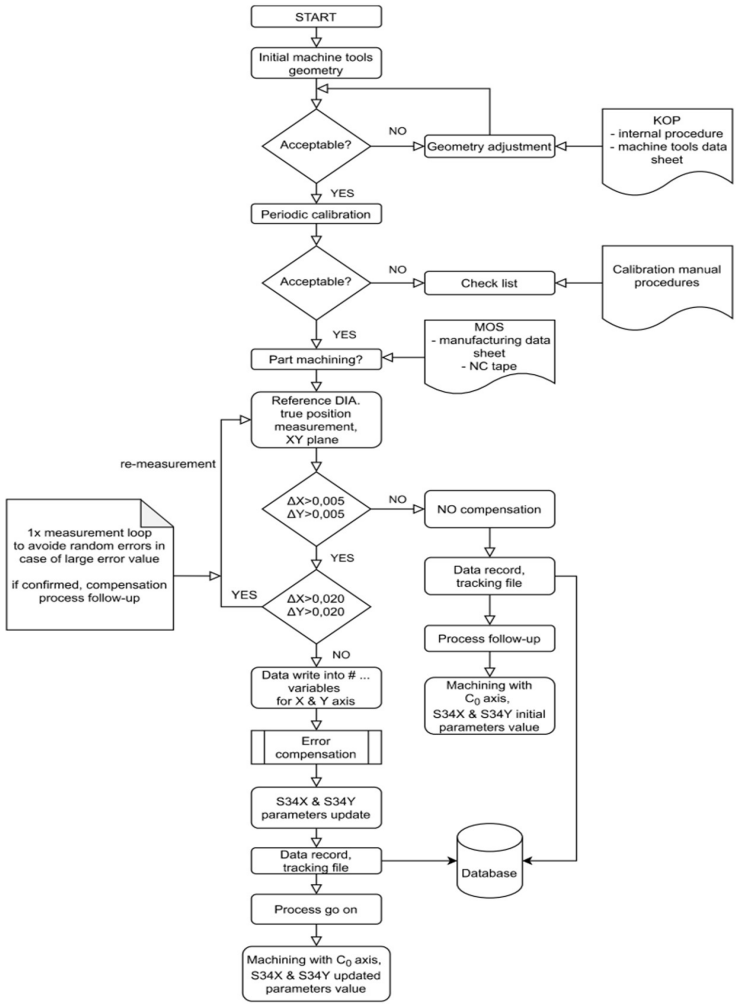


Fig. 10. The block diagram of the dynamic compensation method for analyzed machine Mazak e-1600V

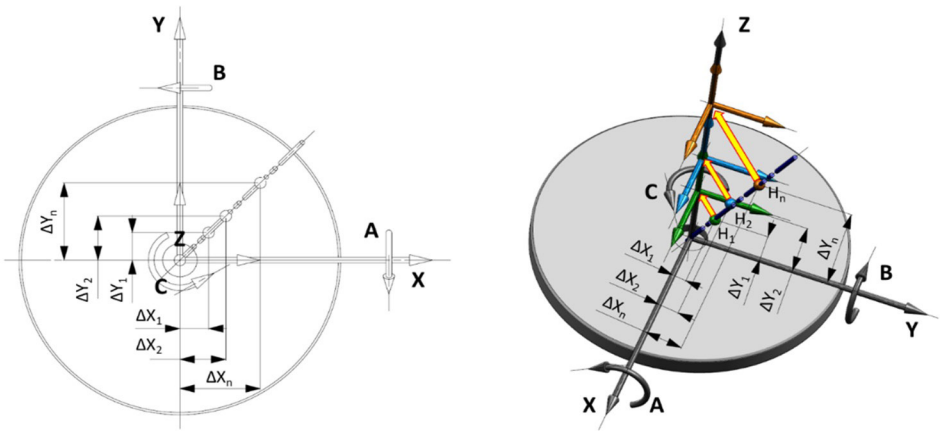


Fig. 11. The visualization of the dynamic error compensation method XOC, YOC offset kinematic center of rotation without interrupting

The diagram shows the idea of dynamic compensation and the principle of "tightening" the coordinate system of the machine tool to the real axis of rotation by continuous compensation of parameters and thus the simultaneous

correction of geometric errors of the machine tool in the XZ and YZ planes along with the change of the machining height, which directly affect the XOC, YOC errors.

In the developed method, no pattern is required (it can also be used), the compensation is performed on the diameters of the machined units, bored during the multitasking operation, which become the reference elements. General requirements for introducing dynamic compensation:

- measuring probe, e.g. RMP600 by Renishaw, centered and calibrated,
- reference diameter machined with circularity <0.010 [mm],
- it is recommended to use a 4-point cycle for measuring the product, or at least 3-point with an angle opening 95 - 120 [°],
- for purely milling machining, it is possible to use reference elements from a machining fixture, provided that the tool is centered and the reference elements are centered with respect to the axis of rotation C <0.005 [mm] and the height arrangement is compatible with the machined flanges with the group of holes.

Testing and implementation results of the proposed methodology

The main goal of thetests was to confirm the assumptions of the adopted method of dynamic compensation during the process. Testing and then production implementation took place in stages and included:

- Stage one – tests using a calibration and test device developed at PWR with the possibility of direct verification of the axis position by measuring with dial gauges (a stage carried out together with the machine tool supplier), the initial state of the geometry complies with the requirements of ISO10791-1 [11], test G8V, G9V [10] ISO tolerance tightened to max. 0.006 [mm], for the 500x500 [mm] pattern.
- Stage two – tests with the PWR calibration device and the actual workpiece, fuselage - fan housing with data acquisition from the course of compensation during the process with verification of the compensated part by CMM measurement, initial geometry non-compliant for the XZ plane (G9V).
- Stage three – tests in production on an increased production sample, with the tracking of the results for each part from the measurements on the CMM, the initial geometry condition for the XZ plane (G9V).
- Stage four – production, with additional measurement of the position of 5 fixed holes with a measuring probe on the machine tool, in correlation to the CMM measurement results, the initial geometry state is inconsistent with the XZ plane (G9V), the
- Fifth stage – production, standard supervision of the part production, the initial state of the geometry in accordance with the requirements of ISO10791-1 [11], G8V, G9V ISO tolerance tightened to max. 0.006 [mm], for the pattern 500x500 [mm].

Fig. 12 shows the stages of implementing the compensation method, from testing to serial production.

a) b) c)

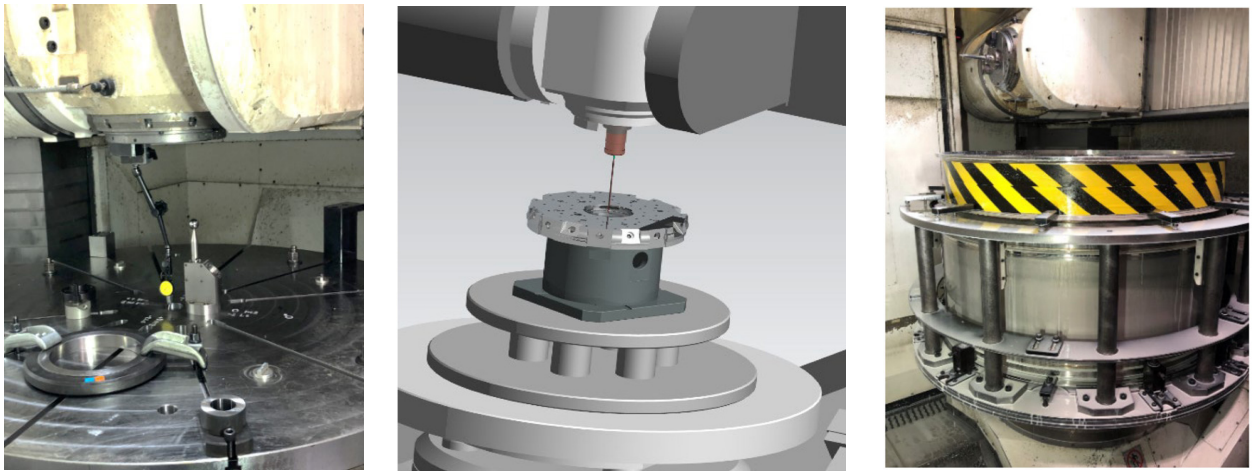
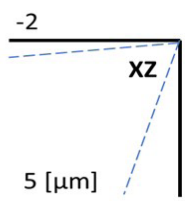
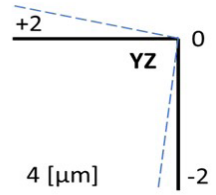
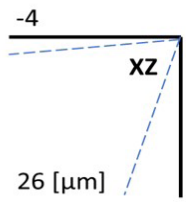
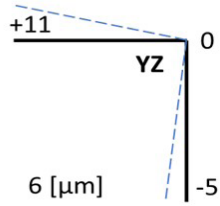
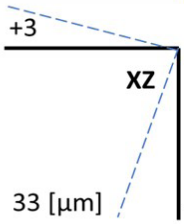
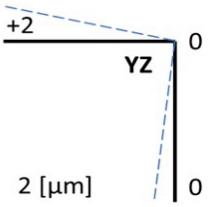
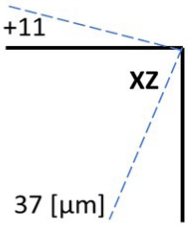
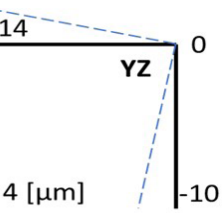
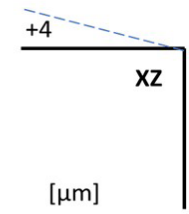
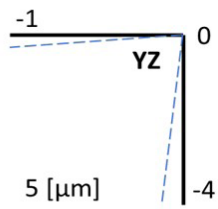


Fig. 12. Stages of testing and implementation of the active compensation methodology:
a) tests with the use of the PWR calibration device,
b) tests with the use of the PWR device, c) tests in production conditions on real products, fuselage - fan housing for a turbine engine.

