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CONTENTS / W NUMERZE

3
Jacek Ogrodniczek, Anna Rudawska, Izabela Miturska-Barańska, Elżbieta Doluk

Influence of technological factors on the strength of wood adhesive joints

Wpływ czynników technologicznych na wytrzymałość drewnianych połączeń klejowych

8
Leszek Tomczewski, Jagoda Muszyńska-Pałys

Analysis of the influence of turning parameters of CuZn39Pb3 and AW 6060 materials on surface roughness

Analiza wpływu parametrów toczenia materiałów CuZn39Pb3 i AW 6060 na chropowatość powierzchni

15
Magdalena Dąbrowska, Katarzyna Maciejewska

Optimising the sealing station in production process of tubes for catalytic converters involving SMED method – a case study

Optymalizacja stanowiska uszczelniania w procesie produkcyjnym przewodów do katalizatorów z wykorzystaniem metody SMED – studium przypadku

24
Tomasz Samborski, Andrzej Zbrowski, Stanisław Kozioł

Test system to verify thermal shock resistance

System testowy do badania odporności na szoki termiczne

32
Władysław Zielecki, Jan Godzimirski, Ewelina Ozga

The influence of shot peening on the stress state in the adhesive layer and the load capacity of adhesive joints

Wpływ pneumokulkowania na stan naprężeń w spoinie klejowej i nośność połączeń klejowych

41
Joanna Graczyk-Tarasiuk, Kanisius Karyono

The framework for the supplier qualification system for the world leader home appliances industry

Kwalifikacja dostawców na podstawie systemu obowiązującego w zakładach światowego lidera branży AGD

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INFLUENCE OF TECHNOLOGICAL FACTORS ON THE STRENGTH OF WOOD ADHESIVE JOINTS

WPŁYW CZYNNIKÓW TECHNOLOGICZNYCH NA WYTRZYMAŁOŚĆ DREWNIANYCH POŁĄCZEŃ KLEJOWYCH

Abstract

The article presents the results of a statistical analysis of adhesive joints with identical structural and material factors in relation to technological factors. Four types of adhesive joints were made: butt joints, lap joints, scarf joints and wedge joints. The joined materials were pine and oak wood. Each type of adhesive joint was joined in the following wood configurations: pine-pine, pine-oak, oak-oak. The technological factors were the type of adhesive, the humidity of the wood and the surface preparation of the samples. The U Mann-Whitney test was used to perform the statistical analysis. Results of statistical tests showed the influence of the used adhesive on pine-oak butt joints and wood moisture on pine-oak butt joints. Furthermore, the effect of wood configurations on the strength for each of the tested adhesive joints was compared using the Dunn's statistical test. The test showed that there were not statistical differences between the joints in configurations pine-pine and pine-oak.

Keywords: adhesive joints, statistical analysis, wood adhesives

Streszczenie

W artykule przedstawiono wyniki analizy statystycznej połączeń klejowych o jednakowych czynnikach konstrukcyjnych i materiałowych względem czynników technologicznych. Wykonano 4 rodzaje konstrukcji połączeń klejowych: doczołowe, zakładkowe, skośne, klinowe. Materiałami łączonymi było drewno sosny i dębu. Każdy rodzaj połączenia klejowego łączono w konfiguracji drewna: sosna-sosna, sosna-dąb, dąb-dąb. Czynnikami technologicznymi był rodzaj kleju, wilgotność drewna oraz przygotowanie powierzchni próbek. Do wykonania testu statystycznego wykorzystano test U Manna-Whitneya. Analiza statystyczna wykazała wpływ rodzaju kleju na połączenia doczołowe sosna-dąb oraz wilgotności drewna na połączenia skośne sosna-dąb. Ponadto porównano wpływ gatunku drewna na wytrzymałość każdego z badanych połączeń klejowych przy pomocy testu Dunna. Test wykazał, że połączenia sosna-sosna nie różnią się statystycznie od połączeń sosna-dąb.

Słowa kluczowe: połączenia klejowe, analiza danych, kleje do drewna

1. Introduction

Wood is a natural construction material widely used in the civil engineering and furniture industry. It is anisotropic material with porous structure. The mechanical properties of wood depend on the type and species of timber used. Wood can be divided into two types of trees: coniferous (e.g. pine, spruce) and deciduous (e.g. oak, alder) [1,2,3].

Wood is susceptible to ageing and loss of strength. The main factors affecting the strength of wood are temperature, changes in humidity, water, insects and fungi. There are a lot of methods which modify the structure of the wood and prepare this material for required application. This method can be divided into 4 categories: heat treatment, chemical treatment, surface treatment and impregnation [4,5,6].

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Heat treatment enhances wood structure by reducing the fluid content in the material and increases dimensional stability. However, it has a negative effect on static and dynamic strength. The chemical treatment of wood modifies the wood cell walls and increases the strength of the material. That method protects wood against moisture [7,8].

The most common method of modifying wood is surface treatment and impregnation. The surface of the wood is abraded with a sanding tool to prepare the surface for application of a layer impregnating agent, which protects the material from external factors. Impregnating agents are usually of natural origin and are based on linseed oil [9,10,11].

Wood selected for the study was pine (*Pinus sylvestris*) and oak (*Quercus robur*). Pine wood is a commonly used material, which is due to its easy availability. Pine trees can adapt to different environmental conditions and grow fast. Oak wood has high strength and is resistant to external factors such as insects and fungi [12].

The aim of this paper was to compare the influence of material and technological factors on adhesive joints with different type of joint construction. The technological factors in the study were type of the used adhesive, preparation of surface and wood moisture. Statistical analysis comparing adhesive joints was prepared using RStudio and Statistica software.

2. Research methodology

During the process of preparation adhesive joints, samples were divided according to the type of wood, joints construction and technological factors such as the type of adhesive, wood moisture and the surface treatment of the wood. In the study, one sample of each adhesive joint was made, characterized by selected construction, material and technological factors.

2.1. Samples preparation

96 samples were prepared for each wood species. Half of them had 6-8% wood humidity (dry) whereas the other half had 16-18% wood humidity (wet). The length of the sample was 50 mm and cross-section was 20 x 20 mm. The first step of the study was a mechanical treatment which shaped samples for the selected adhesive joints construction. In the study, the following adhesive joints were made: butt joints, lap joints, scarf joints and wedge joints. The dimensions of the samples used in the aforementioned adhesive joints are shown in fig. 1-4.

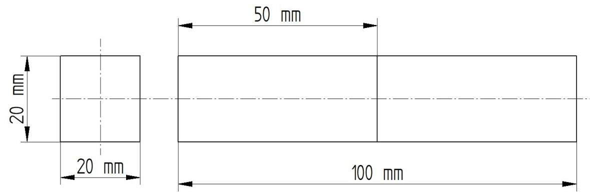

Fig. 1. Dimension of sample used in butt joint

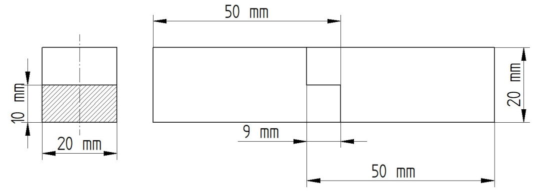

Fig. 2. Dimension of sample used in lap joint

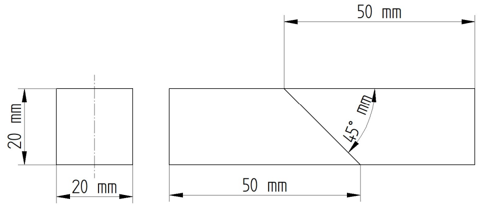

Fig. 3. Dimension of sample used in scarf joint

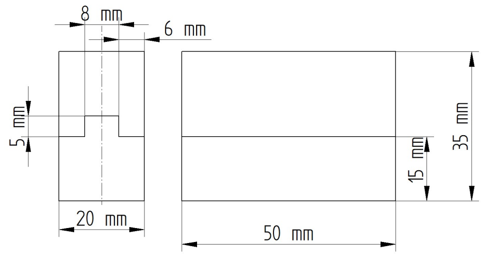

Fig. 4. Dimension of samples used in wedge joint

For each construction of the adhesive joint, a division was made into the type of used wood and humidity. Materials were joined in the following configurations: pine-pine, pine-oak, oak-oak. As a result of the division, 8 adhesive joints of identical construction and material were formed. In the case of adhesive joints with the wedge construction, where dissimilar materials were used, the grove was formed from the oak wood. In addition, to increase the number of possible factors influencing the adhesive joints, the samples were further processed. The surface of half the dry and wet samples was abraded with P120 sandpaper. The abrasion of the adhesive samples was done manually by 20 making 20 circular movements.

During the sample preparation process, the ambient temperature was 23°C ± 1°C and humidity was 50% ± 1%.

2.2. Adhesive technology and tensile tests

Polyurethane adhesive (trademark: PUR adhesive, producer: Würth, Künzelsau, Germany) and PVAC-based adhesive (trademark: D3 PVA wood adhesive, producer: Würth, Künzelsau, Germany) were used to make adhesive joints. This made it possible to create adhesive joints with identical constructional and material factors, as well as identical technological processing, differing in the adhesive used. Both adhesives were one-component.

While making adhesive joints, the adhesive was applied to the surface of one sample of the adhesive joint. The bottle of polyurethane adhesive had a dispenser to apply the adhesive. In the case of the PVAC-based adhesive, the adhesive was applied with a spatula.

The adhesive joints were subjected to curing for a period of 7 days. The samples were pressed by a specimen holder, which made an impact with a value of 0.8 MPa. Strength tests of adhesive joints were carried out on a Zwick/Roell Z150 testing machine according to PN-EN 311:2004 [13].

2.3. Statistical analysis

The aim of the statistical analysis was to demonstrate the influence of technological factors on the strength of adhesive joints with equal structural and material factors. Due to the lack of normal distribution in most of the compared groups, the non-parametric statistical U Mann Whitney test was used to perform the statistical analysis. The test is equivalent to the parametric t-student test. As hypothesis H_0, the similarity between the strength of adhesive joints in the groups studied was accepted [14,15].

The results of the strength tests were compared with respect to one of the following technological factors: the type of adhesive used, the method of preparation of the surface of the samples and wood humidity. During the comparative analysis, against one factor, the remaining technological factors in the group were treated as the same type of adhesive joint. The test significance value for the U Mann-Whitney test was $\alpha = 0{,}05$.

The statistical analysis also compared the structural strength of the adhesive joints against the material factor. Dunn's test was used to make the comparison. Technological factors were not considered when comparing the strength of the joint structure.

3. Results

3.1. Tensile strength results

The results of the tensile strength of the tested adhesive joints are shown in table 1. The table presents the descriptive statistics for the adhesive joints in relation the joint construction and material factor.

Table 1. Tensile strength results of the tested adhesive joints

Joint	Wood	Number of samples	Mean [MPa]	Median [MPa]	Maximum [MPa]	Minimum [MPa]	Variance [MPa]	Stand. Deviation [MPa]
Butt joint	Oak-Oak	8	2.783	2.209	1.539	5.276	1.870	1.368
	Pine-Oak	8	1.710	1.829	0.889	2.704	0.533	0.730
	Pine-Pine	8	1.456	1.465	0.616	2.662	0.423	0.650
Lap joint	Oak-Oak	8	3.534	3.171	2.205	5.372	1.427	1.194
	Pine-Oak	8	2.194	2.264	1.309	3.499	0.647	0.804
	Pine-Pine	8	2.132	2.231	0.832	3.330	0.631	0.794
Scarf joint	Oak-Oak	8	1.149	1.056	0.720	1.718	0.129	0.359
	Pine-Oak	8	0.646	0.633	0.359	0.929	0.031	0.177
	Pine-Pine	8	0.585	0.565	0.389	0.774	0.015	0.121
Wedge joint	Oak-Oak	8	3.382	3.373	1.996	4.810	0.826	0.909
	Pine-Oak	8	1.812	1.840	1.397	2.184	0.077	0.278
	Pine-Pine	8	1.948	1.712	1.433	3.430	0.429	0.655

On the basis of the results from the table 1 it can be concluded that the adhesive joints with the scarf joint construction obtained the lowest strength of all the adhesive joint constructions. The highest strength was achieved by three adhesive joints:

- Butt joint/Oak-Oak/Wet/PUR/Unpolished (5.276 MPa),
- Lap joint/Oak-Oak/Wet/PUR/Polished MPa (5.277 MPa),
- Lap joint/Oak-Oak/Wet/PVAC/Unpolished (5,372 MPa).

3.2. Statistical analysis results

The performed statistical results of the U Mann-Whitney test for each type of adhesive joint construction are presented in table 2-5. The tables show the p-value for each type of joint compared against one technological factor.

Table 6 reveals the results of Dunn's tests which compared the strength of adhesive joints for each kind of material used.

Table 2. Results of U Mann-Whitney tests for butt joints

Butt joints	Type of material		
	pine - pine	pine - oak	oak - oak
	p-value		
Type of adhesive	0.886	0.486	0.486
Wood humidity	0.486	0.029	0.686
Surface preparation	0.686	0.343	0.886

Table 3. Results of U Mann-Whitney tests for lap joints

Lap joints	Type of material		
	pine - pine	pine - oak	oak - oak
	p-value		
Type of adhesive	0.343	0.400	0.343
Wood humidity	0.200	0.857	0.486
Surface preparation	0.686	0.229	0.486

Table 4. Results of U Mann-Whitney tests for scarf joints

Scarf joints	Type of material		
	pine - pine	pine - oak	oak - oak
	p-value		
Type of adhesive	0.343	0.029	0.200
Wood humidity	0.886	0.886	0.486
Surface preparation	1.000	0.686	0.886

Table 5. Results of U Mann-Whitney tests for wedge joints

Wedge joints	Type of material		
	pine - pine	pine - oak	oak - oak
	p-value		
Type of adhesive	0.686	0.486	0.343
Wood humidity	0.114	0.686	0.686
Surface preparation	0.686	0.114	0.686

Tabela 6. Dunn's test results

Compared values between materials	Type of joint			
	Butt joint	Lap joint	Scarf joint	Wedge joint
	p-value			
Oak - oak, Pine - oak	0.472	0.069	0.019	0.009
Oak - oak, Pine - pine	0.065	0.049	0.003	0.013
Pine - pine, Pine - oak	1.000	1.000	1.000	1.000

Analysing the results of statistical calculations comparing technological factors for individual adhesive joint constructions, statistical significance can be seen in 2 cases. Both of them concern joints formed from pine-oak materials.

More information about the results of statistical tests is presented in the next point.

4. Discussion of results

The first type of joints showing statistical significance are butt joints. The technological factors which indicates the difference in the strength of adhesive joints is the moisture content in the wood. The joined pine and oak samples showed equal moisture content. In this test, adhesive joints were compared between a group of adhesive whose wood moisture content was 6-8% and a group whose wood moisture was 16-18%. The p-value for the U Mann--Whitney test comparing effect of wood moisture of butt adhesive joints formed by joining pine and oak samples was $p = 0.029$. This value is lower than the test significance value.

The second type of joints showing statistical significance are scarf joints. The technological factor which affects the difference between the compared strength results of adhesive joints is the type of adhesive used for joining pine and oak samples. The p-value for U Mann-Whitney test comparing the effect of glue on the strength of butt joints formed by joining pine and oak samples is 0.029. The value is lower than the test significance value.

The remaining results of statistical calculations performed with the Mann-Whitney U test, show that there is no statistical significance for the tested adhesive joints compared against technological factors.

The strength results were also compared against the material factor for each type of joint design. Dunn's test was used to perform statistical calculations comparing adhesive joints against the material factor (Table 6). The graph in Fig. 5 illustrates the median and standard deviation of the strength values of adhesive joints of different designs against the material used in the adhesive joints.

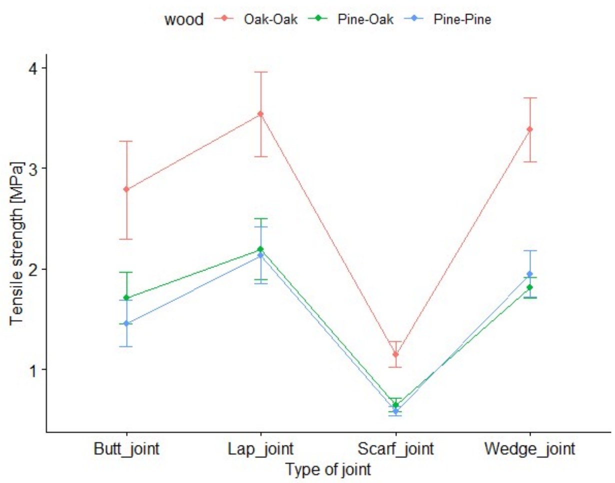

Fig. 5. Strength of adhesive joints

From the graph in Fig. 5, it can be concluded that for all adhesive joint designs, the strength of pine wood joints and pine and oak wood joints are similar. This fact is confirmed by the Dunn test.

The butt joint shows a lack of statistical significance, resulting from the Dunn statistical test result. In the case of this adhesive joint construction, there are no statistical differences between the material factors. The lack of statistical significance is manifested by the comparison of the results of the strength of lap joints between adhesive joints of oak-oak and pine-oak samples.

5. Conclusion

The performed strength tests and statistical analysis allow the following conclusions to be drawn:

- the technological factor significantly affecting the strength of a butt adhesive joint is the moisture content of the wood,
- a technological factor significantly affecting the strength of a slanting adhesive joint is the type of glue used,
- technological factors such as the type of adhesive used, the moisture content of the wood, or the preparation of the surface of the glued specimens do not affect the strength of lap and wedge adhesive joints of wood,
- in adhesive joints formed as a result of joining pine wood and oak wood, oak wood does not influence the increase of the strength of the adhesive joint.

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ANALYSIS OF THE INFLUENCE OF TURNING PARAMETERS OF CUZN39PB3 AND AW 6060 MATERIALS ON SURFACE ROUGHNESS

ANALIZA WPŁYWU PARAMETRÓW TOCZENIA MATERIAŁÓW CUZN39PB3 I AW 6060 NA CHROPOWATOŚĆ POWIERZCHNI

Abstract

The article presents an analysis of the turning parameters of two non-ferrous materials. The tested materials were: brass CuZn39Pb3 and aluminum alloy AW 6060. A Kyocera turning knife and a WNMG 080404 AH plate were used to make the samples. Three parameters were tested: rotational speed, feed and depth of cut at three levels of variability. The roughness parameters Ra and Rz were selected for the analysis. On the basis of the obtained results, it was shown that the feed used during machining has the greatest influence on roughness, while the change of depth or cutting speed does not cause significant differences in roughness.