A detailed summary of the results for the course of the entire test is shown in Table 3, which collectively presents the variability of the compensation range for XOC and YOC errors for 5 states of machine tool geometry in the XZ and YZ planes verified at 2 working heights.

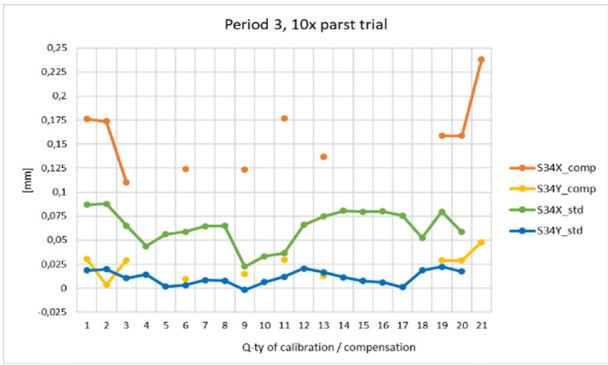
Fig. 13 a), b) and c) show the variability of the compensation range from the height for a representative sample of machined workpieces and the amount of compensation. Fig. 13a and 13b concern the condition of the machine tool geometry not in accordance with the requirements, and Fig. 13c refer to the state of the machine geometry in accordance with the manufacturer's requirements and the ISO10791-1 standard. The graphs a) and b) clearly show shifted compensation values in the

Table 3. Summary of the compensation results in the individual study periodse.

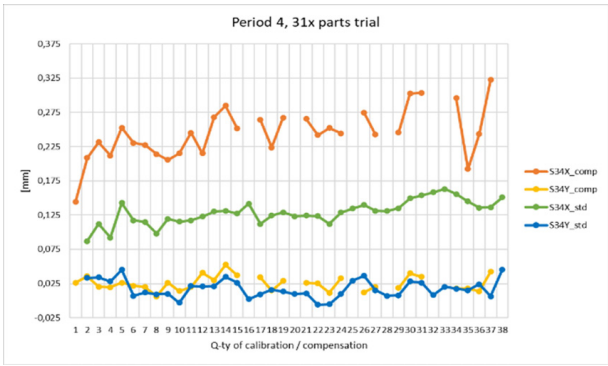
	Checking of squareness between the X/Y-axis motion and the Z-axis motion. Acc. to ISO10791-1 G8V& G9V tests, master 500x500 [mm]			C axis position compensation data relate to XYZ axis intersection point [mm]						Results conforming acc. to CMM
	Plane			Std comp. H0 = Z-1200		Comp. trial H1 = Z-950		Comp. part H2 = Z-500		
	XZ	YZ		S34X	S34Y	S34X	S34Y	S34X	S34Y	
Nominal geometry set-up			Min. [mm]	-0,0108	0,0000	0,0220	0,0117	-	-	
			Max. [mm]	0,0455	0,0304	0,0381	0,0154	-	-	
		3x tests	Δ	**0,0563**	**0,0304**	**0,0161**	**0,0037**	**-**	**-**	**0,0267**
Geometry Condition "1" 3x month set-up Jan - Mar			Min. [mm]	0,0651	0,0038	-	-	0,1334	0,0087	
			Max. [mm]	0,0883	0,0231	-	-	0,1959	0,0303	
		3x tests on real parts under full control	Δ	**0,0232**	**0,0193**	-	-	**0,0625**	**0,0216**	**-0,0023**
Geometry Condition "2" 5x month set-up Apr - Aug			Min. [mm]	0,0227	-0,0017	-	-	0,1101	0,0034	
			Max. [mm]	0,0876	0,0222	-	-	0,238	0,0477	
		10x tests on real parts under full control	Δ	**0,0649**	**0,0239**	-	-	**0,1279**	**0,0443**	**-0,0204**
Geometry Condition "3" 4x month set-up Sep - Dec			Min. [mm]	0,1112	-0,006	-	-	0,1922	0,0116	
			Max. [mm]	0,163	0,0454	-	-	0,3225	0,0421	
		31x tests on real parts, limited control	Δ	**0,0518**	**0,0514**	-	-	**0,1303**	**0,0305**	**0,0209**
Nominal geometry restore Jan - Mar			Min. [mm]	-0,0156	-0,0345	-	-	-0,0063	-0,0221	
			Max. [mm]	0,0298	0,0135	-	-	0,0253	0,0047	
		27x tests on real parts, production mode	Δ	**0,0454**	**0,0480**	-	-	**0,0316**	**0,0268**	**0,0212**

XZ plane, ∆comp. = 0.063-0.079 [mm] in relation to the lower position of the C axis rotation kinematic point. Large differences are the result of a significant deformation of the geometry in the XZ plane, which directly translates into the value of the compensation parameters. For the YZ plane, this difference is essentially constant, ∆Comp. = 0.0204-0.0212 which results from the correct output perpendicularity and the observed changes in the values of the compensation parameters are the result of the influence of the environment and the variable load on the machine tool.Fig. 13d shows collectively the maximum ∆MIN. - MAX. for the entire range of the test.

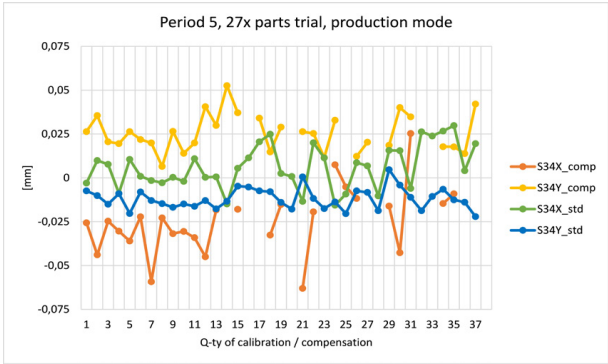
a)



b)



c)



d)

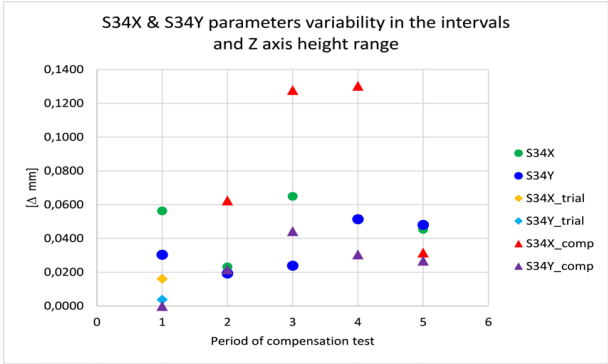


Fig. 13. The scope of changing the S34X and S34Y parameters (XOC, YOC error compensation), depending on the machining height: a) for the initial test stage 10 pcs. b) for the implementation stage 31 pcs. c) for the production stage after the machine tool geometry has been introduced, d) maximum variability of S34X and S34Y parameters in the intervals for the analyzed periods

Summary

The presented compensation methodology has found its application in production conditions for the selected machine tool park. The described method is not universal. It is a dedicated solution for machine tools with a CNC control system, in which it is possible to change the parameters of the kinematic center of rotation in real time, without the need to reset or restart the machine control system. Another important aspect is direct access to variables enabling active change of the machine tool compensation parameters. Good cooperation with the supplier of the machine tool is essential in this respect. Additionally, it should also be noticed of the risk posed by direct interference in changing these parameters, therefore the use of the described method should be individually analyzed in terms of the impact on the behavior of the machine tool, the impact on the technological process or the shape and dimensional requirements of the workpiece. It is also necessary to ensure high purity of the measured surfaces of the product and to ensure the appropriate surface quality and geometry of the measured diameters, especially with regard to the circularity condition.

The main advantages of the described method are as follows:

- the possibility of active compensation of the kinematic center of rotation by minimizing XOC and YOC errors, automatically,
- compensation at different heights of the machine in the place required by the machining process, which allows to reduce the impact of deformation of the geometry in the XZ and YZ plane on the quality of parts,
- the method does not require special equipment, it is based on the existing equipment of the machine tool,
- the compensation process is based on the parameters obtained during technological measurements carried out during the process and thus does not extend it,
- the compensation values are subject to acquisition and registration in order to monitor the variability of compensation and the state of geometry machine tools or capturing anomalies (jumps in values beyond the expected range) in a long period of work, the compensation process itself is secured in the form of control gates.

The undoubted advantage of the method is its simplicity and efficiency even in the case of significant non-perpendicularity of the axis or variability of the production environment conditions as shown in Table 3.