Keywords: turning, non-ferrous metals, surface roughness

Streszczenie

W artykule przedstawiono analizę parametrów toczenia dwóch materiałów nieżelaznych. Materiałami poddanymi badaniom były: mosiądz CuZn39 Pb3 i stop aluminium AW 6060. Do wykonania próbek użyto noża tokarskiego firmy Kyocera i płytki WNMG080404AH tej firmy. Badaniom poddano trzy parametry: prędkość obrotową, posuw i głębokość skrawania na trzech poziomach zmienności. Do analizy wybrano parametr chropowatości Ra i Rz. Na podstawie uzyskanych wyników wykazano, że największy wpływ na chropowatość ma posuw stosowany podczas obróbki, natomiast zmiana głębokości czy tez prędkości skrawania nie powoduje znaczących różnić w chropowatości.

Słowa kluczowe: toczenie, metale nieżelazne, chropowatość powierzchni

1. Introduction

Machining processes include shaping machine and device elements by removing the stock in the form of chips. For this purpose, it is necessary to properly select the right tool and processing parameters of a given material. The materials used for processing are divided into six treatment groups according to ISO [11]. One of these groups is the group of materials marked as N - non-ferrous metals, softer metals such as aluminum, copper, brass, etc.

After the machining process, an important element is to determine the surface roughness. It is an important factor apart from the shape and dimensional accuracy [5]. Nowadays, roughness parameters are determined by contact technique using profilometers or by optical technique [1].

The surface geometry of machine parts is shaped as a result of the machining process. There are geometric errors on the machined surface. Due to the geometric features and dimensions, the following surface errors are distinguished: macroscopic (shape, position and waviness), microscopic (roughness) and submicroscopic (submicron inequalities). As a result of machining, the surface geometry is characterized by errors in shape, position, waviness and roughness. The surface geometry represents the surface layer, which is the layer of material that delimits the actual surface. The elements that make up the surface layer are, among others, surface roughness. The roughness of the surface represents the actual state with unevenness such as raised or depressions [8]. In order to achieve the assumed quality of the treated surfaces, it is

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necessary to determine the relationship between the controlled technological parameters.

2. Research methodology

From the group of non-ferrous materials, two materials were selected for testing: brass CuZn39Pb3 and aluminum alloy AW 6060. Brass with the designation CuZn39Pb3 is a soft and very easy-to-process material. Brass does not produce long chips during machining, unlike many copper alloy materials [3]. The chemical composition of this material is shown in Table 1.

Table 1. Chemical composition of CuZn39Pb3 [6]

Material	%Cu	%Fe	%Pb	%Zn	%Ni	%Sn	%Al
CuZn39Pb3	57,7	0,2	3,3	38,49	0,1	0,2	0,01

This material is widely used in water supply installations and plumbing because it transfers heat very easily and is resistant to corrosion [2].

The second material is AW 6060 aluminum alloy. These alloys are widely used in the aviation industry. AW 6060 alloy is characterized by medium tensile strength and fatigue strength. It is susceptible to welding and anodizing [9]. The chemical composition of this material is shown in Table 2.

The mechanical properties of both tested materials are shown in Table 3.

All the tools used to perform the tests are presented in Table 4.

Table 2. Chemical composition of AW 6060 [5]

Material	%Al	%Mg	%Si	%Fe	%Zn	%Mn	%Cu	%Cr	%Ti
AW 6060	rest	0,4	0,5	02	0,15	0,1	0,1	0,05	01

Table 3. Mechanical properties of tested materials [2,8]

Indication	$R_{0,2}$ [MPa]	R_m[MPa]	A_5 [%]	HB	ρ [g/cm^3]	E [GPa]
CuZN39Pb3	365	502	18	120	8,47	97
AW 6060	160	215	16	60	2,7	72,5

Table 4. Input data for the experiment

Machine tool	HAAS ST20
Turning tool	DWLNL2525M-08 Kyocera
Plate	WNMG080404 AH Kyocera
Workpiece material	CuZn39 Pb3
	AW 6060
Profilometer	Surtronic S128 TalyProfile Silver

Variable parameters in the tested samples were rotation, feed and depth of cut. These parameters were selected as the maximum, average and minimum parameters according to the recommendations of the cutting plate manufacturer [10]. The selected parameters are presented in Table 5.

Table 5. Technological parameters

Rotation [rpm]	Feed f [mm/rev]	Depth of cut a_p [mm]
3200	0,2	1,5
2400	0,1	0,5
1600	0,03	0,2

For three variable parameters on three levels, 27 samples were made for each of the materials on a 20 [mm] diameter shaft. In the next step, roughness measurements were carried out using the Surtronic S128 profilometer – It is a universal device for roughness measurement both in laboratory and workshop conditions [12]. The TalyProfile Silver software was used for the measurement. A Gaussian filter was used to calculate the roughness parameters. Two roughness parameters were analyzed: Ra [µm] and Rz [µm]. According to Leach R. [7] the Rz parameter have a significant influence on friction, wear, lubrication and mechanical tightness.

3. Results and discussion

Standard methodology for surface roughness analysis was used for each sample measured. All measurements were repeated three times and mean values were determined. Surface leveling was used in each measurement. The surface roughness was filtered (Gauss-Sow filter), and then the roughness parameters were determined according to ISO 4287. The selection of the surface roughness parameters depends on the operational purpose of the treated surface [8].

The parameters used and the results of the obtained measurements are presented in Table 6.

Table 6. Measurement results

				CuZn39 Pb3		AW 6060	
Lp.	n [rpm]	a_p [mm]	f[mm/rev]	Ra [µm]	Rz [µm]	Ra [µm]	Rz [µm]
1	3200	1,5	0,2	1,81	9,52	1,76	7,84
2	3200	1,5	0,1	0,92	4,92	0,82	4,11
3	3200	1,5	0,03	0,41	2,80	0,62	3,79
4	3200	0,5	0,2	1,84	9,84	1,81	8,48
5	3200	0,5	0,1	0,90	5,14	0,72	3,55
6	3200	0,5	0,03	0,42	2,64	0,34	2,05
7	3200	0,2	0,2	1,78	9,72	1,79	7,78
8	3200	0,2	0,1	0,92	5,19	0,66	3,04
9	3200	0,2	0,03	0,34	2,61	0,27	1,88
10	2400	1,5	0,2	1,91	9,66	1,66	7,49
11	2400	1,5	0,1	0,92	5,29	0,74	3,69
12	2400	1,5	0,03	0,44	2,73	0,42	2,75
13	2400	0,5	0,2	1,90	**10,24**	1,70	7,73
14	2400	0,5	0,1	0,93	5,50	0,69	3,48
15	2400	0,5	0,03	0,44	2,78	0,33	2,14
16	2400	0,2	0,2	1,90	9,99	1,77	7,62
17	2400	0,2	0,1	0,97	5,26	0,68	3,10
18	2400	0,2	0,03	0,31	2,14	0,31	2,06
19	1600	1,5	0,2	1,72	9,29	1,80	8,22
20	1600	1,5	0,1	0,96	5,57	0,72	3,64
21	1600	1,5	0,03	0,36	2,43	0,49	3,72
22	1600	0,5	0,2	**1,93**	9,82	**1,94**	**13,13**
23	1600	0,5	0,1	0,91	5,20	0,95	7,15
24	1600	0,5	0,03	0,34	2,34	0,35	2,55
25	1600	0,2	0,2	1,84	8,94	1,80	8,58
26	1600	0,2	0,1	0,83	4,65	0,86	6,23
27	1600	0,2	0,03	**0,24**	**1,71**	**0,23**	**1,36**

On the basis of the obtained results, a large variation in the roughness parameter Ra for individual tests can be noticed.

Fig. 1 shows an example of the roughness profile and the measurement results obtained for sample 1 for the AW 6060 material, while Fig. 2 shows the same for the CuZn39Pb3 material.

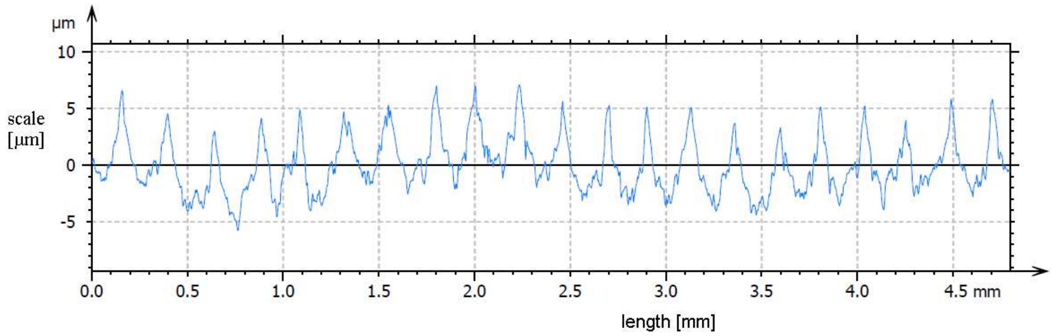


Fig. 1. Roughness profile of the AW 6060 material for sample 1

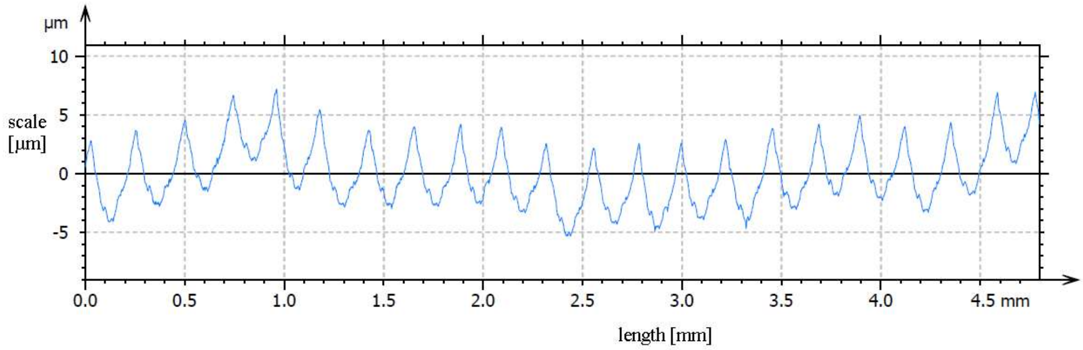


Fig. 2. Roughness profile of CuZn39Pb3 material for sample 1

On the basis of the obtained results (Table 6), it can be seen that the smallest values of the roughness parameter Ra and Rz were obtained for the measurement of sample No. 27. Both for CuZn39 Pb3 and AW 6060 materials, they were 0.24 µm and 0.23 µm, and Rz 1.71 µm and 1.36 µm, respectively. In the case of the Rz parameter for the material AW 6060, its highest value was recorded for sample No. 22 and the value was 13.13 µm. For the material CuZn39 Pb3 the highest Rz was 10.24 µm for the sample No. 13. In order to analyze the obtained results in more detail, graphs of the dependence of the feed and the depth of cut on the roughness parameter Ra and Rz were prepared for specific rotational speeds. There is a different dependence for the tested materials than in the case of steel turning. For steels, the surface roughness decreases when the depth of cut and feed decrease, while the rotational speed increases [4].

Fig. 3 shows the effect of feed and depth of cut on the surface roughness Ra at n = 3200 rpm. From the obtained results, it can be seen a significant influence of the decrease in the roughness parameter value with the decrease of the machining feedrate. On the other hand, the change of the cutting depth does not significantly affect the Ra parameter.

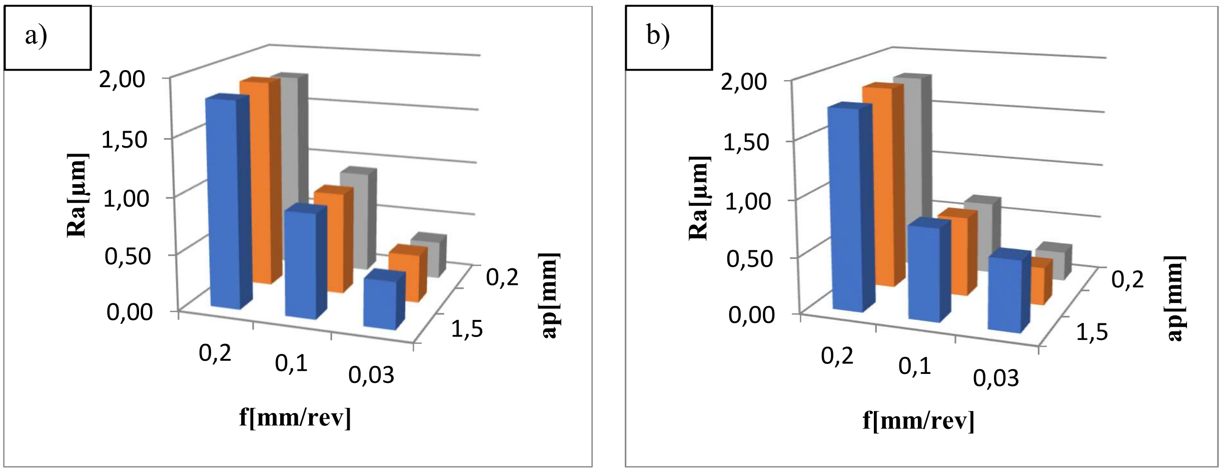
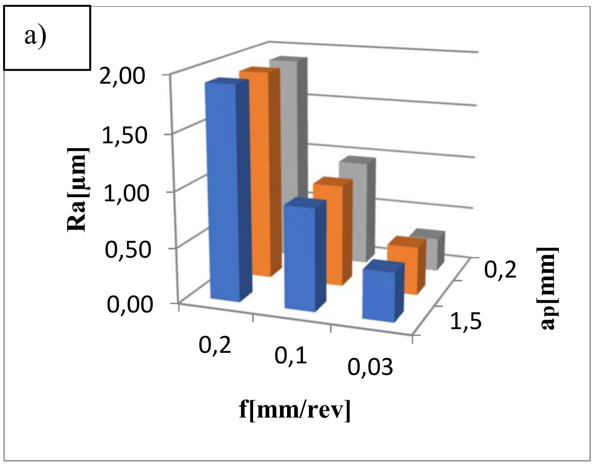


Fig. 3. Influence of feed and depth of cut on the Ra parameter at n = 3200 [rpm]: a) CuZn39Pb3, b) AW 6060

Identical charts were prepared for the remaining rotational speeds. For the rotational speed of 2400 rpm, the results are shown in Fig. 4, and for n = 1600 rpm in Fig. 5 for each rotational speed, there is an identical relationship for both analyzed materials.



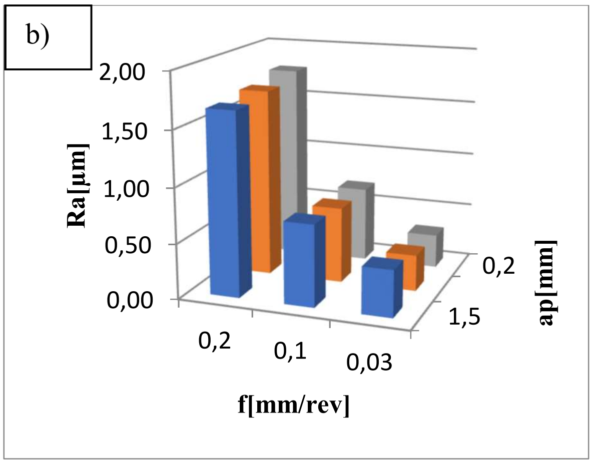
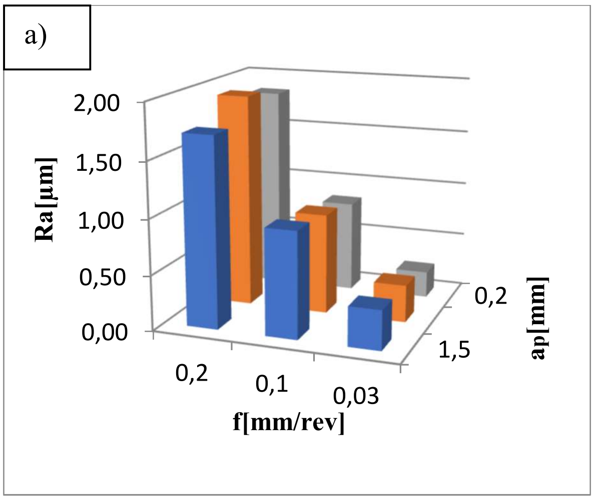


Fig. 4. Influence of feed and depth of cut on the Ra parameter at n = 2600 [rpm]: a) CuZn39Pb3, b) AW 6060



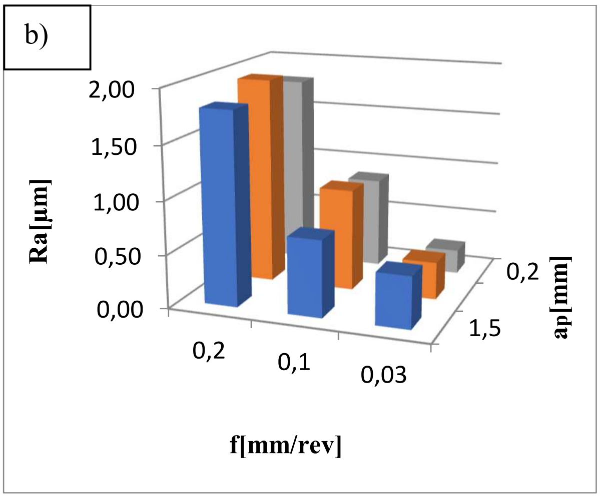


Fig. 5. Influence of feed and depth of cut on the Ra parameter at n = 1600 [rpm]: a)CuZn39 Pb3, b) AW 6060

The lowest values of the roughness parameter Ra were obtained at the lowest feeds and depths of cut in all tested rotational speeds. For a more precise analysis, a graph of the relationship between the rotational speeds and the Ra parameter was drawn up at the lowest feed and the smallest depth of cut. The result is shown in Fig. 6

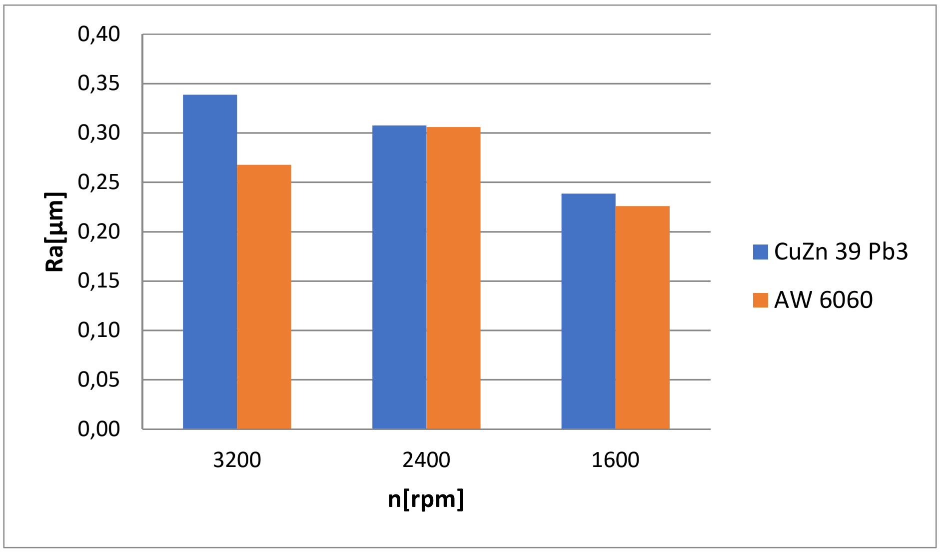


Fig. 6. Dependence of the Ra parameter on the rotational speed

As can be seen (Fig. 6), the lowest Ra parameter value can be obtained during turning with the lowest recommended technological parameters for both analyzed materials. The largest difference in Ra parameter was obtained between the tested materials for the highest rotational speed.

A similar analysis was performed for the Rz parameter. Fig. 7 shows the influence of feed and depth of cut on the roughness parameter Rz at n = 3200 [rpm]. From the obtained results, it can be seen the influence of the decrease in the roughness parameter value along with the decrease of the machining feed rate, for aluminum this decrease at lower feed rates is not so rapid. On the other hand, changing the depth of cut does not significantly affect the Rz parameter, as it did in the case of the previous Ra parameter.

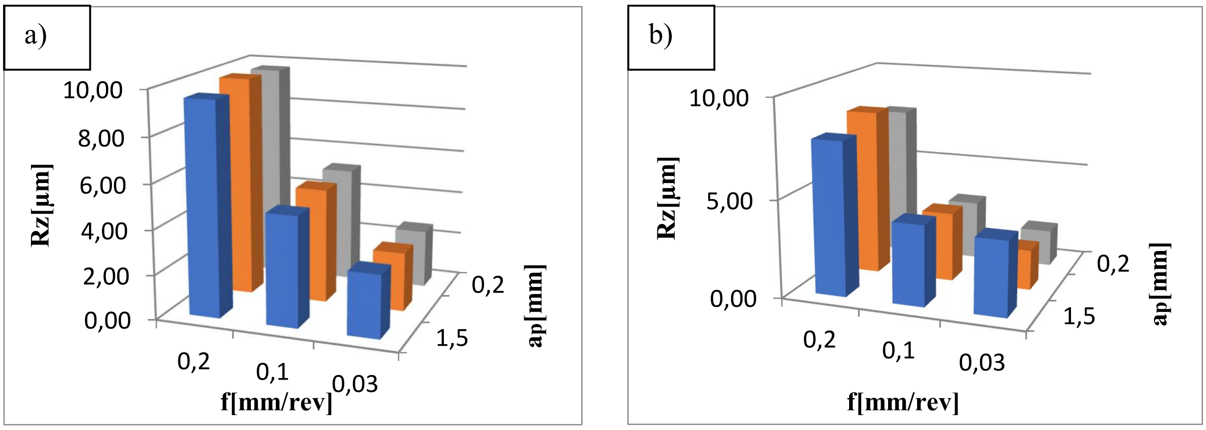


Fig. 7. Influence of feed and depth of cut on the Rz parameter at n = 3200 [rpm]: a) CuZn39 Pb3, b) AW 6060

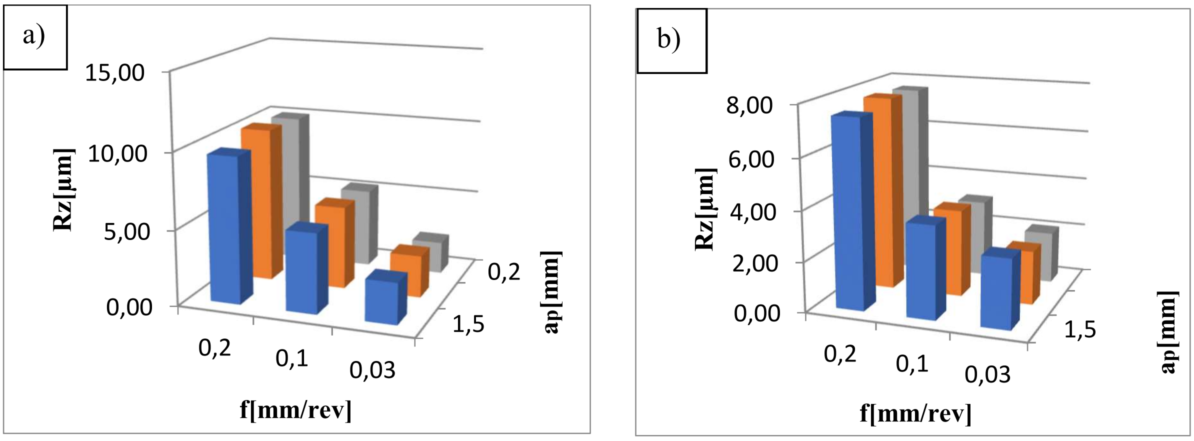


Fig. 8. Influence of feed and depth of cut on the Rz parameter at n = 2600 [rpm]: a) CuZn39 Pb3, b) AW 6060

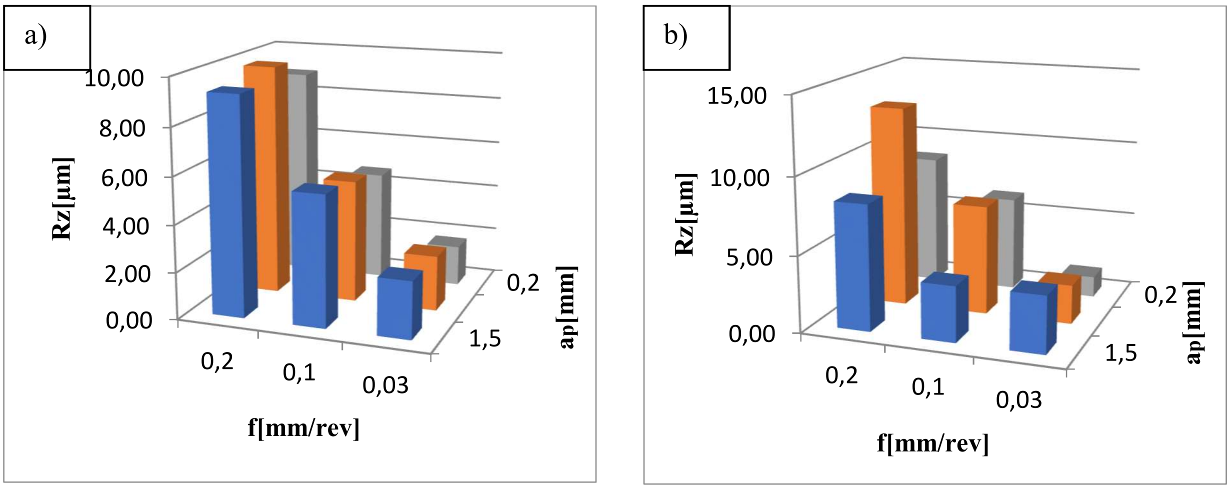


Fig. 9. Influence of feed and depth of cut on the Rz parameter at n = 1600 [rpm]: a) CuZn39 Pb3, b) AW 6060

Identical charts were prepared for the remaining rotational speeds. For the rotational speed of 2400 rpm, the results are shown in Fig. 8. Also in this case, the relationships are the same as for the speed of 3200 rpm. On the other hand, for n = 1600 rpm (Fig. 9), a significant decrease in the value of the Rz parameter can be seen for a depth of cut of 1.5 mm and 0.2 mm at the highest feed.

4. Conclusions

In this work, experimental studies of the influence of cutting parameters on the roughness of the obtained surfaces were carried out for the CuZN39Pb3 brass alloy and the AW 6060 aluminum alloy. Based on the obtained results, the following conclusions can be drawn:

- Turning various materials from the N group, non-ferrous materials and aluminum, with the selected tool, does not cause significant differences in the roughness Ra parameter, these differences can only be observed for the Rz parameter for the lowest speed and the highest feed.
- The highest values of the Ra and Rz roughness parameters were obtained for the lowest rotational speed n = 1600 rpm, the highest feed 0.2 mm/rev, and the average depth of cut for the AW 6060 material, while for CuZN39Pb3 the highest value of the Rz parameter was obtained for a higher rotational speed n = 2400 rpm.
- The smallest values of the roughness parameter Ra and Rz were obtained for the smallest parameters of the rotational speed n = 1600 rpm, feed 0.03 mm / rev, and cutting depth 0.2 mm.
- The greatest difference in measurements for the same parameters was obtained for Ra for sample No. 17 and the difference was 0.29 µm, while for Rz for sample No. 22 it was 3.32 µm.

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OPTIMISING THE SEALING STATION IN PRODUCTION PROCESS OF TUBES FOR CATALYTIC CONVERTERS INVOLVING SMED METHOD – A CASE STUDY

OPTYMALIZACJA STANOWISKA USZCZELNIANIA W PROCESIE PRODUKCYJNYM PRZEWODÓW DO KATALIZATORÓW Z WYKORZYSTANIEM METODY SMED – STUDIUM PRZYPADKU

Abstract

The article presents the stages of the development of the lean management concept. The authors presented the SMED methodology. They made the analysis of the sealing station in the production process of tubes for catalytic converters in relation to the real model. Optimisation the sealing station in production process of tubes for catalytic converters has been done in this article. For this purpose was used one of the tools of Lean Manufacturing, SMED. Diagnosis of machine changeover operations was carried out and also measurement of the times necessary for doing these operations. Using spaghetti diagram, the path which is covered by the operator during machine changeover, was shown. Delegation of specific tasks carried out previously by the operator to production workers and implementation of organisational and technical solution has had the effect of relieving of the operator and shortening of time necessary for machine changeover and increasing productivity at the sealing station .

Keywords: lean management, SMED, optimisation, production process, spaghetti diagram

Streszczenie

W artykule przedstawiono etapy rozwoju koncepcji lean management. Autorki zaprezentowały metodologię SMED. Dokonały analizy stanowiska uszczelniania w procesie produkcyjnym przewodów do katalizatorów w odniesieniu do modelu rzeczywistego. W artykule dokonano optymalizacji stanowiska uszczelniania w procesie produkcyjnym przewodów do katalizatorów. W tym celu zastosowano jedno z narzędzi Lean Production, a mianowicie SMED. Dokonano diagnozy czynności wykonywanych podczas przezbrajania maszyny oraz dokonano pomiaru czasów niezbędnych do wykonania wskazanych czynności. Wykorzystując diagram spaghetti zilustrowano drogę, którą pokonuje operator podczas przezbrojenia maszyny. Oddelegowanie wybranych czynności wykonywanych uprzednio przez operatora na obsługę produkcji oraz wprowadzenie rozwiązania organizacyjno-technicznego wpłynęło na odciążenie operatora i skrócenie czasu niezbędnego do przezbrojenia maszyny i zwiększenia produktywności na stanowisku uszczelniania.

Słowa kluczowe: lean management, SMED, optymalizacja, proces produkcyjny, diagram spaghetti

1. Introduction

There are many definitions of Lean Management and Lean Production in the literature. In the light of the selected definitions the conception of Lean Management is perceived as strategy, with regard to others as philosophy, and still others as a method [1], [3], [4], [6], [10], [12], [13], [18], [20]. For the first time the concept of Lean Production was used in 1988 and was used for the purpose of showing the difference between classic mass production system (traditional management) and management based on pillars of Toyota Production System – TPS (lean management) [5]. The evolution of Toyota production system started in 1948 from implementation of suction system at the engine department. There was implemented the order to reverse to the previous operational position in order

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to take inventory parts necessary for production. The aim of the action was to eliminate interim stocks by in-depth stock control which was dictated by losses due to inflation and lack of armaments procurement. The suction system was applied at the processing department in 1949. Due to low demand from the market, all machines were not fully loaded and hence one employee had to operate several machines at the same time. In 1950 the decision about the extension of the concept of pull system on marketing activities, synchronisation of departments and introduction of traffic lights was undertaken. The undertaken decision about synchronisation of engine machining and gearboxes with department of final assembly had an impact on further reduction of interim stocks. The introduction of traffic lights on selected production lines contributed to shortening the notification time to the supervisiory services about occurring problems. In 1953 kanban system was implemented (more on kanban system see [9], [11]). In order to simplify production, purchase and transportation processes, there was implemented standardisation of parts and components in the enterprise. In 1955 Toyota introduced solutions giving possibility of further reduction of stocks through line delivery control systems, it also started balancing production (both in terms of quantity and range) taking into consideration better use of machinery and equipment (more on heijunka technique see [2] [8]). In 1957 traffic lights were introduced on all production lines and four years later Toyota implemented kanban system to factories of selected suppliers. In 1962 existing kanban system was extended to all departments and production units. This approach enabled production according to pull principle with respect to small batches and on a company-wide basis. Additionally, error prevention system was introduced, its aim was to eliminate defects and prevent overproduction. Achieving economically viable production in small batches, more efficient use of machinery and equipment, reduction of stocks as well as reduction of production lead times were achieved by reduction of changeover times of many production machinery and plant. In 1963 labour productivity was increased. Employees started to handle five machines on average (comparing: up to 1947 they handled one machine, in 1947 – two machines, in 1949 – from three to four machines). Two years later kanban system was extended to external suppliers. In addition, practices for redeployment of assembly workers between different operational posts were introduced. In 1973 Toyota started to integrate suppliers with its internal parts flow system and thereby making it possible to deliver parts directly to the assembly line by their suppliers [7], [19].

According to reference literature, the most important tools in Lean Production are [17]: 5S, Kaizen, Just in Time, Kanban, SMED, TPM, VSM.

The aim of this article is optimisation of the sealing station in the production process of cables for catalytic converters based on the application of the SMED method. The optimization criteria are: reduction of the changeover time of machine, increasing productivity at sealing station, shortening the distance for the operator during changeover the machine.

2. SMED methodology

The aim of the method is changeover within a few minutes. Machines changeover is labour-intensive process which does not add value but is time-consuming. Application of SMED method allows for the reduction of changeover time [15]. The starting point for the application of this method is breakdown of changeover activities into internal operations and external operations. Internal operations are performed on a switched-off machine. However, it is important to remember that to the duration of this activity must be added start time, machine start-up time, time to reach full capacity. External operations are activities which can be done without shutting down the machine (can be done during machine operation). These are mostly preparatory activities aiming introduction of changes. Internal operations cause not only loss of working efficiency, but also reduce production time. Change-over time is time counted from the moment of making the last good item made for the "old order" to the production of the first good item of "new order". SMED methodology is based on four steps [14] [16]:

- step 0 – observation and recording of change-over process,
- step 1 – analysis of the collected materials and division of activities into internal and external changeover,
- step 2 – transformation of internal activities into external ones,
- step 3 – streamlining all aspects of changeover operations.

First step is to specify all changeover operations. Next, every operation must be described using status „internal operation" or "external operation" – according to the adopted definition. Then all operations are grouped. All external operations are included in group of external operations and all internal operations are included in the group of internal operations. Each activity has assigned duration. His way, sum of the times of „external operations" and sum of the times of "internal operations" are obtained. Internal operations should be divided taking into consideration possibility of their fulfilment in system of external operations. If there is such a possibility, they shall be given the new status of "external operations". Other activities do not change their status. This results in a new distribution of operations, thus reducing sum of the times of internal operations.

3. Analysis of the sealing station in the production process of tubes for catalytic converters – real model

Size of production orders of tubes for catalytic converters is variable and varies from 50 items/order (this is minimum order size because of the changeover time and cost-efficiency) to 500 items/production order. Changeover on assembly station is always made by machine operators. It means that the more changeovers and their longer duration the more decreases machine capacity and hence – the whole production line.

The changeover procedure is based on 15 activities. Operator starts changeover from finishing previous order in MMS system and starting of the new order. The barcode, which is presented on the production order is scanned into the system by the use of a scanner. The system reads the order and displays to the operators all the necessary information: order and article number which will be produced, types of components which must be used in production and information about necessary equipment which should be used. The operator who has all information starts the changeover process. The operator using suitable keys (hex key) unscrews the handle that stabilises the position of the coupling during the sealing process. Handles vary depending on type of coupling used in order and use of incorrect handle may cause coupling failure. Equipment removed from the machine is put away on special stand and at the same time the handle necessary for production of next order is taken. Next, the operator starts dismanling so called dice and assembling the right dice which hold the cable on the machine in order to avoid its damage. They differ in diameter depending on type of protective hose used in production. When the correct equipment is fitted, the operator can adjust the program in the machine to indicated in production order. Next, the right length of belt on the dispenser is adjusted (in some cases it has to be changed). Next step is emptying of containers with sealing strips and taking bulk packaging to the supermarket and collection of bulk packaging with suitable sealing strips indicated in order from supermarket. Next step is to apply the right amount of strips to smaller containers located in the machine. The machine is converted and components which were placed in it, will be used in production. Then the operator completes job documentation and error sheet, these are documents which contain all information concerning the order. The documents are signed by the operator. Then the employee goes to the conduit container and takes the appropriate amount of conduits and starts their sealing (Table 1). The average total changeover time per machine is 16 min 39 sec. During one shift the amount of changeovers varies from 4 to 9, depending on the size of orders. Table 2 presents summary of changeover times per day and per week for minimal (1), average (4) and maximum number of changeovers (9). Table 3 presents summary of distances covered by operator during changeover per day and per week for minimal (1), average (4) and maximum number of changeovers (9). The cable sealing position is a socket. The machines are close to each other. Nearby there are storage rack for equipment necessary for changeovers and supermarket with components required in production. Figure 1 presents, with the help of spaghetti diagram, the path of moving of one operator during preparation of machines for the next order. The operations are numbered according to list of actions presented in Table 1. Other actions, which are not marked on the diagram, the operator carries out on site (they do not require mobility).