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Grzegorz Szyszka, MSc
Pratt& Whitney Rzeszów SA
Hetmańska 120,
35-959 Rzeszów

Daniel Kwiatanowski, MSc
Pratt& Whitney Rzeszów SA
Hetmańska 120,
35-959 Rzeszów

Jarosław Sęp, Prof. PhD, Ds.C, Eng.
Faculty of Mechanical Engineering and Aeronautics
Rzeszow University of Technology
Powstańców Warszawy 8,
35-959 Rzeszów

Katarzyna Antosz PhD, Ds.C, Eng.
Faculty of Mechanical Engineering and Aeronautics
Rzeszow University of Technology
Powstańców Warszawy 8,
35-959 Rzeszów

INCREASING ECONOMIC EFFICIENCY THROUGH THE USE OF CYBER-PHYSICAL SYSTEMS

Zwiększenie efektywności ekonomicznej przez zastosowanie systemów cyber-fizycznych

Robert KIJAK
Artur DMOWSKI ORCID: 0000-0002-9280-1475

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Abstract: Most industrial plants in Poland are still on the eve of implementing the vision of 'Industry 4.0' (Fourth Industrial Revolution), which was still conceived at Hannover Messe at the beginning of the previous decade. In the context of water management, the term 'Water 4.0' is used, which takes into account a whole range of technologies and digital tools. Its implementation relies in particular on cyber-physical systems to ensure the optimal level of network connectivity using digital tools, between virtual and physical water management facilities during their planning, construction and operation phases.The aim of this article is to identify and demonstrate the key benefits and opportunities of implementing cyber-physical systems in the context of industrial sewage management in Poland - based on selected case studies. The article has demonstrated: (1) rational management of asset renewal funds (CapEx), (2) economic efficiency of operation & maintenance (lower OpEx and TotEx), (3) maintenance planning and improved safety, and (4) various environmental benefits.
Keywords: Water 4.0, cyber-physical systems, digital twins, industrial wastewater

Streszczenie: Większość zakładów przemysłowych w Polsce jest ciągle w przededniu wdrożenia wizji „Przemysłu 4.0" (Czwartej Rewolucji Przemysłowej), która powstała jeszcze na targach Hannover Messe na początku poprzedniej dekady. W kontekście gospodarki wodnej używany jest termin „Woda 4.0", który uwzględnia całą gamę technologii i narzędzi informatycznych. Jej wdrożenie opiera się zwłaszcza na systemach cyberfizycznych w celu zapewnienia optymalnych poziomem połączeń sieciowych, z wykorzystaniem narzędzi informatycznych, pomiędzy wirtualnymi i materialnymi obiektami gospodarki wodnej na etapie ich planowania, budowy i eksploatacji. Celem artykułu jest – i wykazanie podstawowych korzyści i szans płynących z wdrożenia systemów cyberfizycznych w kontekście zarządzania w Polsce ściekami przemysłowymi - na podstawie wybranych studiów przypadku. W artykule wykazano: (1) racjonalność gospodarowania środkami odtworzeniowymi, (2) efektywność ekonomiczna eksploatacji, (3) możliwość planowania obsługi i zwiększenie bezpieczeństwa, jak i (4) różne korzyści środowiskowe.
Słowa kluczowe: Woda 4.0, systemy cyberfizyczne, cyfrowe bliźniaki, ścieki przemysłowe

Introduction

As in many other European Union (EU) countries, industrial facilities in Poland are often still based on technologies from the early 21st century or older, and therefore do not yet reflect the scientific and technological advances associated with the Fourth Industrial Revolution and the vision of 'Industry 4.0' which emerged at Hannover Messe at the beginning of the previous decade. Industry 4.0 generally uses *digital twins*, wireless sensors integrated into assets, industrial internet of things (IoT), cloud computing and predictive analytics increasingly utilising artificial intelligence, i.e., automated 'machine learning'. ('Assets' are defined in this article in accordance with PN-ISO 55000:2017-09 [14]. 'Physical assets', on the other hand, are a subset of these, such as machinery, equipment and infrastructure (ibid).)

The hitherto low level of implementation of Industry 4.0 technologies in Poland is partly associated with the fact that many of the industrial plants were outsourced to Poland after our country's integration into the EU. This also applies to associated industrial wastewater treatment plants (or pre-treatment plants). Whilst municipal wastewater treatment plants in Poland have been built or extended / upgraded over the last 10 –15 years, largely through EU funding, many industrial wastewater treatment plants, and the industrial facilities themselves, are often still in the phase of being upgraded. In the case of discharge and treatment of domestic/municipal wastewater in Poland, the degree of utilisation of technologies of the era of the Fourth Industrial Revolution is often above that of the industry itself.

The largest industrial plants in Poland, especially in the energy, chemical, petrochemical and refining industries, tend to discharge their wastewater directly to the receiving waters - after treatment to comply with the regulatory standards. The other plants usually discharge their wastewater to municipal sewers after pre-treatment so that the contaminant load does not exceed the design capacity of municipal wastewater treatment

plants – for compliance with the *Regulation of Minister for Construction on the implementation of responsibilities of industrial wastewater producers and the conditions for wastewater discharges to sewers*. In this instance, the mixture of industrial and domestic wastewaters is discharged after treatment (effluent) to waters.

The aim of this article is to identify and demonstrate the key benefits and opportunities of implementing cyber-physical systems in the context of managing industrial wastewater. This includes municipal wastewater that is a mixture of, amongst other things, industrial and domestic wastewaters.

The concept of Water 4.0

The term 'Water 4.0' is used in the context of water management (including water and wastewater management). Figure shows the stages of development of water and wastewater management starting with 'Water 1.0' in the times of Roman Empire [1].

As the German Water Partnership defines [9], Water 4.0 emphasises digitisation and automation and incorporates the same main characteristics and terms used as Industry 4.0. In particular, the implementation of Water 4.0 is based on cyber-physical systems to ensure the optimal network connectivity, using digital tools, between virtual and physical water management facilities during their planning, construction and operational phases.

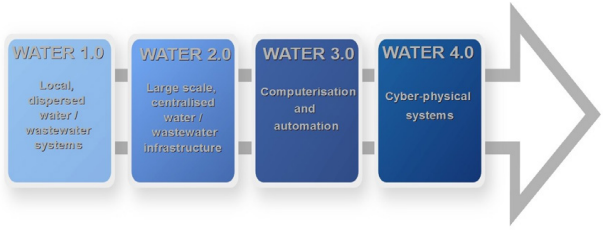

Fig. 1. Phases in the development of water and wastewater infrastructure (Source: prepared based on [1])

Water 4.0 is a new, innovative and multidisciplinary field, but not fully defined yet. Its definition and understanding are evolving along with the published case studies such as those described below in Chapter 3.

The number of topical publications is, however, limited. A previously conducted literature review is contained [12], where an attempt is also made to define this field in the context of various business processes, engineering and industry sectors of '4.0' and relevant technologies, methods and tools, as well as some of the opportunities and risks relating to Water 4.0.

Method

The research method is based on the analysis of a number of topical case studies from various countries (including Poland), which are related to the topic of Water 4.0 in the context of industrial wastewater management.

They address the optimisation of the efficiency/ performance of municipal wastewater treatment plants and associated sewers which accept industrial wastewater. Optimisation reduces the number of overflows/bypasses of the wastewater treatment plant and provides in parallel, a 'protection' to the plant from the excessive flow and pollutant load, as well as ensures a consistent quality of the treated effluent.

This will reduce the impact of industrial wastewater and substances it contains, on the receiving waters.

As with the municipal sewerage systems, the same technologies, methods or digital tools can be applied to large industrial wastewater treatment plants and associated sewers, especially in the energy, chemical, petrochemical and refining industries, which are fed from numerous internal units and departments by often heterogeneous wastewater whose sources are difficult to identify.

Technology-wise, cases studies presented in Tab. can be subdivided as follows:

A. *Digital twins* with 'hybrid analytics', where hybrid analytics for the purposes of this article, involves the analysis of historical and real time data, but may incorporate a form of prediction made by digital tools and/ or the operator based on the analyses conducted for the aforementioned data.

B. *Digital twins* with predictive analytics.

The case studies (as mentioned above) are based on information received from technology suppliers' publications, methods and tools. Therefore, not all details of the case studies, as well as the technology itself are available to the authors of this article. However, an earlier literature review [12] showed that case studies on Water 4.0 in scientific journals remain relatively rare.

Table presents information from these four suppliers divided into case studies using *digital twins* with hybrid analytics and *digital twins* with predictive analytics (A and B). For each of these, "Description of digital technologies and tools" is provided (1.1 - 4.1), followed by "Selected case study (purpose, method, outcome)" (1.2 – 4.2).

Selected case studies involving the optimisation of control processes for the transmission and treatment of industrial wastewater	
1.	**A. *Digital twins* with hybrid analytics**
	Danish Hydraulic Institute - DHI (Denmark)
	1.1 Description of digital technologies and tools

Digital tools which apply to wastewater treatment processes [2], but also with applications, for example, to water distribution networks, sewers and rivers are as follows [3, 4, 5]:
WEST – models (digital twins), simulates and evaluates physical, biological and/or chemical processes [2, 4].
DIMS.CORE – a central data depository for customised real time solutions: monitoring, reporting and control. Converts data into information. Provides data / information to global users through customised reports [2, 3].
MIKE OPERATIONS – real time data management including compliance reports together with supporting data. Online modelling for both forecasting and control [2, 5].
The subsequent case study concerns WEST.

1.2 A selected case study (objective, method, outcome)

Water Resources Recovery Facility in West Lafayette, Indiana (United States) **[6].**
The goal was to reduce the carbon footprint by 50% by 2025 while improving the quality of treated wastewater. Only minor infrastructure redevelopment was permissible.
Modelling of the treatment plant processes was carried out using WEST that enabled different aeration control strategies to be tested in real time and in a virtual environment. Parallel optimisation of the digesters identified the potential for doubling energy recovery from biogas.
Modelling resulted in improved quality of the treated wastewater. The treatment plant also became 60% energy neutral. Operating costs (OpEx) were reduced by $293,000.