Table 1. List of operations and times during changeover before optimisation

Singular	Operation	Operation time (1 machine)	Operation time (3 machines)	Time (total)	Path [m]	Path (total)	Internal operation	External operation	Comments
1.	End of order in the system and start of a new order	00:02:06	00:02:06	00:02:06	2	2		X	One of operators finishes and starts order in system
2.	Dismantling of the handle that stabilises the position of coupling	00:00:56	00:02:48	00:04:54	2	4	X		
3.	Putting the equipment back in place	00:00:43	00:02:09	00:07:03	7,5	11,5		X	Operators have to move: butyl 1 - 3m, butyl 2 - 3m, butyl 3 - 1,5m

Table 1 (cont.). List of operations and times during changeover before optimisation

Sin-gular	Operation	Operation time (1 machine)	Operation time (3 machines)	Time (total)	Path [m]	Path (total)	Internal operation	External operation	Comments
4.	Finding and retrieving suitable equipment	00:03:19	00:09:57	00:17:00	7,5	19		X	Operators have to move: butyl 1 - 3m, butyl 2 - 3m, butyl 3 - 1,5m
5.	Connecting a new holder to stabilise the position of coupling	00:00:57	00:02:51	00:19:51	0	19	X		
6.	Dismantling and assembly of remaining dice	00:01:54	00:05:42	00:25:33	0	19	X		
7.	Setting the programme in the machine	00:00:34	00:01:42	00:27:15	0	19	X		
8.	Setting up the dispenser	00:00:18	00:00:54	00:28:09	0	19	X		
9.	Putting back the sealing strips from the containers into the bulk packaging	00:01:42	00:05:06	00:33:15	0	19		X	
10.	Putting back the bulk packaging to supermarket	00:00:26	00:00:26	00:33:41	3	22		X	One of the operators puts back component to the supermarket
11.	Pickup the appropriate bulk packaging from the supermarket	00:00:31	00:00:31	00:34:12	3	25		X	One of the operators picks up component from the supermarket
12.	Picking up sealing strips from bulk packaging to containers	00:01:07	00:03:21	00:37:33	0	25		X	
13.	Completing documentation and error sheet	00:00:53	00:02:39	00:40:12	0	25	X		
14.	Cable collection	00:00:07	00:00:21	00:40:33	4,5	29,5	X		The distance of the container with cables from each operator is 1,5m
15.	Production and inspection 1 item.	00:01:06	00:03:18	00:43:51	0	29,5	X		
	TOTAL	00:16:39	00:43:51	00:43:51	29,5	29,5	8	7	

Table 2. Changeover times per day and per week

Number of changeovers	Changeover time of 1 machine	Changeover time of 3 machines	Changeover time of 1 machine/ week	Changeover time of 3 machines / week
1	00:16:39	00:49:57	01:23:15	04:09:45
4	01:06:36	03:19:48	05:33:00	16:39:00
9	02:29:51	07:29:33	12:29:15	01:13:27:45

Table 3. List of distances during changeover per day and per week

Number of changeovers	path / 1 shift [m]	path / week [m]
1	29,5	147,5
4	118	590
9	265,5	1327,5

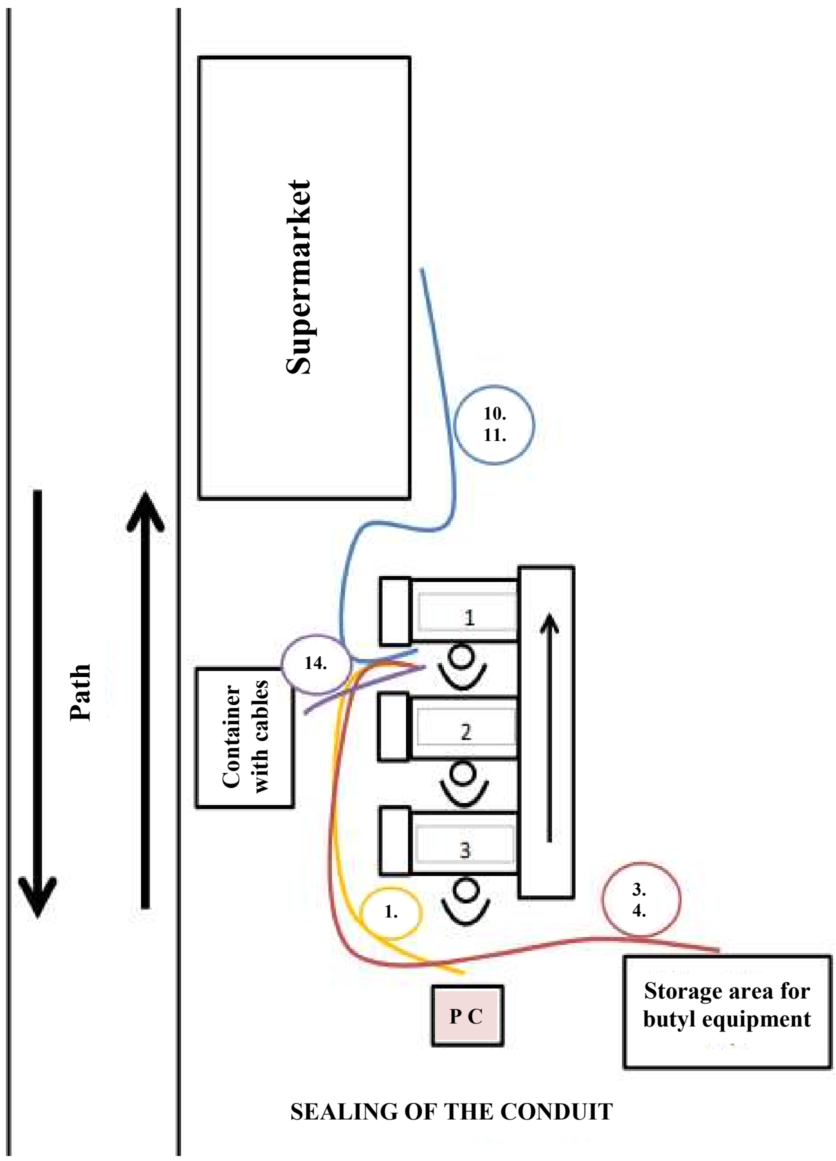

Figure 1. Spaghetti diagram of operator's mobility during changeover – real model

4. Conversion of internal operations into external operations at sealing station – alternative model

Because of the presence of the communication path close to sealing station, there is no possibility to change layout, also in terms of moving supermarket with components closer to workplaces. It was necessary to involve production workers in the changeover process. Some of the operations done by operators can be done by production workers. So that operators can operate machines. Components and equipment necessary for production of the next order can be prepared earlier by production workers and delivered on workplace also components and equipment from the previous order can be put back on site by production workers after changeover made by operators (Table 4).

Operations which require mobility of the operator, for example putting down and taking up new equipment, were transferred to production workers. This reduced the movement of operators to minimum.

In Table 5 there is presented list of operations and times during changeover after optimisation.

In Figure 2 there is presented, with the help of spaghetti diagram, the path of moving of the operator during preparing machines for the next order after taking into consideration proposed organisational and technical solutions. Operations were numbered according to list of operations presented in Table 1. Other operations, which were not marked in the diagram, the operator does on site (they do not require the mobility).

In the Figure 3 there is presented comparison of duration of operations connected with changeover before optimisation and after optimisation.

Table 4. List of operations and assignment of responsibility

Sin-gular	Before optimisation			After optimisation		
	Operation	**Opera-tor**	**Produc-tion worker**	**Operation**	**Opera-tor**	**Produc-tion worker**
1	End of order in the system and start of a new order	X		End of order in the system and start of a new order	X	
2	Dismantling of the handle that stabilises the position of coupling	X		Dismantling of the handle that stabilises the position of coupling	X	
3	Putting the equipment back in place	X		Putting the equipment back in place		X
4	Finding and retrieving suitable equipment	X		Finding and retrieving suitable equipment	X	
5	Connecting a new holder to stabilise the position of coupling	X		Connecting a new holder to stabilise the position of coupling	X	
6	Dismantling and assembly of remaining dice	X		Dismantling and assembly of remaining dice	X	
7	Setting the programme in the machine	X		Setting the programme in the machine	X	
8	Setting up the dispenser	X		Setting up the dispenser		X
9	Putting back the sealing strips from the containers into the bulk packaging	X		Putting back the sealing strips from the containers into the bulk packaging		X
10	Putting back the bulk packaging to supermarket	X		Putting back the bulk packaging to supermarket		X
11	Pickup the appropriate bulk packaging from the supermarket	X		Pickup the appropriate bulk packaging from the supermarket		X
12	Picking up sealing strips from bulk packaging to containers	X		Picking up sealing strips from bulk packaging to containers		X
13	Completing documentation and error sheet	X		Completing documentation and error sheet	X	
14	Cable collection	X		Cable collection	X	
15	Production and inspection 1 item	X		Production and inspection 1 item	X	
TOTAL		**15**	**0**	**TOTAL**	**9**	**6**

Table 5. List of operations and times during changeover after optimisation

Sin-gular	Operation	Operation time (1 machine)	Operation time (3 machines)	Time (total)	Path [m]	Path (total)	Internal operation	External operation	Comments
1.	End of order in the system and start of a new order	00:02:06	00:02:06	00:02:06	2	2		X	One of operators finishes and starts order in system
2.	Dismantling of the handle that stabilises the position of coupling	00:00:56	00:02:48	00:04:54	0	2	X		
3.	Putting the equipment back into trolley	00:00:03	00:00:09	00:05:03	4,5	6,5		X	Distance from the trolley for each operator is 1,5m
4.	Picking up appropriate equipment from the trolley	00:00:03	00:00:09	00:05:12	4,5	11		X	Distance from the trolley to workplace for each operator is 1,5m
5.	Connecting a new holder to stabilise the position of coupling	00:00:57	00:02:51	00:08:03	0	11	X		
6.	Dismantling and assembly of remaining dice	00:01:54	00:05:42	00:13:45	0	11	X		
7.	Setting the programme in the machine	00:00:34	00:01:42	00:15:27	0	11	X		
8.	Setting up the dispenser	00:00:18	00:00:54	00:16:21	0	11	X		
9.	Putting back the sealing strips into the trolley	00:00:08	00:00:24	00:16:45	0	11		X	

Table 5 (cont.). List of operations and times during changeover after optimisation

Sin-gular	Operation	Operation time (1 machine)	Operation time (3 machines)	Time (total)	Path [m]	Path (total)	Internal operation	External operation	Comments
10.	Picking up sealing strips for the new order from the trolley	00:00:08	00:00:24	00:17:09	3	14		X	
11.	Completing documentation and error sheet	00:00:53	00:02:39	00:19:48	0	14	X		
12.	Cable collection	00:00:07	00:00:21	00:20:09	4,5	18,5	X		The distance of the container with cables from each operator is 1,5m
13.	Production and inspection 1 item	00:01:06	00:03:18	00:23:27	0	18,5	X		
	TOTAL	00:09:13	00:23:27	00:23:27	18,5	18,5	8	5	

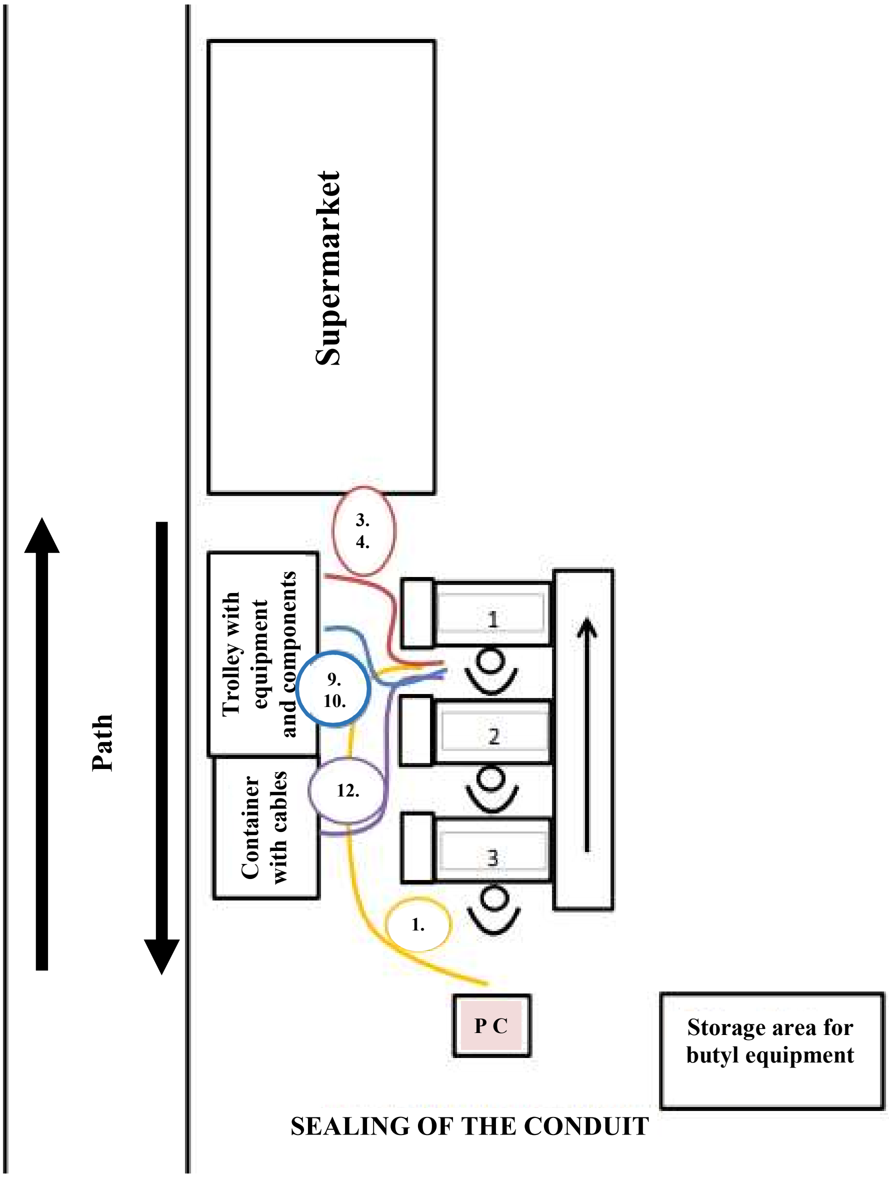

Figure 2. Spaghetti diagram of operator's mobility during changeover – alternative model

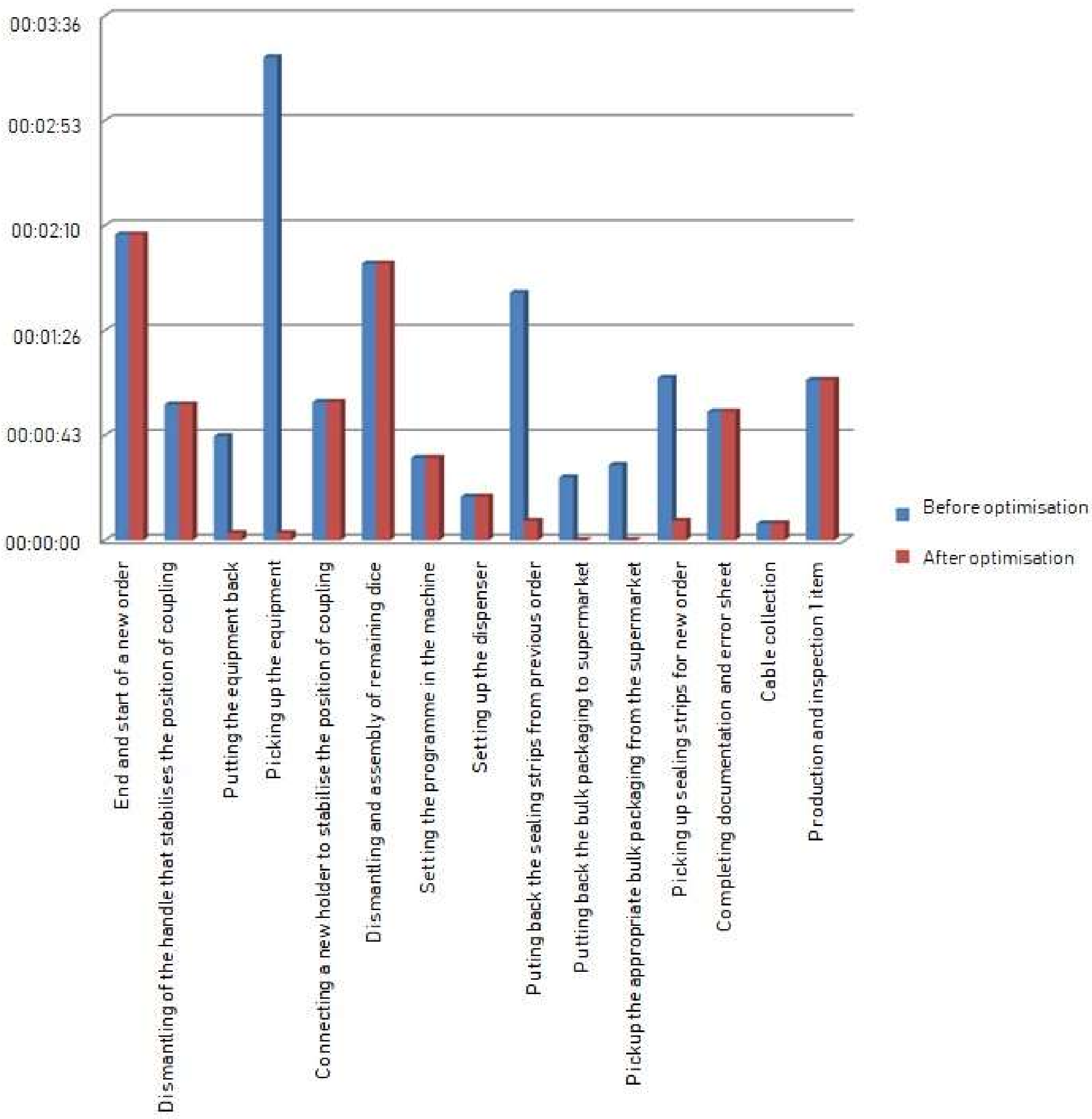

Figure 3. Comparison of duration of operations connected with changeover before optimisation and after optimisation.

5. Conclusion

Before optimisation, the operator was responsible for all operations connected with machine changeover (starting from removal of all unnecessary equipment and components from workplace, to supplying of the workplace with new components and equipment necessary for production of a new order). Involvement of production workers in changeover process helps to relieve the burden of the operator, which is beneficial. Changeover time of one machine has shortened from 16 min 39 sec to 9 min 13 sec which is 7 min 26 sec less. The operator can use saved time to produce cables. Taking into consideration necessary time to do the operation at this workplace, the operator can seal 6 cables more. On the assumption that average number of changeovers made during shift is 4, the operator saves 29 min 44 sec which results in the possibility of sealing 24 cables more. The distance for the operator during changeover the machine has shortened from 29,5 m to 18,5 m..

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TEST SYSTEM TO VERIFY THERMAL SHOCK RESISTANCE

SYSTEM TESTOWY DO BADANIA ODPORNOŚCI NA SZOKI TERMICZNE

Abstract

The article presents the method and the prototype system to verify the resistance of technological objects to environmental impacts in the form of increased or decreased temperatures or sudden temperature changes (i.e. thermal shocks), developed in accordance with the following PN-EN 60068 standard requirements as regards environmental testing: PN-EN 60068-2-1:2009 – Test A: Cold [7]; PN-EN 60068-2-2:2009 – Test B: Dry heat [8]; and PN-EN 60068-2-14:2009 – Test N: Change of temperature [9]. The developed solution is also aligned with the testing procedure requirements applicable to military equipment tests [12]. The system is mainly designed for testing prototype technological devices subject to significant changes in the temperature of the environment in which they operate, including thermal shocks; it also enables periodic quality checks of manufactured goods [1, 2]. With the developed system the following may be tested: the operation of individual mechanisms; the shape stability and resistance [10]; the resistance to damage; as well as the operability of electronic systems [3]. The flexible method of programming tests used in the system enables the performance of both normative and non-standard tests, depending on the requirements of the research to be carried out. The article describes the system design process, its architecture, structure, and operation, as well as the prototype verification test results. The validated prototype test system was incorporated into the structure of the laboratory for the identification and verification of technical safety of industrial and special-purpose applications under environmental conditions established at the Łukasiewicz Research Network – Institute for Sustainable Technologies (Łukasiewicz–ITEE).

Keywords: Thermal shocks, tests, environmental impacts, changeable operating temperature

Streszczenie

W artykule przedstawiono metodę i prototypowy system do badania odporności obiektów technicznych na narażenia środowiskowe w postaci znacznie obniżonej lub podwyższonej temperatury otoczenia oraz szybkich zmian temperatury - szoków termicznych. System opracowano na podstawie wymagań następujących norm dotyczących badań środowiskowych: PN-EN 60068-2-1 - "próba A - zimno" [7], PN-EN 60068-2-2 - "próba B - suche gorąco" [8] i PN-EN 60068-2-14 "próba N - zmiany temperatury" [9]. Opracowane rozwiązanie przystosowano również do wymagań procedur testowych stosowanych w badaniach sprzętu wojskowego [12]. System jest przeznaczony przede wszystkim do testowania prototypowych rozwiązań technicznych, które podczas eksploatacji są narażone na znaczne różnice temperatury środowiska pracy, w tym na szybkie zmiany temperatury (szoki termiczne) oraz do okresowej kontroli jakości produkowanych wyrobów [1, 2]. Testowaniu podlegają między innymi: działanie mechanizmów, stabilność kształtu i wytrzymałość [10], odporność na uszkodzenia i sprawność układów elektronicznych [3]. Zastosowany w systemie elastyczny sposób programowania przebiegów testu umożliwia nie tylko realizację badań normatywnych, ale również niestandardowych procedur wynikających ze szczególnych wymagań realizowanych prac badawczych. W pracy opisano proces projektowania systemu, jego strukturę, budowę, zasadę działania oraz wyniki badań weryfikacyjnych prototypu. Zweryfikowany, prototypowy system testowy został włączony w strukturę utworzonego w Łukasiewicz ITEE laboratorium identyfikacji i weryfikacji bezpieczeństwa technicznego aplikacji gospodarczych i specjalnych w warunkach środowiskowych.

Słowa kluczowe: Szoki termiczne, badania testowe, narażenia środowiskowe, zmienna temperatura pracy

1. Introduction

Ensuring safety, durability and reliability of new technological devices requires comprehensive tests to be carried out on a representative product sample in an environment simulating real-life operating conditions in which the device will be subject to various environmental impacts including, most importantly, temperature, air dustiness and humidity, mechanical vibrations, and precipitation. The innovative system to

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monitor the safety of technological objects operating in an environment characterised by significant, and often sudden, temperature changes, developed at the Łukasiewicz–ITEE and described in this article, is an example of a solution proposed in response to a "challenge us" request made in the technical safety area.

As per the PN-EN 60068 standard series, comprehensive environmental tests should be performed on specimens in conditions similar to actual operating conditions, and they should involve tests in which the most significant environmental impacts can be observed. Table 1 contains examples of tests universal for most devices.

Table 1. Examples of tests complying with the PN-EN 60068-1 standard requirements [6] universal for most devices

Test	Comment
A – Cold	Mechanical stress may occur, which may make the specimen more sensitive to impacts assessed in other tests to follow.
B – Dry heat	
N – Sudden temperature change	
E – Shock	Mechanical stress may occur, which may either lead to immediate destruction of the specimen or make the specimen more sensitive to impacts assessed in other tests to follow.
F – Vibration	
M – Low air pressure	These tests reveal the impact of the preceding thermal and mechanical tests.
Db – Damp heat, cyclic (12 h + 12 h cycle)	
Damp heat (steady state)	
K – Salt spray	
L – Dust and sand	These tests may amplify the impacts of the preceding thermal and mechanical tests.
Permeation of solids	
Permeation of water (e.g. rain)	

The system developed by the authors is suitable for the first three tests listed in Table 1. Tests are carried out in thermally isolated chambers with the capacity sufficiently high compared to the size of the specimen and amount of the heat it dissipates. Test severities expressed as the temperature and duration should be provided in the product specification, defined based on dedicated tests, and fall within the values recommended in relevant standards:

- cooling chamber temperature: between –65ºC and +5ºC;
- heating chamber temperature: between +30ºC and +200ºC;
- test duration in a cooling or heating chamber: between 2 and 96 hours;
- individual test duration in Test N (sudden temperature change): between 10 to 180 minutes.

As regards Test N – Sudden temperature change, important test parameters include the number of temperature change cycles and the time of the specimen transfer from one test chamber to another (Fig. 1). If separate requirements do not state otherwise, it is recommended to include five (5) cycles in a test lasting 3 hours. The first cycle starts in point A and ends in point B. Time (t_2) of the specimen transfer between chambers with predefined temperatures T_A and T_B should not extend 3 minutes.

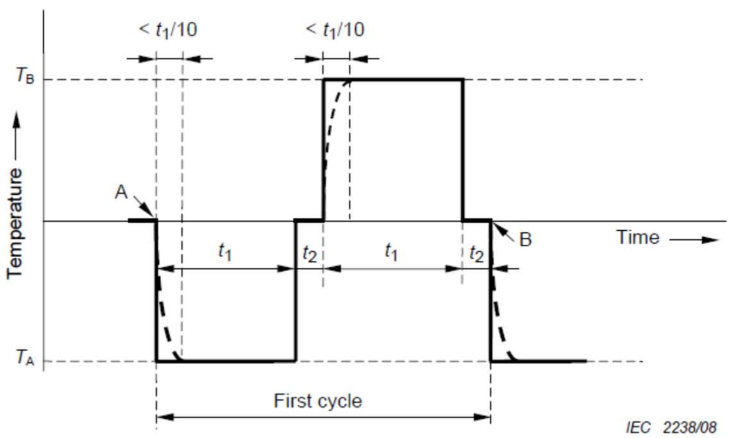


Fig. 1. Temperature change diagram Test N: Temperature changes [9]

2. Technological assumptions

The authors defined the scope of the system application for product groups and its functions including:

- the verification of the impact of temperature changes (also sudden) on performance parameters of prototype mechanical, electric, and mechatronic devices;
- the study of coatings affected by temperature changes; and
- the modelling of the dynamics of variability of environmental parameters impacting technological objects.

Then, based on the assumed system functionality, the authors specified the technical parameters of the two-chamber test system in changeable temperature conditions (Table 2).

Table 2. Basic technical parameters of the test system.

Parameter	Value
Test area dimensions	1000 x 400 x 400 mm
High temperature ranges	between +30°C and +200°C
Low temperature ranges	between –65°C and +5°C
Time to reach maximum temperature	90 min (from ambient temperature to +200°C)
Time to reach minimum temperature	90 min (from ambient temperature to –65°C)
Specimen transfer time	<15 s
Maximum specimen weight	30 kg

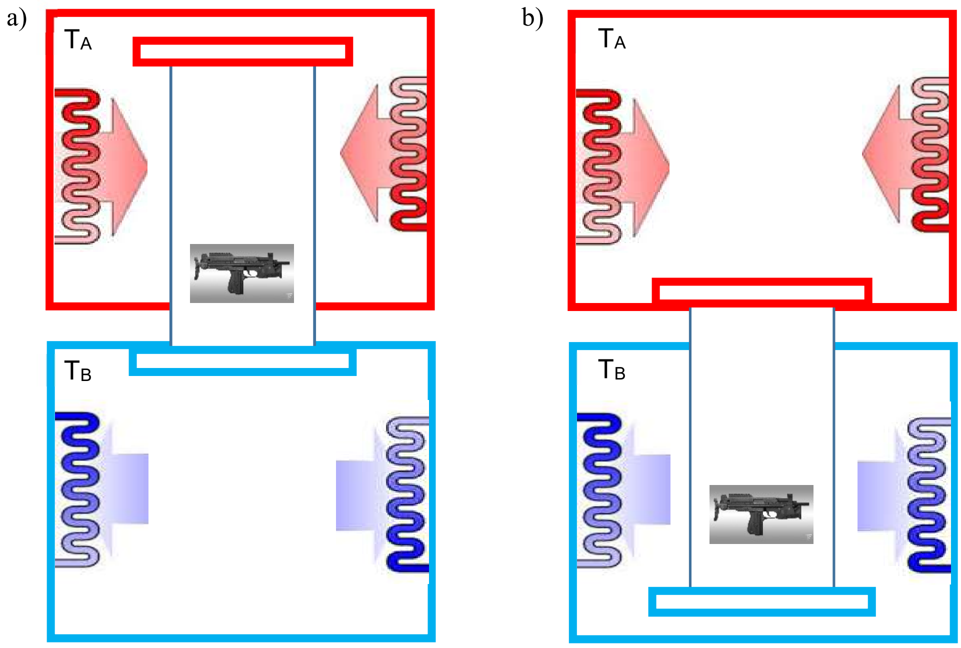


Fig. 2. Concept of the test system and test object transfer: a) hot test phase, b) cold test phase.

It was assumed that the test system will be designed as a system of vertically placed chambers (top – heating chamber and bottom – cooling chamber), as depicted in Figure 2. As regards the heating chamber, the resistive heating elements are the source of the heat, while in the case of the cooling chamber, the source of the cold temperature is the liquid nitrogen directly injected into the chamber.

The chambers are equipped with side doors, and the test object in placed in or removed from each chamber through the top chamber door. The test object is placed in an openwork basket transferred between the chambers with the use of a mechanical lift.

3. 3D model and documentation of the system

The CAD 3D model of the test system was developed based on the adopted technical assumptions (Fig. 3).

The heating and cooling chambers are spaces in which the test object is subject to environmental impacts, i.e. temperatures that are either higher or lower than the ambient temperature. Temperature values in each chamber are obtained and stabilised in accordance with the assumed test parameters. The mechanical lift (Fig. 4) is used to quickly transfer the test object between chambers to cause suitable thermal shock (i.e. a sudden ambient temperature change) in accordance with the test plan. When the lift is in its top position (i.e. when the test object is placed in the heating chamber), its floor constitutes a closing element that separates the chambers; when in the bottom position – the chambers are separated by the ceiling of the lift. Because of the lowest temperature reached in the cooling chamber, the system requires a supply of liquefied gas (nitrogen), the evaporation of which constitutes, in this case, the most efficient method of cooling.

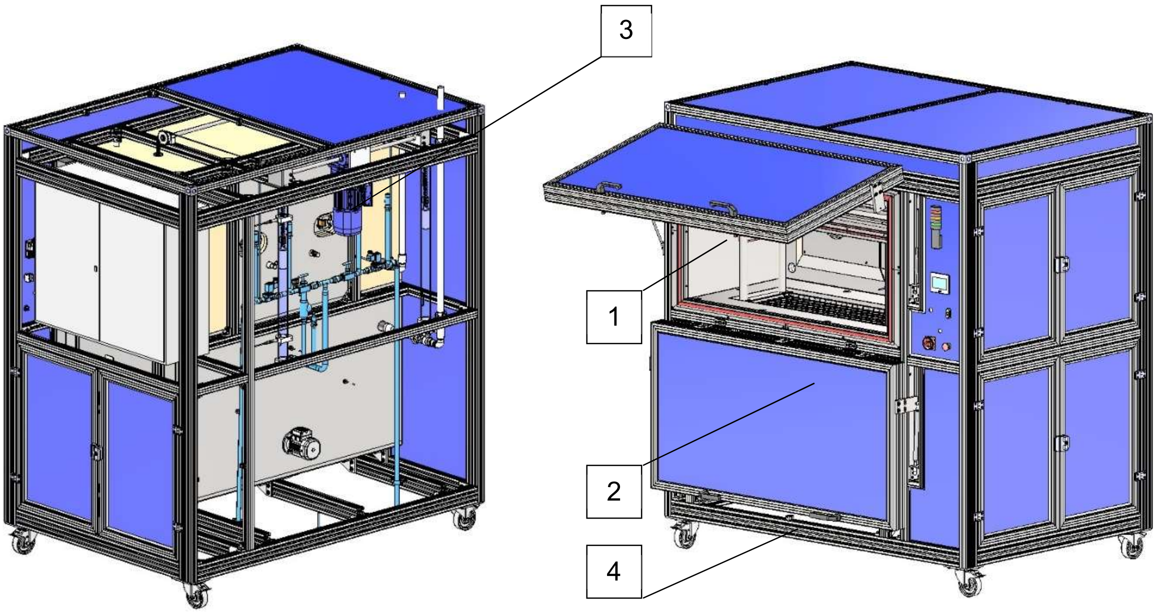


Fig. 3. 3D model of the two-chamber system for tests at variable temperatures 1 – heating chamber; 2 – cooling chamber; 3 – lift's drive system; 4 – load-bearing structure.

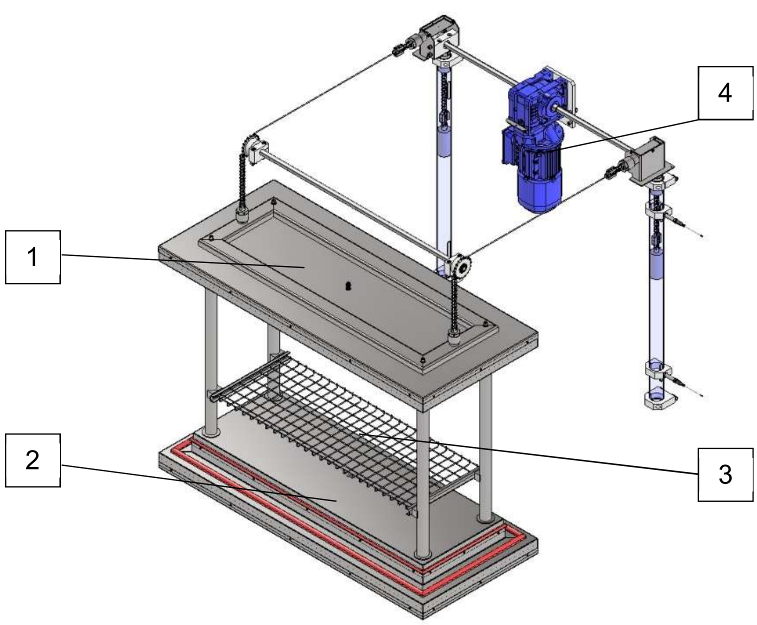


Fig. 4. 3D model of the lift: 1 – ceiling; 2 – floor; 3 – grating for test object positioning; 4 – drive system.

The heating and cooling chambers were designed as thin-walled sheet metal structures filled with thermal insulation whose thickness was adjusted to the assumed temperature gradients. The heating chamber is equipped with electric heating elements, and the cooling chamber – with a liquid nitrogen supply system. In each chamber fans and converters are placed; the first to mix the air, and the latter – to monitor the temperature distribution. The load-bearing structure of the system is made of screwed aluminium struts with casters. In the top part of the system, at the height the heating chamber is located, a control touchscreen panel with dedicated switches is mounted. The system structure is presented in Figure 5.

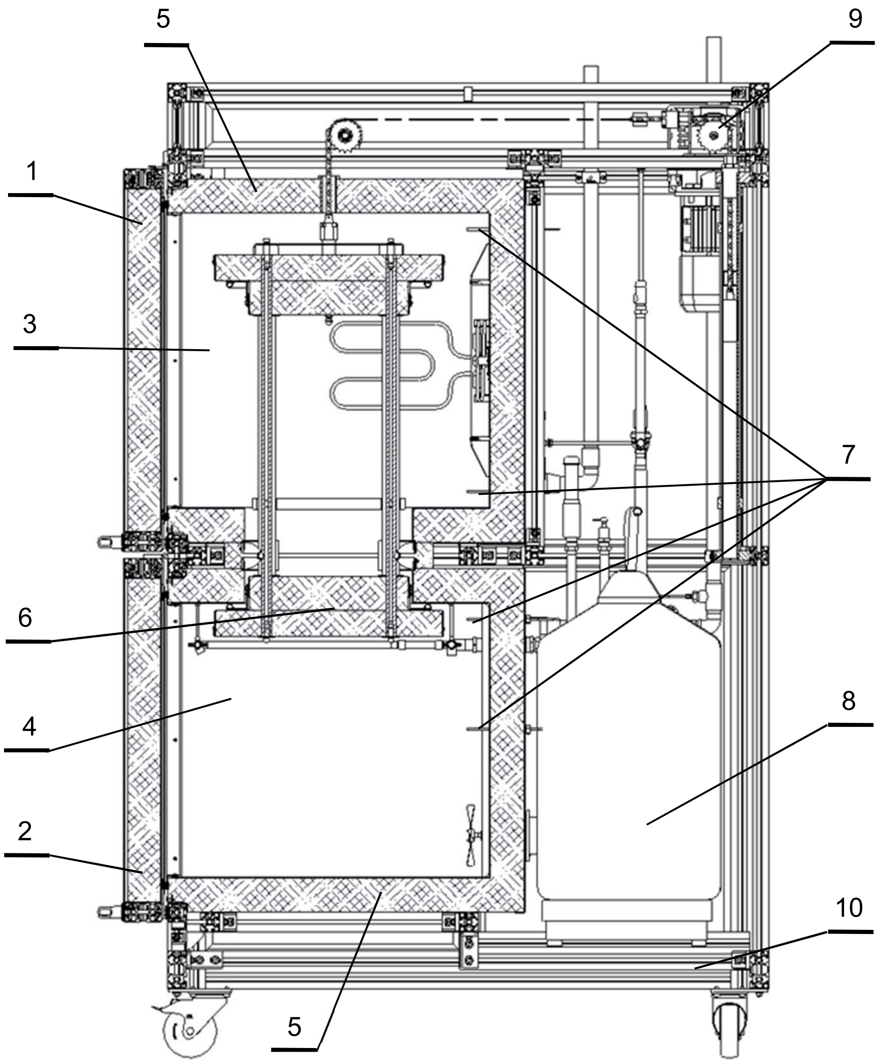


Fig. 5. Test system structure: 1 – heating chamber door; 2 – cooling chamber door; 3 – heating chamber; 4 – cooling chamber; 5 – thermal insulation; 6 – lift; 7 – temperature sensors; 8 – liquid nitrogen tanks; 9 – lift drive system; 10 – load-bearing structure.