2. Endress+Hauser – E+H (Germany)

2.1 Description of digital technologies and tools

The aim of the Liquiline Control CDC81 system (supervisory system) is to achieve the set values for nitrogen and phosphorus compounds with the lowest possible: (1) electricity consumption, and (2) dosage of chemical reagents [8].
The Liquiline Control predictive control system also targets the automation of the process in order to react quickly to: (1) erroneous readings of measured values, and (2) equipment failures, e.g., blowers (remote diagnostics) (ibid).
The system utilises predictive algorithms developed on a mathematical model (e.g., [7, 8]). A few hours in advance, on the basis of the analysis of inflow to biological reactors, the system selects the settings of control devices to optimise the conditions for reducing contaminants [7].
Through continuous measurement and verification of signal quality, Liquiline Control aims to ensure stable operation of the wastewater treatment plant and adequate effluent quality parameters [8]. In the event of erroneous indications or failures, the system sets the respective control loop into an emergency state and generates an error or warning message (ibid).
Utilising the asset networks or wireless technologies, Liquiline Control transmits measurement data to a central control room for the purpose of monitoring the process and possibly changing control algorithm parameters (ibid). The system also uses a mobile communicator to allow remote access (ibid).

2.2 Selected case study (objective, method, outcome)

Water and Wastewater Management Company in Tomaszów Mazowiecki (Poland) **[8]**
Liquiline Control system has been designed to provide full automation of processes from the raw wastewater pumping station and the septage discharge station to the sewage treatment plant located at Tomaszów Mazowiecki. Control algorithms control the processes of mechanical sewage treatment, operation of the grit chamber, fat disposal system, operation of primary settling tanks, sludge thickeners, secondary settling tanks and operation of biological reactors.
The system cooperates with monitoring devices and control devices of the treatment plant. Its main task is to conduct an on-line analysis of monitoring data and calculate the settings of the subordinate control devices.
A real time algorithm assesses characteristics of the inflowing (raw) wastewater and selects the settings of control devices accordingly to create conditions for the optimal reduction of contaminants.
The operating parameters / settings constitute the basis for the automatic execution of the nitrification / denitrification process. The operating parameters of the biological reactor such as duration and intensity of aeration and the duration of anaerobic conditions are defined.
The system algorithm operates in real time and interfaces with the SCADA system. It monitors pollutant loadings and provides emission standards for treated effluent in a predictive manner.
The guidelines defined by the operator (in this case the technologist) are crucial in the configuration of the system / master system for running the nitrification / denitrification process. It defines the control area for the host system. It specifies the ranges of variation for individual parameters. It also defines the required parameters of the treated effluent at the reactor outlet and the process parameters. The master system, on the other hand, ensures that the treatment process progresses in an optimal way.

Any anomalies that may occur in the performance of measuring probes and actuators are monitored in real time. In a possible emergency, the system can automatically take predefined actions, but the final decision is ultimately left to the operator.
Automation of the aeration process reduces operating costs (OpEx). One of the main benefits of the system is the reduction in electricity costs.

B. *Digital twins* with predictive analytics

3. Xylem (United States)

3.1 Description of digital technologies and tools

The following description and case study apply to Xylem's BLU-X method / tool. BLU-X is applicable, amongst other things, to catchments of municipal sewage treatment plants. Xylem refers to its methodology as decision intelligence. The method is based on big data and its purpose is to improve decision-making and make recommendations for both the operation and planning of new infrastructure [18].
BLU-X is based on advanced analytics which allows the water utility / operator to make optimal decisions, for example to ensure resilience to climate change, as well as to optimise costs (ibid). By understanding how external factors (e.g., weather) interact with operating parameters and analysing an enormous number of scenarios in real time, the organisation can then manage the uncertainties / risks associated with asset planning and ensure cost efficiency (ibid).

Catchments of municipal sewage treatment plants [18]

- Digital twins of the sewerage system optimises, controls and coordinates all system assets in real time. It identifies any potential failures and malfunctions for critical assets with the use of diagnostic tool data and machine learning.
- Intelligent pumping systems transmit information in real time and can thus assist with maintaining the operational reliability.
- As Xylem reports, digital twins can be helpful in optimising the process, reducing energy consumption and ensuring process stability, throughput and treated effluent quality.
- If integrated with real time control of the sewer system, digital twins can optimise the volume of wastewater entering the treatment plant.

***Decision intelligence* [18]**

This functionality provides data integration, analytical and visualisation capabilities so that the operator (water utility company) can: (1) control the intelligent system that has been installed, and (2) use the gathered big data.

3.2 Selected case study (objective, method, outcome)

***City of South Bend, Indiana (United States)* [18, 19]**

The objective was to avoid potential costs of $1 billion associated with legal requirements to reduce frequent storm overflows from the City's combined sewers with industrial wastewater.
The City of South Bend has implemented a BLU-X Intelligent Sewer tool based on wireless sensors linked by SCADA system and machine learning (artificial intelligence) to provide decision support and process control.
The disposal of industrial wastewater through the sewerage system into the Saint Joseph River has been a key issue in relation to the heavy industry that historically existed in the city (e.g., Singer Sewing Company). More recently, the region has re-attracted new industries and has become a technology hub (industrial zone).
The City has implemented the Xylem tool for the catchment area of the sewage treatment plant to reduce overflows from storms (4-8 million m^3 per year) and to optimise the existing combined sewers.
Initially, real time monitoring was installed and implemented on the basis of 120 sensors located within the catchment area of the municipal sewage treatment plant of the City. Following a thorough analysis of the data in 2012 conducted jointly by the City and Xylem, real time decision support system (RT-DSS) based on BLU-X was implemented. It considered sensors and valve actuators, which made possible to 'trade' the available sewer capacity (as with the stock exchange) to prevent wastewater overflowing.
BLU-X RT-DSS transmits information: to operators on SCADA screens, to field workers on smartphones and tablets, to the City engineering staff through web portals. (Operators are able to take control of the system at any time.)
Consequently, the City has reduced storm overflows from the combined sewer system by over 70% and concentrations of E. Coli in the Saint Joseph River by 50%. As a result, the compliance costs have been reduced by more than $500 million.

Royal HaskoningDHV - RHDHV (Netherlands)

4. 4.1 Description of digital technologies and tools

Aquasuite 'virtual operator'

In accordance with the available information, the virtual operator is a tool based on artificial intelligence (automatic machine learning) that has been designed for water and sewage companies and various industries [15]. It makes predictions (predictive control) based on historical data and external information and then automates real time repetitive actions (monitoring and control) (ibid). Hence, the virtual operator improves efficiency ('calms' and 'aligns' the processes of the network and the treatment plant) which will allow the physical operator to focus on more relevant tasks (e.g., strategic) which will increase productivity and ultimately reduce costs (e.g., OpEx) (ibid).

The virtual operator monitors, analyses, visualises (cockpit) and regulates the efficiency of water and sewage management. Based on probe data, weather forecast information and other data/information, it ensures predictions with an accuracy of up to 97% (ibid).

The virtual operator consists of two components: (1) 'analyst', (2) 'autopilot' (ibid).

The virtual analyst conveys real time capacity, flow, load and quality data from SCADA, PLCs, process databases and probes connected via IoT, and comparing them with the past data (ibid). Data visualisation enables the (physical) operator to focus on the proper tasks and make prompt decisions on the basis of available information (ibid).

Auto-pilot is a self-learning and predictive tool that allows (as described) to prevent a problem before it happens by monitoring performance and responding appropriately should it be required (ibid).

The Aquasuite virtual operator applies to processes and is applicable to five products/tools [15, 16], including but not limited to:

- Sewers / wastewater collection and transmission (FLOW)
- Wastewater treatment (PURE).

This article focuses on FLOW.

Sewerage system / wastewater collection and transmission

Virtual Operator (FLOW) can predict, identify and reduce storm overflows from combined sewers. It links weather forecasts with real time process data to forecast future wastewater volumes and their impact on the sewer system (RHDHV 2020).

It may monitor and control pumping stations to optimise the performance of the sewerage system (ibid). It also anticipates and reduces the flow / peak loads coming into the wastewater treatment plant and could bypass the plant (ibid).

FLOW uses a hydraulic model that allows prediction to be made based on current conditions [13]. Prediction of flow during dry weather is made with the use of a heuristic method and adaptive prediction model, which was previously used by RHDHV in optimising the drinking water treatment process (ibid).

4.2 Selected case study (objective, method, outcome)

Vallei en Veluwe Water Board (WSVV) (the Netherlands) [13]

This case study focuses on predictive and prescriptive methods to improve and optimise wastewater treatment processes. This was done within the context of undetermined peak flows associated with rainfall, which inflowed into the treatment plant and consequently poor quality of treated effluent, as well as bypasses of the treatment plant, which had an impact on the receiving waters (eutrophication).

In order to maximise the quality of the treated effluent, the WSVV had previously applied an effluent treatment phase (or tertiary treatment by means of sand or disc filters). The hydraulic capacity of this phase was lower than the maximum hydraulic capacity of the treatment plant (i.e., secondary treatment). This resulted in frequent bypasses of this phase during rainfall periods. Such peak flows were also associated with peak loads of total oxygen demand (TOD) and total solids (TSS).

Optimisation of the inflow to the wastewater treatment plant was carried out by using predictive control rather than conventional measurement of wastewater levels at the pumping stations. The implementation of predictive control is done using flow prediction during dry weather and "flattened" flows / peak loads based on weather forecasts. As opposed to control based only on the measurement level, predictive control waits for the situation to change by anticipating the available sewer retention so as to flatten the inflow to the treatment plant (without additional storm overflows from the combined sewers). In this regard, the FLOW predictive controller was used as a pilot project.

Predictions of flow during dry weather along with weather forecasts were key factors for the FLOW controller. On the basis of these factors and real time measurements of the level and outflow from the pumping station to the sewage system, a forecast was made along with an optimisation of the available sewer retention which allows the reduction of overflows.

Both dry weather flow and weather forecasts along with level and outflow measurements were the input data for the FLOW controller. The current situation (i.e., utilised sewer retention) was continuously calculated on the basis of the level and application of the relevant curves from the sewer models. The prospective situation (i.e., channel retention to be utilised) was predicted on the basis of capacity/volume optimisation techniques.