4. Measuring and control system

The electronic programmable measuring and control system supervises all automatic functions required to prepare and complete the test. The individual test parameters, i.e. the temperature in the heating and cooling chambers, the exposure time in each chamber, the speed of the test object transfer between chambers, and the number of temperature change cycles, may be programmed by the user and automatically applied in compliance with applicable normative regulations or special test plans.

The authors formulated a concept of a control system for tests carried out in changeable temperature conditions. The system is composed of the following subsystems: a subsystem monitoring the high temperature in the heating chamber, a subsystem monitoring the low temperature in the cooling chamber, a subsystem controlling the test object transfer between chambers, a security subsystem, and a monitoring and visualisation subsystem.

Based on the adopted structure, the authors developed the algorithmic model of the control system, taking into consideration information processing circuits as well as the hardware and software layers. The measuring and control elements were selected in accordance with the 24VDC standard for binary signals, 4-20mA/0-10V standard for analogue signals and Modbus RTU/TCP communication protocol.

The temperature control system mounted in the heating chamber controls the heating elements, fans, and the temperature measurement in two points. Additionally, thermocouples were also used to control the temperature of the heating elements.

The temperature control system mounted in the cooling chamber is composed of two low-pressure tanks (0.3 MPa) containing liquid nitrogen (LN2), a gas supply system, two solenoid valves monitoring the amount of the gas supplied, and a system for gas usage measurement.

The subsystem controlling the test object transfer between chambers is composed of a toothed gear reducer controlled by an inverter, and four limit switches to control the lift's position.

5. Prototype verification

The prototype test system was built based on the adopted assumptions, developed model and technical documentation (Fig. 6). The prototype was equipped with a complete set of instrumentation to verify the correct operation of the individual units and software controlling the automatic implementation of test procedures.

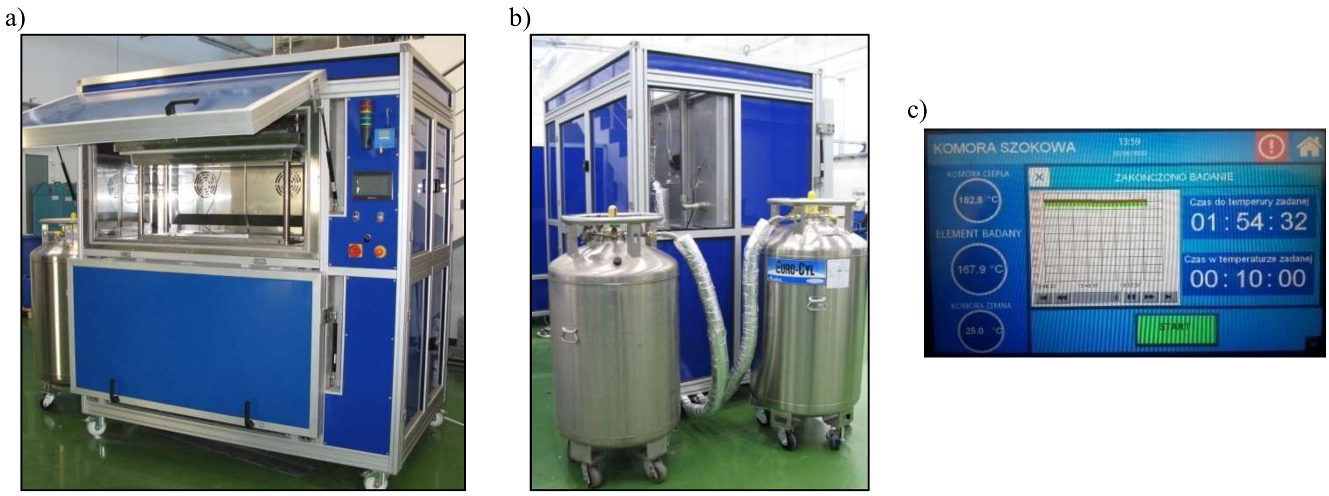
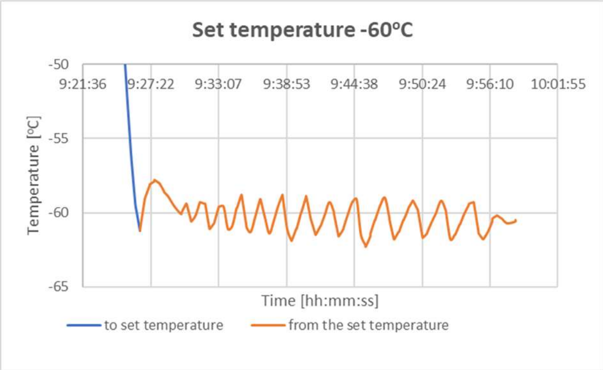


Fig. 6. Test system prototype: a) front view; b) liquid nitrogen supply system; c) control panel

The prototype verification and validation tests were carried out in real-life operating conditions [11]. Particular attention was paid to the adjustment and stabilisation of temperature in the cooling chamber. The custom cooling method (used for the very first time in a solution developed at the Łukasiewicz–ITEE) took a long time to implement and calibrate. With the use of the developed systems the authors were able to stabilise the temperature in cooling and heating chambers (Fig. 7) and carry out sample test procedures involving sudden ambient temperature changes. Figure 8 presents temperature changes in a 60-minute test.

As a result of the verification tests, the structure of the cooling chamber was modified by introducing a fan, which mixes the air inside the chamber and helps to evenly distribute the temperature; eliminating dead spaces that make even temperature distribution difficult; and mounting additional temperature transducers monitoring temperature distribution inside the chamber. Additionally, the liquid nitrogen supply system was also modified to enable the automatic switch from one supply source to another in the event the liquid nitrogen tank currently in use has been completely emptied. The said supply source switch is triggered by the decreased gas pressure in the tank. This enables the reversible replacement of the LN2 tanks and facilitates the performance of long-term tests at low temperatures.

a)



b)

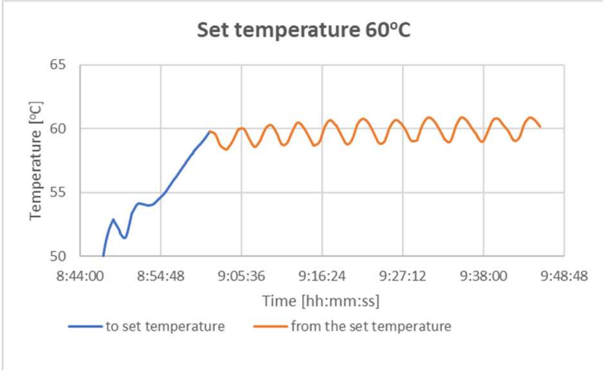


Fig. 7. Sample temperature changes during stabilisation of parameters of the: a) cooling chamber and b) heating chamber.

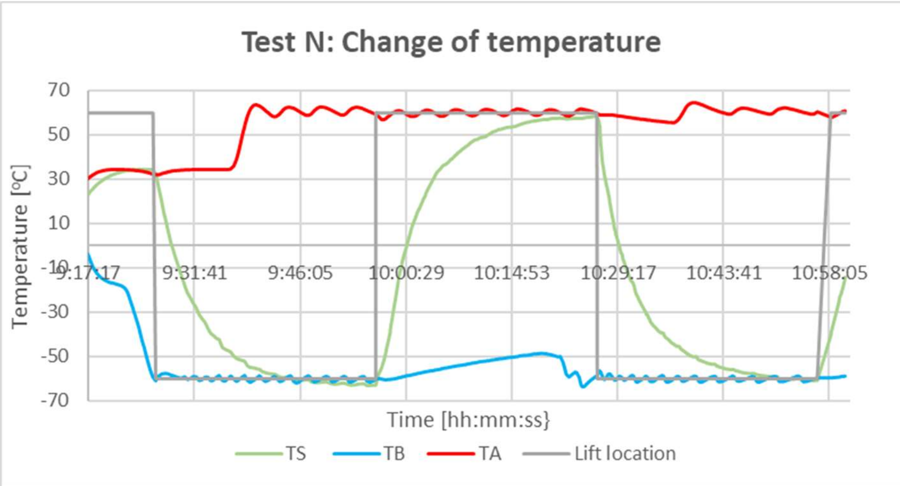


Fig. 8. Sample temperature changes recorded for a test with the following parameters:
T_A = –60ºC, T_B = +60ºC, cycle: 30 min.

The results of the tests carried out after the above-mentioned structural modifications confirmed the compliance of the test system parameters with normative requirements and assumed functionality of the solution.

6. Conclusions

With the developed test system to verify thermal shock resistance, technological objects, and, in particular, electronic systems, mechanisms, and material connections, can be tested in an environment subject to sudden ambient temperature changes. The tests can be carried out in accordance with normative procedures and in an environment with individually defined parameters simulating real-life operating conditions. The test results allow the assessment whether the tested product is fit for its intended purpose and can be used in the environment characterised by sudden and drastic temperature fluctuations.

The developed and validated prototype test system was incorporated into the structure of the laboratory for the identification and verification of technical safety [5] established at the Łukasiewicz–ITEE, and, together with other test devices [4], it enables comprehensive assessment of industrial and special-purpose applications under environmental conditions.

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THE INFLUENCE OF SHOT PEENING ON THE STRESS STATE IN THE ADHESIVE LAYER AND THE LOAD CAPACITY OF ADHESIVE JOINTS

WPŁYW PNEUMOKULKOWANIA NA STAN NAPRĘŻEŃ W SPOINIE KLEJOWEJ I NOŚNOŚĆ POŁĄCZEŃ KLEJOWYCH

Abstract

The aim of the article was to determine the influence of shot peening of the outer surface of the overlap on the stress state in the adhesive layer and the load capacity of single lap adhesive joints made of EN AW-2024-T3 aluminum alloy. Experimental investigations and numerical simulations were carried out. According to the results of experimental analyses, shot peening with balls with a diameter of 1 mm for 120 s with a compressed air pressure of 0.5 MPa increased the load capacity of the adhesive joints by 33%. Numerical simulations have shown that shot peening, by deforming the joined elements, reduces the stress perpendicular to the surface of the adhesive layer which results in a reduction of equivalent (von Misses) stress and an increase in strength of adhesive joints.

Keywords: adhesive joints, shot peening, load capacity, finite element method

Streszczenie

Celem artykułu było określenie wpływu pneumokulkowania zewnętrznej powierzchni zakładki na stan naprężeń w spoinie klejowej oraz nośność połączeń klejowych jednozakładkowych wykonanych ze stopu aluminium EN AW-2024-T3. W ramach badań przeprowadzono doświadczenia eksperymentalne i obliczenia numeryczne. Zgodnie z wynikami doświadczeń eksperymentalnych, pneumokulkowanie połączeń klejowych kulkami o średnicy 1 mm w czasie 120 s z ciśnieniem sprężonego powietrza wynoszącym 0,5 MPa przyczyniło się do wzrostu nośności połączeń klejowych o 33%. Obliczenia numeryczne wykazały, że pneumokulkowanie, poprzez odkształcenie klejonych elementów, zmniejsza naprężenia prostopadłe do powierzchni spoiny klejowej, co skutkuje zmniejszeniem jej wytężenia (naprężenień zredukowanych) i wzrostem wytrzymałości połączeń klejowych.

Słowa kluczowe: połączenia klejowe, pneumokulkowanie, nośność, metoda elementów skończonych

1. Introduction

Adhesive joints are commonly used in different industries and in many cases they are a good alternative to traditional mechanical connections. The advantages of adhesive joints include, among others, the possibility of reducing the weight of the structure, good sealing and damping properties, no need to make holes and the ability to combine various materials and elements of different thickness [4, 21]. The most popular type of adhesive joints is lap joint [18].

The shear stress distribution in the adhesive layer in single lap adhesive joint loaded in tension is not uniform. One of the reasons for the uneven stress distribution is the change in dimensions at the ends of the lap (geometric notch). Another reason for this phenomenon is the difference in plastic properties of the adhesive and the adherend [1, 2, 16, 18]. The maximum stresses occur at the ends of the lap. Therefore, efforts should be made to reduce these maximum stresses in order to increase the strength of the adhesive joints [8]. There are many methods that allow reducing the maximum stresses in the edge zone of the overlap. These include for example:

- using of an adhesive with ductile behavior and low modulus [8],
- leaving a flash of adhesive [23],

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- rounding adherends corners [7, 29],
- tapering the adherends [13, 14],
- sandblasting of the lap zone [10],
- shot peening of the lap zone [18, 30-32].

Shot peening is a dynamic burnishing method. In this cold-working technology, the workpiece surface is bombarded by steel balls which are propelled by a compressed air [19, 27]. The basic parameters of the shot peening are: ball diameter, processing time, compressed air pressure, total number of balls and the distance of the nozzle from the workpiece surface [30]. Shot peening is widely used in different industries to improve the fatigue life [5, 26, 28], to enhance the surface hardness and roughness [26] and to strengthen welded joints [6]. Moreover, as already mentioned, shot peening strengthens the adhesive joints.

The positive effect of shot peening on the strength of adhesive joints has been proven in several studies. In the paper [30] the effect of shot peening on the shear strength of S235JR steel adhesive joints was investigated. The adhesive joints were made with Epidian 5 composition with PAC hardener (flexible joint) and Epidian 5 composition with Z1 hardener (rigid joint). The time of the shot peening treatment was 60 s, the pressure was 0.35-0.55 MPa and the ball diameter was 2 mm. As a result of the shot peening, the strength of the samples with a flexible joint increased by 17–27% and the strength of the samples with a rigid joints increased by 93–112%.

The authors of the work [31] studied the effect of shot peening on the strength of adhesive joints made of 2024 aluminum alloy. The treatment parameters were: ball diameter (2-2.5 mm), time (60-180 s) and pressure (0.2-0.3 MPa). It was shown that as a result of shot peening, the load capacity of the adhesive joints increased by 3.6-20.3%.

According to the results presented in the paper [32], shot peening treatment contributed to the increase in the strength of the adhesive joints of Ti6Al4V titanium alloy by 42-63%. The process was carried out with a constant pressure (0.6 MPa) and a constant ball diameter (1.5 mm). The time was varied in the range of 10-30 s. It was shown that the load capacity of the joints increases as the time increases.

The influence of various factors on the strength of adhesive joints can be analyzed not only experimentally, but also with the use of numerical analyzes. The usefulness of the finite element method (FEM) for calculating the strength of adhesive joints was checked in [12]. The authors of the study pointed out that numerical calculation of adhesive joints in the linear elastic range are not useful for predicting their strength because most adhesives exhibit non-linear properties. According to the authors' observations, the actual characteristics of stress-strain curve should be taken into account when forecasting the strength of adhesive joints.

The authors of the work [11] compared two methods of modeling the adhesive layer in adhesive joints in FEM calculations. The first method was based on modeling the joints with solid elements, and the second method - with cohesive elements. It was found that the use of cohesive elements simplifies the modeling of adhesive joints. Nevertheless, this method is more suitable for an analysis of adhesively bonded structures than for an analysis of adhesive layer strength

The finite element method was also used to analyze the effect of surface roughness on the stress state in the adhesive layer [35], the length of the overlap on the strength of adhesive joints [9], as well as the impact of shot-peening on the stress state in the adhesive joint [30, 33].

The papers [30, 33] explain the mechanism of strengthening adhesive joints using the shot peening method. As a result of the numerical simulations it was shown that under the influence of shot peening, compressive residual stresses are introduced into the outer layer of the lap surface. Under the influence of these stresses, the edge of the lap is deformed and pressed against the bonded material. As a result, the tensile, peel and principal normal stresses are reduced, which in turn translates into an increase in the strength of the adhesive joints (fig. 1).

The analysis of the available literature shows that shot peening can be successfully used as a method of strengthening lap adhesive joints. Therefore, it is justified to conduct further research focused on better understanding of the mechanism of this phenomenon, and thus its better use in industry. Therefore, the aim of the research presented in the article was to expand the current state of knowledge by carrying out experimental analyzes which allowed to determine the impact of shot peening on the load capacity of single lap adhesive joints made of sheets of EN AW-2024-T3 aluminum alloy. Moreover, a numerical simulation was carried out in order to assess the impact of shot peening of the lap zone on the stress state in the adhesive layer. The research presented in this article is a continuation of the research presented in [34].

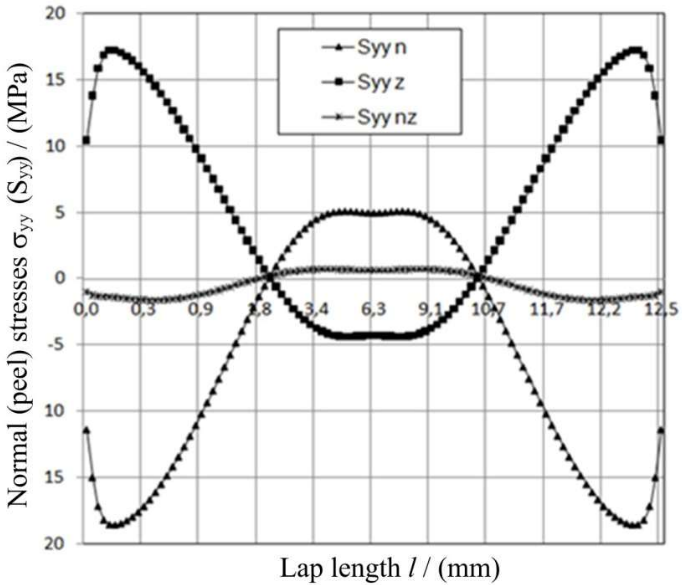

Fig. 1. The distribution of normal (peel) stresses σ_{yy} (S_{yy}) in the middle layer of the adhesive joints: n – shot peened joints, z – joints loaded with external force P = 2000 N, nz – joints shot peened and loaded with external force P = 2000 [30]

2. Material and methods

The first stage of the research involved carrying out experimental analyzes, aimed at determining the impact of shot peening on the load capacity of single lap adhesive joints made of EN AW-2024-T3 aluminum alloy sheets. The chemical composition of the EN AW-2024-T3 aluminum alloy is shown in Table 1.

Table 1. Chemical composition of EN AW-2024-T3 aluminum alloy in wt.% [3]

Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	V	Inne*	Al
max 0,50	max 0,50	3,8 - 4,9	0,30 - 0,90	1,2 - 1,8	max 0,10	-	max 0,25	max 0,15	-	max 0,05	remaining
* Others, total ≤ 0,15%											

The bounding process started with the preparation of the adherend surface of the samples. In order to properly develop the geometric structure and increase the strength of adhesive joints, the surfaces were submitted to abrasive blasting with 95A electrocorundate (granulity of 0.27 mm) using a New-Tech sandblasting cabinet (New-Tech, Wrocław, Poland). The treatment was carried out for 30 s. The applied pressure was 0.7 MPa. The distance of the nozzle from the treated surface was about 0.07 m. The average values of the selected roughness parameters of the adherend surface after abrasive blasting were respectively: Ra = 4.53 µm, Rz = 25.95 µm, Rq = 5.67 µm, Rku = 2.99, RSm = 0.141 mm. The measurements were performed with a Taylor Hobson SURTRONIC 25 contact stylus profilometer and TalyProfile Lite software. The evaluation length was 12.5 mm. The measurements were performed in accordance with the PN-EN ISO 4287:1999 standard [31]. Fig. 2 shows a profilogram of the surface after abrasive blasting.