Channel retention was modelled as separate reservoirs. The reservoir inflow prediction was calculated as the sum of the dry weather flow rate and the rainfall water runoff prediction. The outflow from the reservoir was predicted on the basis of capacity optimisation. To do so, total retention was also optimised taking into account two constraints: (1) critical levels in the sewer, (2) the requirement to empty the sewer before the next significant rainfall.

This case study demonstrates that, in most cases, peak inflows to several WSVV wastewater treatment plants have been flattened and, at the same time, the number of bypasses of the tertiary treatment / further effluent treatment has been reduced (and without causing additional storm overflows). The effectiveness of the primary and secondary treatment has also improved. This resulted in lower concentrations of nutrients (phosphorus) in the treated effluent along with a reduction in energy and chemical reagent consumption (i.e., OpEx).

Results

The use of Water 4.0 technologies may improve the efficiency of the sewerage system and therefore the quality of the treated wastewater (effluent). Regardless of whether the industrial facilities themselves are upgraded to the Industry 4.0 standard or not, the benefits of upgrading the industrial wastewater treatment plants / pre-treatment plants themselves, as well as the municipal sewerage system receiving industrial wastewater, can therefore be summarised as follows: (1) rational management of asset renewal funds (CapEx), (2) economic efficiency of operation & maintenance (lower OpEx and TotEx), (3) maintenance planning: and improved safety (occupational health and safety), and (4) various environmental benefits (e.g., ensuring the required effluent quality). ('TotEx' (Total Expenditure) is the sum of CapEx (Capital Expenditure) and OpEx (Operational Expenditure) over a defined period [11].).

Discussion

The greatest benefits associated with the implementation of technologies of the era of the Fourth Industrial Revolution may be obtained by industrial plants discharging wastewater effluent directly into the receiving waters, especially in those plants where the state of repair of assets still leaves much to be desired. The benefits will, of course, be even greater when the implementation of Water 4.0 technologies is combined with the renewal of wastewater infrastructure. As with the industrial facilities themselves served by wastewater treatment plants, it is possible to gradually implement technologies of the Fourth Industrial Revolution era (e.g., [12]) what increases the economic efficiency.

One of the constraints associated with the low level of application of Fourth Industrial Revolution technologies in this country is generally a quite low level of investment directed towards the implementation of innovative solutions, as well as generally a low level of interest in the contemporary methods of physical asset management and reliability engineering. Popularising the use of the ToTex methodology in accordance with ISO/TS 55010:2019 [11] for the purpose of estimating the costs and benefits of operating facilities (assets), would probably change this unfavourable situation.

It is also worthwhile noting that Poland is a country at risk of water scarcity, especially since nearly 1/3 of the rivers in Poland have non-class water with a 60% contamination index [17]. Water deficits will become even greater with climate change. Water 4.0, through improving the efficiency of process water usage and industrial wastewater treatment (including water reuse rates), can also reduce our carbon and water footprint and certainly improve the resilience to climate change.

Summary

The process of absorption of Water 4.0 related technologies in water and sewage management (both municipal and industrial) in Poland is progressing quite slowly for various reasons. It would have a number of benefits demonstrated and illustrated by a number of case studies, viz: (1) rational management of asset renewal funds (CapEx), (2) economic efficiency of operation & maintenance (lower OpEx and TotEx), (3) maintenance planning and improved safety, and (4) various environmental benefits.

The above-mentioned benefits are shown in this article with the help of selected case studies in the context of cyber-physical systems (digital twins). While some of the case studies refer to municipal sewers, the same digital technologies and tools could be applied to large industrial wastewater treatment plants and their sewage networks especially in the energy, chemical, petrochemical and refining industries, which often receive heterogeneous wastewater from internal units and departments and their sources are difficult to identify.

One of the constraints related to the hitherto insufficient level of new technologies applications in the country is generally quite low level of investments aimed at the implementation of innovative solutions, as well as generally low level of concern for modern methods of material assets management. Properly carried out financial analyses, considering TotEx and OpEx in particular, could change this unfavourable situation.

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dr inż. Robert Kijak
Polskie Naukowo-Techniczne Towarzystwo Eksploatacyjne
ul. Jagiellońska 80
03-301 Warszawa
e-mail: kijakr@gmail.com

dr inż. Artur Dmowski
Wyższa Szkoła Ekonomii i Innowacji w Lublinie
ul. Projektowa 4
20-209 Lublin
e-mail: artur.dmowski@wsei.lublin.pl
(corresponding author)

Tytuły i streszczenia artykułów zamieszczonych w miesięczniku naukowo-technicznym **„Sborka v mashinostroenii priborostroenii”** (Wydawnictwo Maszynostrojenije, Moskwa, Rosja)

Sborka nr 1, 2020

1. Improvement of manufacturing technology of armature winding coils of auxiliary DC machines
Authors: Aydinyan O.V., Gubarev P.V., Shapshal A.S.

The technology of drying the coils of the armature winding of auxiliary DC machines of rolling stock are considered as a result of which the problem of breakdowns and inter-turn closure of the armature winding is determined. To increase the cementing ability of the armature winding of auxiliary DC machines of the rolling stock, GF-95 varnish was selected, which has increased impregnation and coating properties, bringing the binding ability of the auxiliary armature winding of DC machines rolling stock increased by 24 %. Technological process of impregnation and drying sections of the auxiliary DC machines varnish GF-95 tested in Operational locomotive depot Baraysk.

2. Organization of the print queue in 3D printers with automatic product extraction for small scale production
Authors: Drobotov A.V., Omarov A.V., Shemelyunas S.S., Guschin I.A.

Software for queuing 3D printer from various manufacturers was reviewed and analyzed. It is proposed to modify it in order to support additional equipment for automatic extraction of the printed product.

3. Basic stages and provisions for the development and position of production of arms and military equipment for production
Authors: Derendyaeva E.A., Vaulina L.M.

The main stages of development and production of weapons and military equipment provided for by the State military standards of the Russian Federation are considered. The analysis of the main guidelines for the organization of the development and production of military products is carried out.

4. Experimental studies of the drilling of copper alloy holes in the stress-strain material of the workpiece
Authors: Kuts V.V., Byishkin A.S., Razumov M.S., Kochergin V.S.

Experimental studies of the drilling of copper alloy holes in an stress-strain material of the workpiece have been carried out. It is show that the axial cutting force decreases. The magnitude of this force plays an important role in drilling small-diameter holes.

5. Control of piston rings on pistons of internal combustion engines ICE of cars
Author: Dubovik E.A.

The process of technological control of piston rings on the pistons of internal combustion engines (ICE) of cars, as well as the tool used in this process, is considered.

6. Improvement of tribological characteristics of plastic greases at addition of additives based on nonstochiometric compounds of molybdenum and tungsten
Authors: Karpenko K.I., Myasnikova N.A., Myasnikov F.V., Avilov V.V.

The results of the use of additives based on non-stoichiometric compounds Mo and W to improve railway greases LZ-CNII and CIATIM 201 are presented. It has been established that the introduction of lubricants of this type of additives into the dispersion medium improves the tribological properties without deteriorating the performance parameters of these lubricants.

7. Influence characters and parameters of microgeometry the tool surface on the coefficient friction in combined burnishing methods
Authors: Schedrin A.V., Chikhacheva N.Yu., Bekaev A.A., Tomskaya N.V.

Basing on the theoretical foundations of I.V. Kragelskii adhesion-deformation theory of friction for influence of characters and parameters of the tool surface microgeometry on coefficient of sliding friction in the methods of the combination (deforming-cutting) the machining holes has been investigated.

8. Analysis of operating parameters of the vibrating screen based on dynamic models of his work
Authors: Volkov E.B., Sitdikova S.V.

The technique to determine the effectiveness of the theoretical way of screening at the stage of multiple alternation of free flight of the particle with the blows before

passing it through the grating, is described. A new solution to the actual scientific and practical problem of improving the efficiency of vibration screens based on the choice of rational values of their operating parameters is given.

9. Synthesis and analysis of adaptive friction clutch with a combined feedback

Author: Shishkarev M.P.

It is shown that the application of a positive-negative feedback in the adaptive friction clutch, acting in the time-division mode of its components, can significantly improve the accuracy of operation and the load capacity of the clutch. The obtained dependences for determining the rational parameters of the clutch allow to optimize the processes of automatic control in the clutch under the action of the control device of positive and negative feedback.

Link: http://www.mashin.ru/eshop/journals/sborka_v_mashinostroenii_priborostroenii/2026/16/

Sborka nr 2, 2020

1. Version of the modernized machine for bending copper strips on the edge in power-consuming machine and instrument making

Authors: Kiselëva O.V., Zvyagintseva P.A., Makarova D.G., Egorenko M.P.

A variant of the modernized machine for bending the copper winding of the turbine generator rotor in power-consuming machine and instrument making is presented. The analysis of basic machines and technologies of bending of half-coils is made. The proposed model of the machine for bending copper strips can improve the quality of products and reduce labor intensity.

2. Flexible modular assembly lines type on a single structural basis

Authors: Ivanov A.A., Kretinin O.V.

The assembly of the main range of products on flexible lines of a new generation was analyzed, in a single structural basis which is a reconfigurable base module that includes all the necessary systems: loading and unloading, transport, executive in the form of assembly heads, control, including control and diagnosis.

3. Evaluation of the quality of the process during its design

Authors: Nepomiluev V.V., Sokolova E.YU., Belova N.S.

A technique is proposed for ensuring the quality of the designed technological process based on a quantitative assessment of it from the point of view of internal and external consumers, taking into account the technological cost. The technique can be used to justify technical and economic solutions in mechanical engineering.

4. Assembly of the air pre-treatment system

Authors: Mikaeva S.A., Mikaeva A.S., Larshina E.L., Dyukin A.A.

The assembly of the air pretreatment system designed to reduce high concentrations of hydrogen sulfide and volatile organic compounds through the use of specialized catalytic backfill is described. The system is a 20 or 40 foot insulated sea container in which two catalytic backfill units are located: worker and reserve. Each unit contains one cleaning step with a specialized ferruginous backfill. The system does not have its own fan and is connected to the existing ventilation system be installed in front of the installation VENTLIT.

5. The level of congestion in the adaptive friction clutches with variable gain

Author: Shishkarev M.P.

It is shown that the adaptive friction clutch with negative feedback and variable gain does not provide complete stabilization of the torque. The magnitude of the overload is influenced by the speed of its growth and the number of pairs of friction of the friction coupling Assembly. The overload value increases with the increase in the rate of its increase and with a decrease in the number of friction pairs of the friction unit.

6. Vibration and creep at elastic bodies rolling (wheel—rail)

Author: Fridberg A.M.

The appearance of significant, noticeable creep can be attributed to small vibrations occurring at the point of contact of two elastic bodies. Due to vibration and crisp rolling of bodies smoothly, without breaking into sliding, changes in a large range of modes of movement and is a carried out as the most economical movement. An interaction between a wheel and a rail was studied in various synthetic tests and at real motion of a freight train with a locomotive. Creep can be taken advantage to make significantly better machines and mechanisms, or to approach technical challenges in a different way. For example in a modernized wheelset, differential of the

rip of its wheels on the curved sections of the track is realized by the chip.

7. Methods of changing the state of self-oscillations in a system with a Van der Pol characteristic taking into account nonlinearities of a complex type
Author: Erlich B.M.

The method of significant state change (quenching or excitation) of self-oscillations of machines and mechanisms using power impact is considered. The methodology takes into account in two versions one of the types of characteristics of a self-oscillating type, a characteristic of the Van der Pol type separately and together with the presence of various types of nonlinearities of a complex type − elastic, dissipative, or both elastic and dissipative. The structure and parameters of the force action are determined on the basis of the methods of the theory of optimal control. All the calculations confirm the effectiveness of the proposed method.

8. Ways to reduce residual volumes in planetary rotary hydraulic machines with floating satellites
Authors: Volkov G.Y., Smirnov V.V., Fadyushin D.V.

The possibilities of minimizing the residual volumes of their working chambers of planetary rotary hydraulic machines with floating satellites as vacuum pumps, compressors and pneumatic motors are analyzed. It is found that for the difference in the wave numbers of the non-circular central wheels of the stator and rotor N – M = 2, the volume change coefficient cannot exceed ε = 2.5...3. When N – M = 1 this ratio is as high as ε = 4. The maximum values of the coefficient (ε = 10 and more) can be achieved in hydraulic machines with "standstills" at M = N, when the radii of the rotor and stator centroid in certain areas do not change according to the harmonic law, but become constants.

9. Methodology for the development of kinematic diagrams of devices for automated assembly of products based on structural process control circuits
Authors: Zhitnikov Y.Z., Zhitnikov B.Yu., Matrosov A.E.

A methodology for the development of kinematic diagrams of devices for automated assembly of products using the example of a multi-spindle screw of device based on the technological sequence of assembly operations and structural process control circuits is proposed.

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Sborka nr 3, 2020

1. UV system assembly
Authors: Mikaeva S.A., Mikaeva A.S., Larshina E.L., Vasileva L.A.

The work is devoted to the construction of an ultraviolet system for air disinfection. The article describes the main parts of the system and presents the technical characteristics of the assembled ultraviolet system.

2. Automated installation of flexible annular rubber seals into outer grooves of cylindrical parts
Authors: Zhitnikov Yu.Z., Zhitnikov B.Yu., Matrosov A.E.

Description of operation of automated device for installation of elastic rubber ring seals in external grooves of cylindrical parts is performed and power parameters of assembly are justified.

3. The assembly of the hull of integrated circuits
Authors: Ivanov A.A., Kretinin O.V.

It is shown how IC assembly technologies are implemented on lines and sets of equipment as part of an automated shop, the structure of which includes: complexes of main, service and backup equipment, automated warehouse, and tool and repair services. The use of computer technology and vision systems in the equipment ensure the ability of assembly machines to self-learning and allow for quick changeover of automated sections of the shop for the assembly of various types of IC in buildings of a wide range.

4. The determination of the dependence of the wear intensity on the load by the results of tribotechnical tests using fi lm-forming lubricants
Author: Kuleshova E.M.

The results of comparative tests of steel and bronze test samples on the friction test machine MT-8 are presented. The dependence of the wear rate on the load using fi lm-forming lubricants was obtained.

5. Optimization of design parameters the safety spring-ball clutch
Author: Shishkarev M.P.

A dependence is found that takes into account the current axial movement of the movable coupling half and

the constancy of the maximum axial movement of the movable coupling half of the safety spring-ball coupling. It is shown that there is a limit distance at which the ball protrudes from the socket at the time of reducing the torque at the exit of the coupling halves from one another.

6. Repair of cylinder block of internal combustion engines of cars
Author: Dubovik E.A.

The technology of repair of the cylinder block of internal combustion engines of cars is considered.

7. Determination of wear resistance of sieves of vibrating screens on the basis of dynamic model of movement particles of rock
Authors: Volkov E.B., Sitdikova S.V.

One of the most important indicators of the inclined vibrating screen is analyzed – the efficiency of separating rocks by size classes which is influenced by many different factors: the angle of inclination of the working body, the shape of the sieve holes, the height of the material supply, etc, these factors determine the probability of passage of particles through the screen lattice. A model is proposed for the selection rational operating and design parameters of the installation, corresponding to the specified criterion of efficiency and wear resistance.

8. Condition and prospects of rational use and reduction of loss of fuel and lubricants of the Republic of Uzbekistan
Author: Mamasalieva M.I.

The problem of rational use of fuel and energy resources of the Republic of Uzbekistan is analyzed.

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ASSEMBLY AUTOMATION

Emerald Publishing Limited
Howard House
Wagon Lane
Bingley BD16 1WA
United Kingdom
e-mail: emerald@emeraldinsight.com

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ABSTRACTS:

1. Preparation of complex surface coatings based on electrospark computer integrated deposition system
Authors: X.R. Wang, Z.Q. Wang, T.S. Lin, P. He, R.J. Wang, M.Y. Bao

Electrospark deposition (ESD) attracts special attention from scientists and engineers because of its unique advantages. However, the ESD process has been carried out by hand up to the present. This prevents ESD from preparing complex curve/surface coatings owing to manual operation characteristics. To meet the coating precise preparation requirements for a lot of parts with complex surface from various industrial fields, this paper aims to obtain a new automatic ESD equipment, process and preparation methodology for complex surface coatings.

By designing a special deposition holder and re-programming programmable machine controller, an ESD power supply and a computer numerical control milling machine are integrated to obtain an electrospark-computer integrated deposition system (ES-CIDS). Then, based on the ES-CIDS, a new ESD process, named electrospark-computer numerical control deposition (ES-CNCD) is developed. Furthermore, complex surface coatings are depicted using non-uniform rational B-spline mathematical model and modeled in a special software developed via MATLAB. Finally, deposition programs for a complex coating are generated using golden section interpolation method, and transferred to and executed by the ES-CIDS to accomplish the preparation of the complex surface coating.

This paper demonstrates that it is possible and feasible to prepare complex surface coatings via an automatic ESD process (namely, ES-CNCD) precisely.

2. Application of sensitive dimensionless parameters and PSO–SVM for fault classification in rotating machinery
Authors: Aisong Qin, Qin Hu, Qinghua Zhang, Yunrong Lv, Guoxi Sun

Rotating machineries are widely used in manufacturing, petroleum, chemical, aircraft, and other industries. To accurately identify the operating conditions of such rotating machineries, this paper aims to propose a fault diagnosis method based on sensitive dimensionless parameters and particle swarm optimization (PSO)–support vector machine (SVM) for reducing the unexpected downtime and economic losses.

A relatively new hybrid intelligent fault classification approach is proposed by integrating multiple dimensionless parameters, the Fisher criterion and PSO–SVM. In terms of data pre-processing, a method based on wavelet packet decomposition (WPD), empirical mode decomposition (EMD) and dimensionless parameters is proposed for the extraction of the vibration signal features. The Fisher criterion is applied to reduce the redundant dimensionless parameters and search for the sensitive dimensionless parameters. Then, PSO is adapted to optimize the penalty parameter and kernel parameter for SVM. Finally, the sensitive dimensionless parameters are classified with the optimized model.

As two different time-frequency analysis methods, a method based on a combination of WPD and EMD used to extract multiple dimensionless parameters is presented. More vital diagnosis information can be obtained from the vibration signals than by only using a single time-frequency analysis method. Besides, a fault classification approach combining the sensitive dimensionless parameters and PSO-SVM classifier is proposed. The comparative experiment results show that the proposed method has a high classification accuracy and efficiency.

3. Peg-in-hole assembly based on master-slave coordination for a compliant dual-arm robot

Authors: Yanjiang Huang, Yanglong Zheng, Nianfeng Wang, Jun Ota, Xianmin Zhang

The paper aims to propose an assembly scheme based on master–slave coordination for a compliant dual-arm robot to complete a peg-in-hole assembly task.

The proposed assembly scheme is inspired by the coordinated behaviors of human beings in the assembly process. The left arm and right arm of the robot are controlled to move alternately. The fixed arm and the moving arm are distinguished as the slave arm and the master arm, respectively. The position control model is used at the uncontacted stage, and the torque control model is used at the contacted stage.