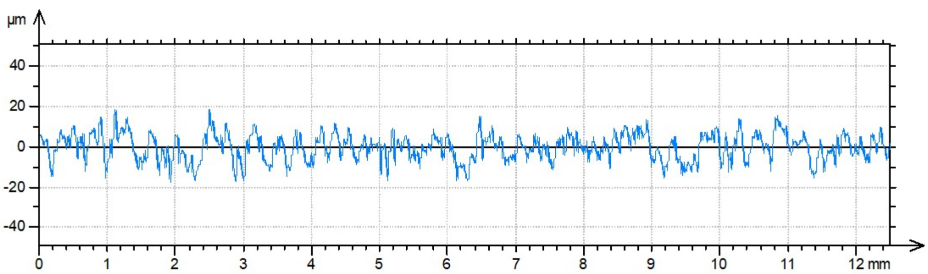

Fig. 2. Profilogram of the adherend's surface after abrasive blasting

After abrasive blasting, the adherents' surfaces were degreased in order to remove grease contamination and dust residues. Degreasing was performed with acetone.

The next step was to create single lap adhesive joints. The joints were made using the Loctite EA 3430 two-component epoxy adhesive (Loctite, Düsseldorf, Germany), which is suitable for joining poorly adhering or rough wooden, metal, ceramic or plastic surfaces [20]. After measuring the resin and hardener (in an amount not exceeding 20 g), the products were mixed together by hand for about 15 seconds. The ratio of epoxy resin to hardener was 1:1. The mixed adhesive was applied to both adherents' surfaces using a comb device. The air temperature during the preparation and crosslinking of the adhesive was 22 ±1°C, while the air humidity was 50%. The created adhesive joints were placed in the mechanical device and loaded with a constant force using one-kilogram weights. The adhesive connections were kept in the mechanical device (Fig. 3) for 3 days (62 hours). Figure 4 shows a scheme of the resulting adhesive connections.

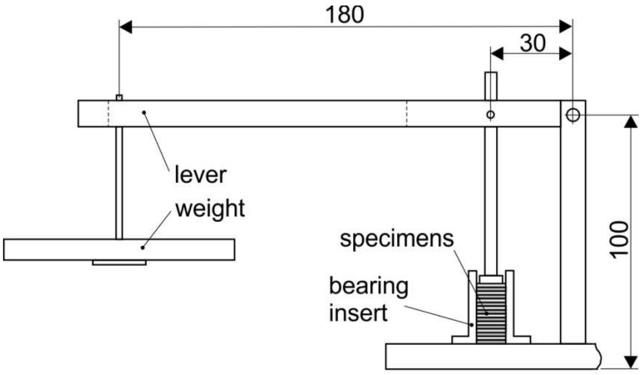

Fig. 3. The samples placed in a mechanical device (units in mm)

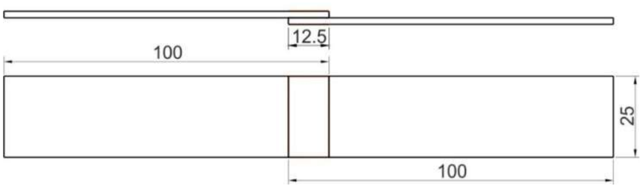

Fig. 4. The scheme of the adhesive joint

In total, 8 lap adhesive joints were made. The overlap lengths in the prepared adhesive connections were 12.5 + 0.1 mm.

The outer surface of the overlaps of the adhesive joints was then subjected to the shot peening. The device used for shot peening consisted of a working chamber closed with a lid. At the bottom of the working chamber, steel balls with a diameter of 1 mm were placed. The balls were propelled by a stream of compressed air supplied to the working chamber by a set of nozzles. The compressed air pressure was 0.5 MPa. The speeding balls hit the workpiece attached to the inside of the lid. The distance between the nozzle and the treated surface was 100 mm. Both sides of the adhesive joint overlap were shot peened. The processing time for one side of the overlap was 120 s. Only the overlap zone was shot peened. The remainder of the sample was protected using covers. The scheme of shot peening is shown in Fig. 5.

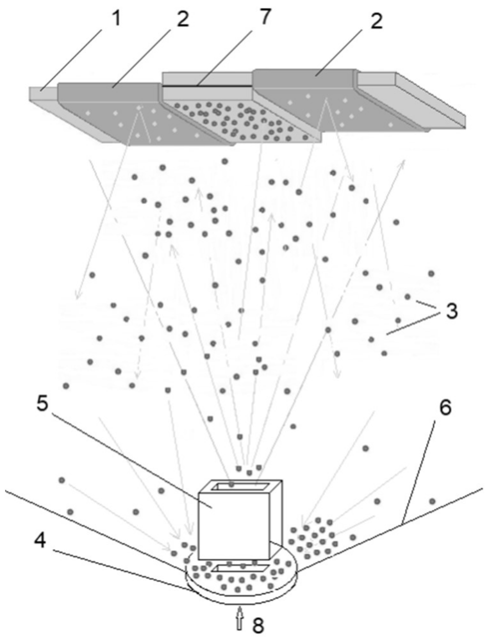

Fig. 5. Illustration of the shot peening process: 1 – specimen, 2 – cover, 3 – steel balls, 4 - compressed air nozzle, 5 – de Laval nozzle, 6 – bottom of the working chamber, 7 – adhesive, 8 – compressed air supply [17]

The adhesive joints subjected to and not subjected to shot peening were assessed in terms of their load capacity. For this purpose, a static tensile test was carried out in accordance with PN EN 1465:2009 [24]. The test was carried out using a ZWICK/ROELL Z100 testing machine (Zwick/Roell, Ulm, Germany). The samples were loaded with an axial force with a speed of 5 mm/min. The force at which the adhesive joint broke was considered as the load capacity of the adhesive joint Pt [N].

The second stage of the research was to carry out numerical simulations. The purpose of the simulations was to assess the impact of shot peening of the overlap zone on the stress state in the adhesive joint. Numerical calculations were performed in the Ansys 16.2 simulation software. The adopted model dimensions were as shown in Fig. 4. The information related to the data necessary to perform the numerical analysis was adopted on the basis of the authors' experience. The assumed thickness of the adhesive layer was 0.2 mm. As part of the numerical analysis, the stress state in the adhesive joints subjected to and not subjected to the shot peening process was compared.

As mentioned in the introduction to the article, shot peening of thin sheets introduces compressive stresses into their surface layer and causes plastic deformation of the sheets. This deformation can be described by the value of the deflection arrow f_A [mm]. In order to model the shot peening effect of adhesive joints in the Ansys program, the value of the deflection arrow for the shot peened EN AW-2024-T3 aluminum alloy sheet was determined. The sheet was subjected to shot peening with the following input parameters: ball diameter 1 mm, processing time 120 s, compressed air pressure 0.5 MPa. Only one side of the sheet was processed. The deflection arrow was measured with an Almen TSP TSP-3B plate deflection tester (Electronics Inc., Mishikawa, IN, USA). The measured value of the deflection arrow was 0.183 mm.

The next step was creating a numerical model of a single lap adhesive joint subjected to shot peening. It was assumed that the sheet in the model consisted of two layers with different thermal expansion. The thickness of the first layer (shot peened/with visible shot peeling effects) was 0.15 mm and its linear expansion coefficient was 7 10^{-5} 1/K. The second layer (non-shot peended/ without visible shot peening effects) was 1.85 mm thick and had a linear expansion coefficient of 5 10^{-5} 1/K. In order to model the effect of shot peening, the sheet was subjected to an elevated temperature of 325°C. As a result of the high temperature, the sheet was deformed. The deflection arrow of the deformed sheet was 0.183 mm (Fig. 6).

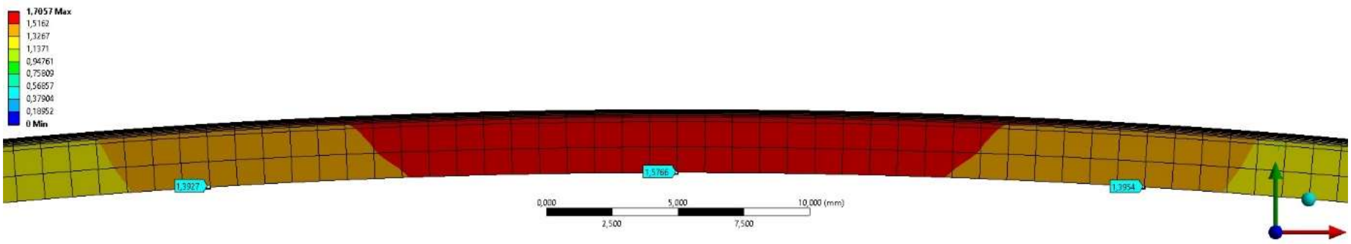

Fig. 6. Model of the sheet deformed in the results of shot peening

The thickness of the adhesive layer assumed in the model was 0.2 mm. In order to ignore the influence of temperature, it was assumed that the linear expansion coefficient of the adhesive was the same as that of the second layer (5 10^{-5} 1/K). The adhesive's modulus of elasticity was 2000 MPa

With the aim of investigating the influence of shot peening on the stress state in adhesive joints, numerical analyzes were carried out:

- for the model of an adhesive joint loaded with a tensile force of 4000 N (adhesive joint not subjected to shot peening),
- for the model of an adhesive joint loaded with a tensile force of 4000 N and additionally subjected to elevated temperature (325°C) in order to model the effect of shot peening (adhesive joint subjected to shot peening).

3. Results

The results of experimental tests carried out in order to determine the effect of shot peening on the load capacity of single lap adhesive joints made of EN AW-2024-T3 aluminum alloy are presented in Table 2. The mean load capacity of the connections was determined on the basis of 8 samples and the confidence interval 1-α = 0.95 was calculated.

Table 2. The results of experimental tests and the results of additional calculations for the adhesive joints subjected to and not subjected to shot peening

Variant	The results of measurements of the load capacity of adhesive joints P_t, N								Average value of the load capacity	Standard deviation
	P_{t_1}	P_{t_2}	P_{t_3}	P_{t_4}	P_{t_5}	P_{t_6}	P_{t_7}	P_{t_8}	$\overline{P_t}$, N	σ, N
With shot peening	9553	7483	9273	9653	9237	10507	10815	9024	9443±791	946
Without shot peening	8163	6164	6110	6535	7959	8396	7938	5372	7080±907	1084

On the basis of the results of experimental tests presented in Table 2, it can be concluded that the load capacity of shot peened adhesive joints is higher than the load capacity of untreated adhesive joints. Shot peening of the overlap zone allowed increasing the load capacity of adhesive joints by 33%.

The results of numerical calculations carried out in order to determine the stress distribution in the adhesive layer of the joints subjected to and not subjected to shot peening are shown in Figures 7-14. The maximum values of the analyzed stresses are summarized in Table 3.

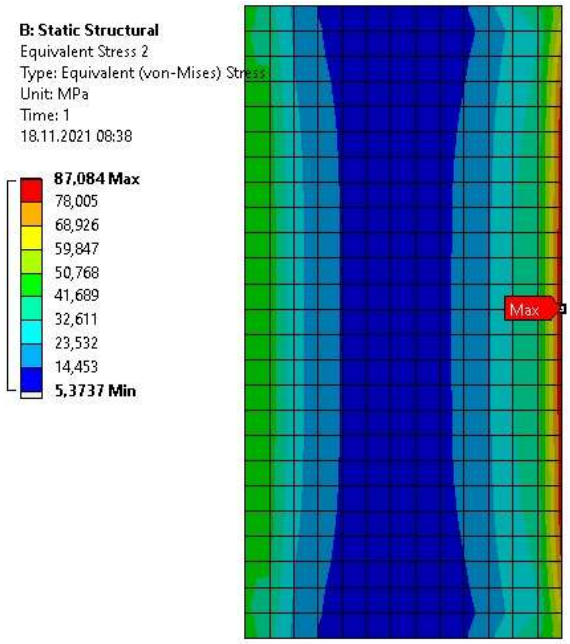

Fig. 7. Von Misses stress in the adhesive layer – without shot peening (load 4000 N)

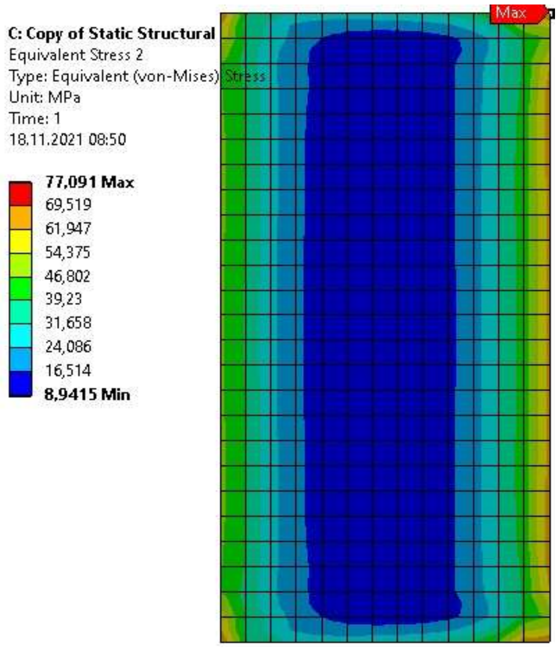

Fig. 8. Von Misses stress in the adhesive layer – with shot peening (load 4000 N, temperature 325°C)

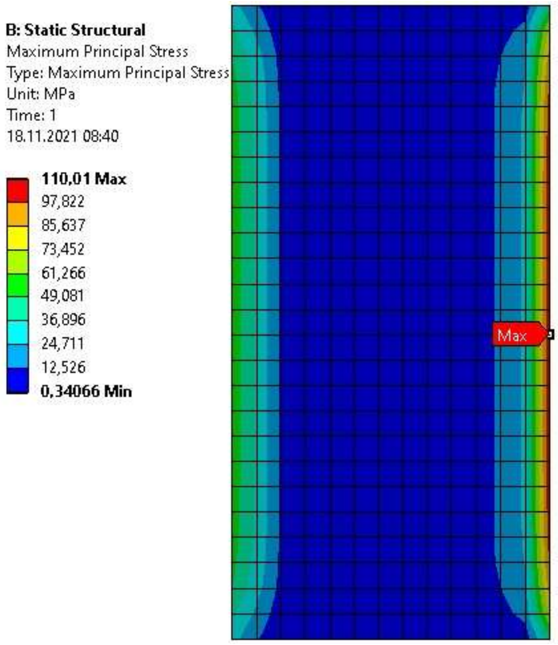

Fig. 9. Maximum principal stress in the adhesive layer – without shot peening (load 4000 N)

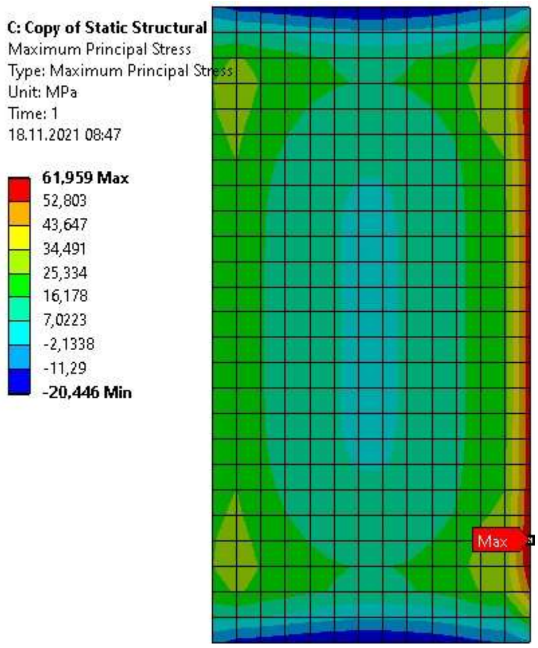

Fig. 10. Maximum principal stress in the adhesive layer – with shot peening (load 4000 N, temperature 325°C)

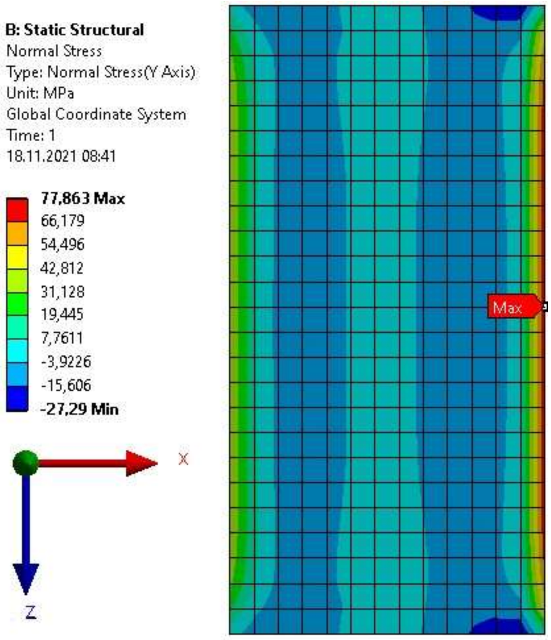

Fig. 11. Normal stress perpendicular to the adhesive layer – without shot peening (load 4000 N)

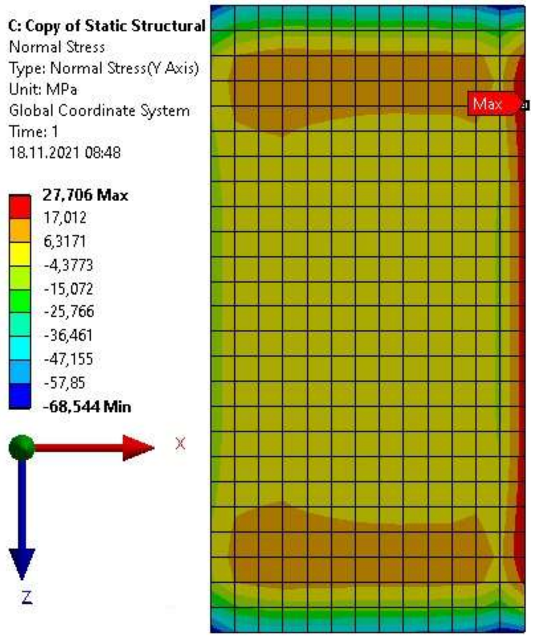

Fig. 12. Normal stress perpendicular to the adhesive layer – with shot peening (load 4000 N, temperature 325°C)