The proposed assembly scheme is evaluated through peg-in-hole assembly experiments with different shapes of assembly piece. The round, triangle and square assembly piece with 0.5 mm maximum clearance between the peg and the hole can be assembled successfully based on the proposed method. Furthermore, three assembly strategies are investigated and compared in the peg-in-hole assembly experiments with different shapes of assembly piece.

The contribution of this study is that the authors propose an assembly scheme for a compliant dual-arm robot to overcome the low positioning accuracy and complete the peg-in-hole assembly tasks with different shapes parts.

4. A deep learning based automatic surface segmentation algorithm for painting large-size aircraft with 6-DOF robot

Authors: Guolei Wang, Xiaotong Hua, Jing Xu, Libin Song, Ken Chen

This paper aims to achieve automatically surface segmentation for painting different kinds of aircraft efficiently considering the demands of painting robot.

This project creatively proposed one method that accepts point cloud, outputs several blocks, each of which can be handled by ABB IRB 5500 in one station. Parallel PointNet (PPN) is proposed in this paper for better handling six dimensional aircraft data including every point normal. Through semantic segmentation of PPN, each surface has its own identity information indicating which part this surface belongs to. Then clustering considering constraints is applied to complete surface segmentation with identity information. To guarantee segmentation paintable and improve painting efficiency, different dexterous workspaces of IRB 5500 corresponding to different postures have been analyzed carefully.

The experiments confirm the effectiveness of the proposed surface segmentation method for painting different types of aircraft by IRB 5500. For semantic segmentation on aircraft data with point normal, PPN has higher precision than PointNet. In addition, the whole algorithm can efficiently segment one complex aircraft into qualified blocks, each of which has its own identity information, can be painted by IRB 5500 in one station and has fewer edges with other blocks.

Combining deep learning skills with traditional methods, the proposed method is proved to behave much better for surface segmentation task in aircraft painting.

5. Position analysis of brushless direct current motor using robust fixed order H-infinity controller

Authors: Sikander Hans, Smarajit Ghosh

The efficient speed controller is found to be an important requirement to run the motor for the brushless direct current (BLDC) motor. This requirement is considered as superior, as it may increase the operating speed and system efficiency. In the existing methods, proportional plus integral (PI) controller has been included because of its simple architecture. But the PI controller produces load disturbance, control complexity and some parametric (Proportional plus integral) variations. The purpose of this proposed controller is to overcome the problems produced by PI controller in BLDC motor.

The proposed BLDC motor is developed with fixed order H-infinity controller. In this architecture, both the weight functions and transfer functions were included to

design the controller. This controller has been included in this BLDC to detect the rotor position. The optimal position of rotor is identified by introducing particle swarm optimization algorithm.

The torque that obtained in the motor is highly reduced by this proposed controller and also enhances the speed. The BLDC motor is modelled in a MATLAB environment.

The performance of the torque, speed and back electro-motive force is analysed and compared with the existing controllers such as fuzzy proportional plus integral plus derivative, sensing algorithm and fuzzy proportional plus derivative controller.

Simulation results show that the proposed technique gives better results than the other existing controllers.

6. An integrated approach for line balancing and AGV scheduling towards smart assembly systems

Authors: Humyun Fuad Rahman, Mukund Nilakantan Janardhanan, Peter Nielsen

Optimizing material handling within the factory is one of the key problems of modern assembly line systems. The purpose of this paper is to focus on simultaneously balancing a robotic assembly line and the scheduling of material handling required for the operation of such a system, a topic that has received limited attention in academia. Manufacturing industries focus on full autonomy because of the rapid advancements in different elements of Industry 4.0 such as the internet of things, big data and cloud computing. In smart assembly systems, this autonomy aims at the integration of automated material handling equipment such as automated guided vehicles (AGVs) to robotic assembly line systems to ensure a reliable and flexible production system.

This paper tackles the problem of designing a balanced robotic assembly line and the scheduling of AGVs to feed materials to these lines such that the cycle time and total tardiness of the assembly system are minimized. Because of the combination of two well-known complex problems such as line balancing and material handling and a heuristic- and metaheuristic-based integrated decision approach is proposed.

This study is beneficial for production managers in understanding the main decisional steps involved in the designing/redesigning of smart assembly systems and providing guidelines in decision-making. Moreover, this study explores the material distribution scheduling problems in assembly systems, which is not yet comprehensively explored in the literature.

7. ACD^{3}GPSO: automatic clustering-based algorithm for multi-robot task allocation using dynamic distributed double-guided particle swarm optimization

Authors: Asma Ayari, Sadok Bouamama

The multi-robot task allocation (MRTA) problem is a challenging issue in the robotics area with plentiful practical applications. Expanding the number of tasks and robots increases the size of the state space significantly and influences the performance of the MRTA. As this process requires high computational time, this paper aims to describe a technique that minimizes the size of the explored state space, by partitioning the tasks into clusters. In this paper, the authors address the problem of MRTA by putting forward a new automatic clustering algorithm of the robots' tasks based on a dynamic-distributed double-guided particle swarm optimization, namely, ACD^{3}GPSO.

This approach is made out of two phases: phase I groups the tasks into clusters using the ACD^{3}GPSO algorithm and phase II allocates the robots to the clusters. Four factors are introduced in ACD^{3}GPSO for better results. First, ACD^{3}GPSO uses the k-means algorithm as a means to improve the initial generation of particles. The second factor is the distribution using the multi-agent approach to reduce the run time. The third one is the diversification introduced by two local optimum detectors LODpBest and LODgBest. The last one is based on the concept of templates and guidance probability Pguid.

In this methodology, owing to the ACD^{3}GPSO algorithm, task allocation's run time has diminished. Therefore, the proposed method can be considered as a vital alternative in the field of MRTA with growing numbers of both robots and tasks. In PSO, stagnation and local optima issues are avoided by adding assorted variety to the population, without losing its fast convergence.

8. Parallel calibration based on modified trim strategy

Authors: Yaxin Peng, Naiwu Wen, Chaomin Shen, Xiaohuang Zhu, Shihui Ying

Partial alignment for 3D point sets is a challenging problem for laser calibration and robot calibration due to the unbalance of data sets, especially when the overlap of data sets is low. Geometric features can promote the accuracy of alignment. However, the corresponding feature extraction methods are time consuming. The purpose of this paper is to find a framework for partial alignment by an adaptive trimmed strategy.

First, the authors propose an adaptive trimmed strategy based on point feature histograms (PFH) coding. Second, they obtain an initial transformation based on this partition, which improves the accuracy of the normal direction weighted trimmed iterative closest point (ICP) method. Third, they conduct a series of GPU parallel implementations for time efficiency.

In practice, point set alignment for calibration is a technique widely used in the fields of aircraft assembly, industry examination, simultaneous localization and mapping and surgery navigation.

The contributions are as follows: first, the authors introduce a novel coarse alignment as an initial calibration

by PFH descriptor similarity, which can be viewed as a coarse trimmed process by partitioning the data to the almost overlap part and the rest part; second, they reduce the computation time by GPU parallel coding during the acquisition of feature descriptor; finally, they use the weighted trimmed ICP method to refine the transformation.

This study is applicable to rigid transformation so far. It could be extended to non-rigid transformation.

9. Distributed dissipative filtering for flexible manipulator with randomly occurring uncertainties and missing data

Authors: Xiaodong Zhang, Tao Xiao

The purpose of this paper is to investigate the dissipative filtering problem for a flexible manipulator (FM) with randomly occurring uncertainties and randomly occurring missing data.

The randomly occurring phenomena during the filtering procedure are described by Bernoulli sequences. Based on the idea of dissipative theory, the distributed filtering error augmented system is derived for ensuring the prescribed dissipative performance.

By constructing appropriate Lyapunov function, sufficient dissipative filtering conditions are derived such that the filtering error can be approaching zero. Then, the desired distributed filter gains are designed with the help of matrix transformation.

The merit of this paper is proposing a novel distributed filtering framework for an FM with external disturbance under the dissipative framework, which can provide a more applicable filter design.

10. Double-rotator and valve plate distribution radial piston pump

Authors: Peng Dong, Shengdun Zhao, Shuqin Fan, Muzhi Zhu, Peng Zhang

The drive shaft and the distribution shaft of a traditional radial piston pump are in a cantilever state. To solve this problem, this paper aims to present a radial piston pump with through shaft driving and valve plate distribution.

The working principle of the pump is discussed in detail. In this radial piston pump, valve plate distribution parts are designed to distribute oil to the piston chambers, and the distribution shaft is replaced. A bearing is installed between the stator and rotator to reduce the friction. The transmission shaft is supported by two bearings to ensure smooth operation. The support force of the transmission shaft is optimized. In addition, the flow pulsation principle is presented. To accomplish the change, the displacement of the radial piston pump, the proportional control system is designed.

After completing the machining and assembly of the pump, an experimental study was carried out. The results show that the output flow of the pump is basically the same as the theoretical flow.

The friction between the slipping shoes and the stator is greatly reduced due to the function of rolling bearings. The higher stability of the driveshaft is obtained for the reason of double-sided support. The radial piston pump has a novel structural design in reducing the friction between the shoes and the stator and improving the stability of the transmission shaft.

11. Optimization of a multi-constraint two-sided assembly line balancing problem using an improved imperialist competitive algorithm

Authors: Mingshun Yang, Li Ba, Erbao Xu, Yan Li, Yong Liu, Xinqin Gao

Assembly is the last step in manufacturing processes. The two-sided assembly line balancing problem (TALBP) is a typical research focus in the field of combinatorial optimization. This paper aims to study a multi-constraint TALBP-I (MC-TALBP-I) that involves positional constraints, zoning constraints and synchronism constraints to make TALBP more in line with real production. For enhancing quality of assembly solution, an improved imperialist competitive algorithm (ICA) is designed for solving the problem.

A mathematical model for minimizing the weighted sum of the number of mated-stations and stations is established. An improved ICA is designed based on a priority value encoding structure for solving MC-TALBP-I.

The proposed ICA was tested by several benchmarks involving positional constraints, zoning constraints and synchronism constraints. This algorithm was compared with the late acceptance hill-climbing (LAHC) algorithm in several instances. The results demonstrated that the ICA provides much better performance than the LAHC algorithm.

The best solution obtained by solving MC-TALBP-I is more feasible for determining the real assembly solution than the best solution obtained by solving based TALBP-I only.

A novel ICA based on priority value encoding is proposed in this paper. Initial countries are generated by a heuristic method. An imperialist development strategy is designed to improve the qualities of countries. The effectiveness of the ICA is indicated through a set of benchmarks.

12. Wrinkle and boundary detection of fiber products in robotic composites manufacturing

Authors: Kashish Gupta, Marian Körber, Abtin Djavadifar, Florian Krebs, Homayoun Najjaran

The paper aims to focus on a vision-based approach to advance the automated process of the manufacturing of an Airbus A350's pressure bulkhead. The setup

enables automated deformation and draping of a fiber textile on a form-variable end-effector.

The proposed method uses the information of infrared (IR) and color-based images in Red, Green and Blue (RGB) representative format, as well as depth measurements to identify the wrinkles and boundary edge of semi-finished dry fiber products on the double-curved surface of a flexible modular gripper used for laying the fabric. The technique implements a simple and practical image processing solution using a sequence of pixel-wise binary masks on an industrial scale setup; it bridges the gap between laboratory experiments and real-world execution, thereby demonstrating practical and applied research.

The efficacy of the technique is demonstrated via experiments in the presented work. The two objectives as follows boundary edge detection and wrinkle detection are accomplished in real time in an industrial setup. During the draping process, tensions developed in the fibers of the textile cause wrinkles on the surface, which are highly detrimental to the production process, material quality and strength. The proposed method automates the identification and detection of the wrinkles and the textile on the gripper surface. The proposed work aids in alleviating the problems caused by these wrinkles and helps in quality control in the production process.

13. A review: virtual assembly of flexible cables based on physical modeling

Authors: Hongwang Du, Wei Xiong, Haitao Wang, Zuwen Wang

Cables are widely used, and they play a key role in complex electromechanical products such as vehicles, ships, aircraft and satellites. Cable design and assembly significantly impact the development cycle and assembly quality, which is be-coming a key element affecting the function of a product. However, there are various kinds of cables, with complex geo-metric configurations and a narrow assembly space, which can easily result in improper or missed assembly, an unreasonable layout or interference. Traditional serial design methods are inefficient and costly, and they cannot predict problems in installation and use. Based on physical modeling, computer-aided cable design and assembly can effectively solve these problems. This paper aims to address virtual assembly (VA) of flexible cables based on physical modeling.

Much research has focused recently on virtual design and assembly-process planning for cables. This paper systematically reviews the research progress and the current state of mechanical models, virtual design, assembly-process planning, collision detection and geometric configuration and proposes areas for further research.

In the first instance, the main research groups and typical systems are investigated, followed by extensive exploration of the major research issues. The latter can be reviewed from five perspectives: the current state of mechanical models, virtual design, assembly-process planning, collision detection and geometric configuration. Finally, the barriers that prevent successful application of VA are also discussed, and the future research directions are summarized.

14. Compliant assembly deviation analysis of large--scale thin-walled structures in different clamping schemes via ANCF

Authors: Xun Xu, Haidong Yu, Yunyong Li, Xinmin Lai

The structure stiffness is greatly affected by the fixture constraints during assembly due to the flexibility of large--scale thin-walled structures. The compliant deformation of structures is usually not consistent for the non-uniform stiffness in various clamping schemes. The purpose of this paper is to investigate the correlation between the assembly quality and the clamping schemes of structures with various initial deviations and geometrical parameters, which is based on the proposed irregular quadrilateral plate element via absolute nodal coordinate formulation (ANCF).

Two typical clamping schemes are specified for the large-scale thin-walled structures. Two typical deviation modes are defined in both free and clamping states in the corresponding clamping schemes. The new irregular quadrilateral plate element via ANCF is validated to analyze the compliant deformation of assembled structures. The quasi-static force equilibrium equations are extended considering the factors of clamping constraints and geometric deviations.

The initial deviations and geometrical parameters strongly affect the assembly deviations of structures in two clamping schemes. The variation tendencies of assembly deviations are demonstrated in details with the circumferential clamping position and axial clamping position in two clamping schemes, providing guidance to optimize the fixture configuration. The assembly quality of structures with deviations can be improved by configuration synthesis of the clamping schemes.

Typical over-constraint clamping schemes and deviation modes in clamping states are defined for large-scale thin-walled structures. The plate element via ANCF is extended to analyze the assembly deviations of thin-walled structures in various clamping schemes. Based on the proposed theoretical model, the effects of clamping schemes and initial deviations on the deformation and assembly deviation propagation of structures are investigated.

15. Automatically generating assembly sequences with an ontology-based approach

Authors: Yanru Zhong, Chaohao Jiang, Yuchu Qin, Guoyu Yang, Meifa Huang, Xiaonan Luo

The purpose of this paper is to present and develop an ontology-based approach for automatic generation of assembly sequences. In this approach, an assembly sequence planning ontology is constructed to represent the structure and interrelationship of product geometry

information and assembly process information. In the constructed ontology, certain reasoning rules are defined to describe the knowledge and experience. Based on the ontology with reasoning rules, the algorithm for automatically generating assembly sequences is designed and implemented. The effectiveness of this approach is verified via applying it to generate the assembly sequences of a gear reducer.

The main contribution of the paper is presenting and developing an ontology-based approach for automatically generating assembly sequences. This approach can provide a feasible solution for the issue that mathematics-based assembly sequence generation approaches have great difficulty in explicitly representing assembly experience and knowledge.

16. Nonrigid point set registration based on Laplace mixture model with local constraints

Authors: Chao Xu, Xianqiang Yang, Xiaofeng Liu

This paper aims to investigate a probabilistic mixture model for the nonrigid point set registration problem in the computer vision tasks. The equations to estimate the mixture model parameters and the constraint items are derived simultaneously in the proposed strategy.

The problem of point set registration is expressed as Laplace mixture model (LMM) instead of Gaussian mixture model. Three constraint items, namely, distance, the transformation and the correspondence, are introduced to improve the accuracy. The expectation-maximization (EM) algorithm is used to optimize the objection function and the transformation matrix and correspondence matrix are given concurrently. Although amounts of the researchers study the nonrigid registration problem, the LMM is not considered for most of them. The nonrigid registration problem is considered in the LMM with the constraint items in this paper. Three experiments are performed to verify the effectiveness and robustness and demonstrate the validity. The novel method to solve the nonrigid point set registration problem in the presence of the constraint items with EM algorithm is put forward in this work.

17. A multi-object posture coordination method with tolerance constraints for aircraft components assembly

Authors: Yifan Zhang, Qing Wang, Anan Zhao, Yinglin Ke

This paper aims to improve the alignment accuracy of large components in aircraft assembly and an evaluation algorithm, which is based on manufacture accuracy and coordination accuracy, is proposed.

With relative deviations of manufacturing feature points and coordinate feature points, an evaluation function of assembly error is constructed. Then the optimization model of large aircraft digital alignment is established to minimize the synthesis assembly error with tolerance requirements, which consist of three-dimensional (3D) tolerance of manufacturing feature points and relative tolerance between coordination feature points. The non-linear constrained optimization problem is solved by Lagrange multiplier method and quasi-Newton method with its initial value provided by the singular value decomposition method. The optimized postures of large components are obtained, which makes the tolerance of both manufacturing and coordination requirements be met. Concurrently, the synthesis assembly error is minimized. Compared to the result of the singular value decomposition method, the algorithm is validated in three typical cases with practical data. The proposed method has been used in several aircraft assembly projects and gained a good effect.

This paper proposes a method to optimize the manufacturing and coordination accuracy with tolerance constraints when the postures of several components are adjusted at the same time. The results of this paper will help to improve the quality of component assemblies.

18. Optimizing assembly sequence planning using precedence graph-based assembly subsets prediction method

Authors: Nan Zhang, Zhenyu Liu, Chan Qiu, Weifei Hu, Jianrong Tan

Assembly sequence planning (ASP) plays a vital role in assembly process because it directly influences the feasibility, cost and time of the assembly process. The purpose of this study is to solve ASP problem more efficiently than current algorithms.

A novel assembly subsets prediction method based on precedence graph is proposed to solve the ASP problem. The proposed method adopts the idea of local to whole and integrates a simplified firework algorithm. First, assembly subsets are generated as initial fireworks. Then, each firework explodes to several sparks with higher-level assembly subsets and new fireworks are selected for next generation according to selection strategy. Finally, iterating the algorithm until complete and feasible solutions are generated. The proposed method performs better in comparison with state-of-the-art algorithms because of the balance of exploration (fireworks) and exploitation (sparks). The size of initial fireworks population determines the diversity of the solution, so assembly subsets prediction method based on precedence graph (ASPM-PG) can explore the solution space. The size of sparks controls the exploitation ability of ASPM-PG; with more sparks, the direction of a specific firework can be adequately exploited.

The proposed method is with simple structure and high efficiency. It is anticipated that using the proposed method can effectively improve the efficiency of ASP and reduce computing cost for industrial applications.

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