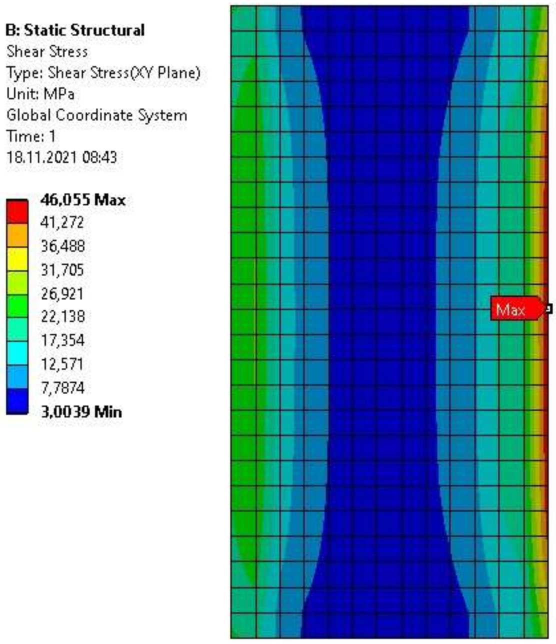

Fig. 13. Shear stress in the adhesive layer – without shot peening (load 4000 N)

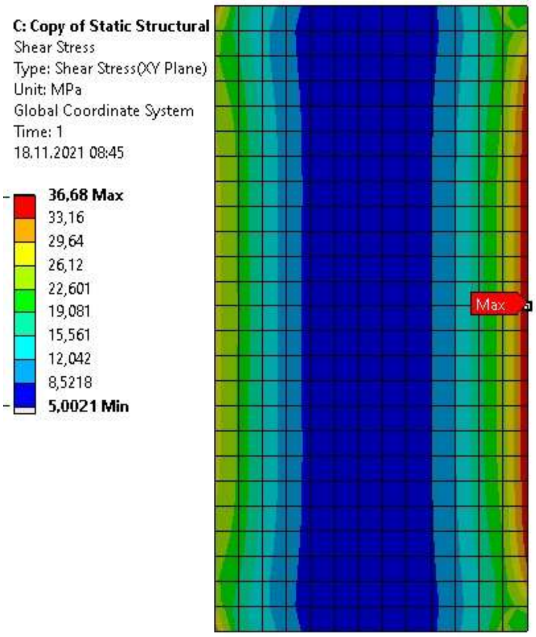

Fig. 14. Shear stress in the adhesive layer – with shot peening (load 4000 N, temperature 325°C)

Table 3. The values of maximum stresses in the adhesive joints

Stress, MPa	Adhesive joint not subjected to shot peening (load 4000 N)	Adhesive joints subjected to shot peening (load 4000 N, temperature 325°C)	Stress value decrease, %
von Misses	87.08	77.09	11
maximum principal	110.01	61.96	44
normal perpendicular to the adhesive layer	77.86	27.71	64
shear	46.05	36.68	20

According to the results of numerical calculations, shot peening of the adhesive joint overlap causes deformation of the joined elements and leads to a reduction in the value of the analyzed stresses. The biggest decrease in the stress value, amounting to 64%, occurred in the case of normal stresses perpendicular to the adhesive layer. Reducing the value of normal perpendicular stresses results in a reduction of equivalent (von Misses) stress and an increase in strength. The results of the performed numerical analyzes are of qualitative and not quantitative importance. Linear properties of the adhesive and adherents were assumed.

4. Conclusions

1. The results of the research show that shot peening can be successfully used to strengthen the adhesive joints (in the adopted range of variability of input factors). The load capacity of the adhesive joints shot peened with the following input parameters: ball diameter 1 mm, processing time 120 s and compressed air pressure 0.5 MPa is higher than the load capacity of the non-processed adhesive joints. Shot peening of the overlap zone allowed increasing the load capacity of adhesive joints by 33%.

2. The results of numerical simulations show that shot peening of the outer surface of the lap leads to a reduction of stresses in the adhesive layer. The biggest decrease in the stress value, amounting to 64%, occurred in the case of normal stresses perpendicular to the adhesive layer. The maximum principal stresses decreased by 44%, the shear stresses by 20%, and the von Misses stresses by 11%.

3. Due to shot peening of the outer surface of the adhesive joint overlaps, the joined elements deform plastically (the overlap edge is pressed against the adherend). The resulting deformation generates compressive stresses in the adhesive layer. Adding up the stresses resulting from deformation and external load causes that the stresses in the adhesive layer in adhesive joints subjected to shot peening are up to 64% lower than the stresses in the adhesive layer of joints not subjected to the treatment.

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THE FRAMEWORK FOR THE SUPPLIER QUALIFICATION SYSTEM FOR THE WORLD LEADER HOME APPLIANCES INDUSTRY

KWALIFIKACJA DOSTAWCÓW NA PODSTAWIE SYSTEMU OBOWIĄZUJĄCEGO W ZAKŁADACH ŚWIATOWEGO LIDERA BRANŻY AGD

Abstract

The aim of this study is to analyze and evaluate the supplier qualification system used in production plants of the world leader in the household appliances industry and to present proposals for improvement actions. The concern uses the "20 Steps Procedure", which is a set of guidelines for each stage of qualifying suppliers of components for production processes. It systematizes individual activities and sets the powers and responsibilities of the departments involved in various phases of the qualification process. This article describes its three phases. An important element of the procedure is a detailed supplier auditing system. It is necessary to be sure that a supplier has an effective management system and controls its production processes, and that the manufactured elements meet all the concern's requirements.

The presented system of supplier evaluation and qualification seems to indicate a rather cautious approach of the concern to the admission of new suppliers of components or semi-finished products. Criteria used in this area are very critical, but formulated in a very clear and transparent manner, understandable both for the company's auditors and for current and future suppliers.

Keywords: assembly, outsourced processes, components quality, supplier qualification, component suppliers, auditing

Streszczenie

Celem niniejszej pracy jest analiza i ocena systemu kwalifikacji dostawców, stosowanego w zakładach produkcyjnych światowego lidera branży AGD i przedstawienie propozycji działań doskonalących. W koncernie wykorzystywana jest „Procedura 20 kroków" będąca zbiorem wytycznych dotyczących poszczególnych etapów kwalifikacji dostawców komponentów do procesów montażu. Systematyzuje ona poszczególne działania oraz wyznacza uprawnienia i odpowiedzialności działów biorących udział w różnych fazach procesu kwalifikacji. Niniejszy artykuł opisuje jej trzy fazy. Ważnym elementem procedury jest szczegółowy system auditowania dostawców. Niezbędne jest uzyskanie pewności, że dostawca ma efektywny system zarządzania oraz kontroluje swoje procesy produkcyjne, a produkowane elementy spełniają wszystkie wymogi koncernu.

Przedstawiony system oceny i kwalifikacji dostawców wydaje się wskazywać na dosyć ostrożne podejście koncernu do dopuszczenia nowych dostawców komponentów czy półwyrobów. Kryteria. stosowane w tym zakresie, są bardzo krytyczne, jednakże sformułowane w sposób bardzo jasny i przejrzysty, zrozumiały zarówno dla auditorów koncernu, jak i dla obecnych i przyszłych dostawców.

Słowa kluczowe: montaż, procesy zlecane na zewnątrz, jakość komponentów, kwalifikowanie dostawców, dostawcy komponentów, auditowanie

1. Introduction

The aim of this study is to analyze and evaluate the supplier qualification system used in production plants of the world leader in the household appliances industry and to present proposals for improvement actions. The supplier qualification system presented later in this work is used in the process of central purchasing carried out for the entire concern. The conducted analysis shows suggestions of improvement actions, the implementation of which at the group level is probably impossible.

Effective qualification of suppliers is an essential element of the management system, having a significant impact on the quality of the delivered products. Until the 1920s, the concept of quality management did not exist in factories and other companies around the world. It is obvious, that in order to avoid

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complaints, the supplier verified the functional features of the delivered products. However, there are no data or studies that would confirm that these activities were carried out in a systematic manner.

In the 20th century, Walter Shewhart conducted pioneering research on the statistical description of variability in production, and on this basis, assumptions for statistical process control, and then statistical quality control, were developed. These methods were used by the US arms industry during World War II. Thanks to William Edwards Deming, a student of W. Shewhart, in the late 1940s, Japanese engineers became interested in quality control. In Japan, he conducted a series of lectures on statistical process and quality control. This stage is considered to be the beginning of the development of a new approach to product quality. Jospeh Juran also promoted the knowledge of statistics and quality in Japan.

The success of Japanese companies drew the attention of American entrepreneurs who began to look for the source of their failures. However, the popularization of quality management in the United States and Europe took place in the 1980s [1]. In 1986, the International Organization for Standardization ISO, based in Geneva, established the international standard ISO 8402: *Quality — Vocabulary*, and on its basis in March 1987 a series of international standards ISO 9000: *Quality management and quality assurance standards* was issued. Thanks to these standards, the concept of quality ceased to be associated only with a material product or service, and the role and importance of the quality of systems as well as the quality of processes taking place in the company and the way of managing them began to be noticed. The use of the process approach is one of the main elements that differentiate the set of standards of the 9000:1994 series from the ISO 9000: 2015 series standards in force until today.

There is a principle in the Japanese management philosophy that only well-educated employees who use good materials and work with good equipment can produce a good product that can be sold at a favorable price. The same principle also applies to services. This means that the selection and evaluation of suppliers plays a significant role in the enterprise and is an important factor in its success.

In an industry such as that represented by the concern that owns considered management system, the added value to a large extent arises outside the organization. The producers actually "only" function as assembly plants.

Many elements determining the quality of the final product (e.g. washing machines) are created in other companies. The uninterrupted course of processes in the production plant is only possible thanks to a perfectly functioning supplier management system.

The supplier management process must meet various expectations, and the requirements for the enterprise can be associated with the following groups [2][3]:

- customer expectations,
- comprehensive links between all interested parties,
- requirements resulting from standards,
- legal requirements,
- technological progress.

Only effective supplier management can ensure the long-term success of the enterprise [4][5].

This study provides an overview of the "20 Steps Procedure" used in the concern production plants, containing guidelines for qualifying suppliers, as well as a description of the principles related to auditing component suppliers. The presented rules of conduct were analyzed and assessed, on the basis of which proposals for improvement actions were presented.

2. Presentation of the company's activities

The company whose system was analyzed is one of the world's largest producers of household appliances and devices for professional use. The manufactured products are refrigerators, dishwashers, washing machines, vacuum cleaners and cookers. The concern's customers buy yearly about 40 million products in 150 countries. The company implements innovative solutions, designed with the use of comments, observations and ideas of customers in such a way as to meet their requirements. This assessed company can represent the other world class companies with their products and distribution facilities.

The group's quality management system is based on the requirements of several international standards. including ISO 9000, 14000, 18000 / 0HSAS, TS 16949, QS 9000, VDA 6.1-6.3 standards. Each of the plants has an individual management system, independent of central procedures.

Below (Fig. 1.) is the PDCA circle related to material supply in the concern's production company. The supplier qualification process is a centrally controlled process carried out by the central Procurement Department.

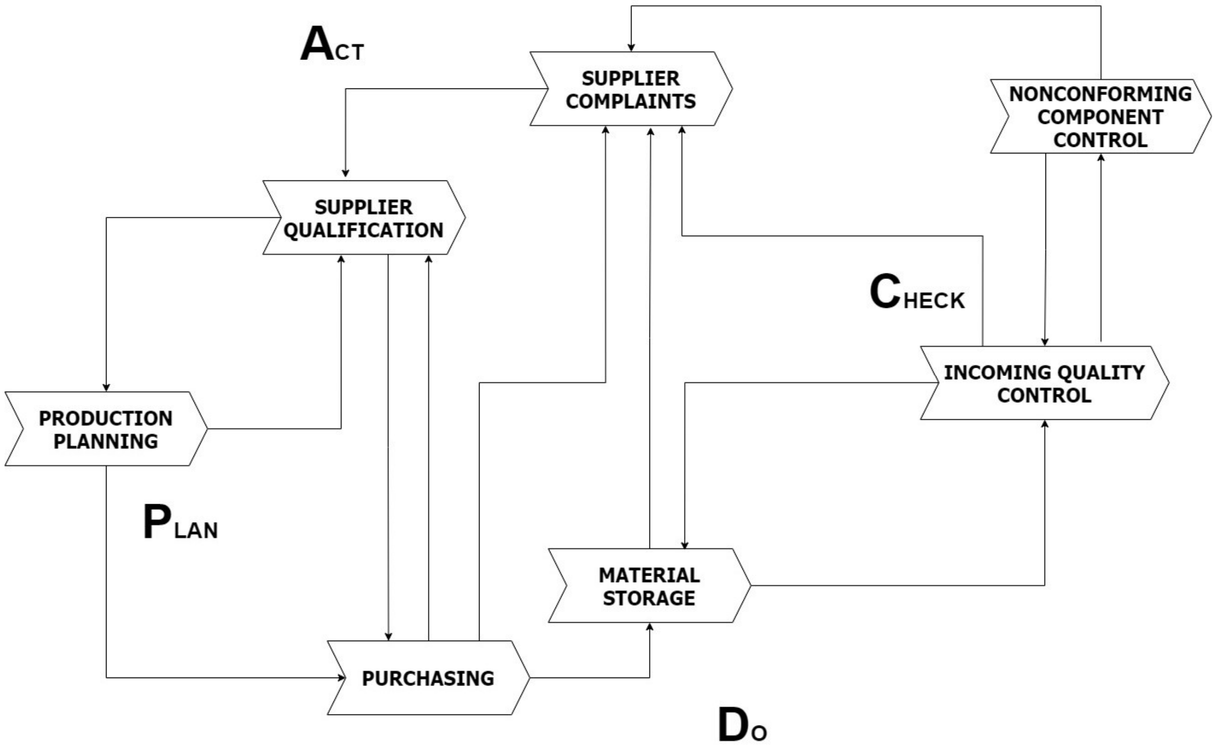

Fig. 1. PDCA circle related to material supply in a production company (source: own study).

3. Presentation of the "20 Steps Procedure" used in the concern

The "20 Steps Procedure" is a set of guidelines for each stage of supplier qualification. It systematizes individual activities and sets the powers and responsibilities of the departments involved in various phases of the qualification process.

The procedure itself can be divided into three phases (Fig. 2.).

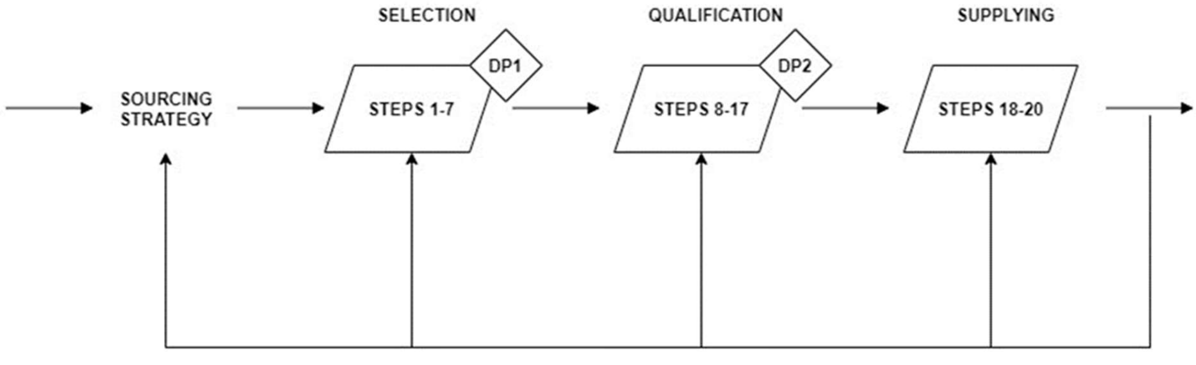

Fig. 2. The phases of the "20 Steps Procedure" (source: own study)

The first phase is "Selection" which covers steps 1-7, the second phase is "Qualification" which covers steps 8-17, the third is "Supplying" which covers steps 18-20. Between the individual phases there are the so-called "Decision points" - moments at which decisions are made to go ahead with individual suppliers.

These phases are preceded by step 0, the purpose of which is to specify the necessary requirements. Costs, component, quality and logistics requirements are defined. These activities involve employees of the Purchasing, Quality, R&D and Logistics Department.

The list of steps is presented collectively in the table below (Tab. 1.).

Table 1. Phases and steps of the “20 Steps Procedure” (source: own study).

Phase	Step	Description
1	-	**Selection**
	1	Market analysis
	2	List of potential suppliers
	3	Valuation
	4	List of selected suppliers
	5	GSQA (Global Supplier Quality Assurance) procedures. Supplier's information and response
	6	Supplier profile - purchasing process
	7	Initial quality audit
2	-	**Qualification**
	8	Specification review
	9	Delivery and contract
	10	Pre-production quality plan
	11	Samples and test results
	12	Component and sampling
	13	Supplier development
	14	Component homologation
	15	Testing under production conditions. Homologation.
	16	Supplier process audit
	17	Contract finalization. Component approval.
3	-	**Supplying phase**
	18	Production start
	19	Ongoing business assessment
	20	Supervision

Step 1: "Market analysis"

At this stage, global markets are reviewed to track current and future trends that will indicate where the appropriate supplier of individual components should be sought. Market analyzes, trade newspapers, and other sources of information are reviewed and may be of assistance at this stage. An in-company study "Commodity Analysis; Commodity Strategy and Action Plan” is also a helpful tool. The Procurement Department is responsible for carrying out these activities, which, through market analysis, indicates the potential sources of supply of individual components.

Step 2: "List of potential suppliers"

The purpose of this step is to prepare a list of at least three potential suppliers who may be able to provide the required components at the appropriate price, quality and cost. At this stage, the lists of current suppliers and market analyzes prepared in Step 1 are reviewed. Financial analysis is also part of the procedure. These activities, as in the case of Step 1, are also performed by the Procurement Department, and their result is a list of recommended potential suppliers.

Step 3: "Valuation"

In this step, the total cost of sourcing components from suppliers is estimated, including production costs, logistics, etc. Additionally, the supplier is informed about the requirements. They get basic information about the part requirements such as quantity, quality, packaging, batch size and availability. The supplier quotes the tooling, production costs, price per item and prepares a schedule. The supplier also receives general requirements – RML, RoHS and Code of Conduct. The Purchasing, Logistics and Quality Departments participate in these activities.

Step 4: "List of selected suppliers"

At this stage, the Purchasing Department selects the suppliers that qualify for the selected supplier list. For this purpose, all information that has been collected so far at individual stages is reviewed and analyzed.

Step 5: “GSQA (Global Supplier Quality Assurance) procedures. Supplier's information and response "

At this stage, the supplier is informed about the procedures of the Quality Department and related measurements.

Step 6: "Supplier profile – purchasing process"

Its purpose is to obtain sufficient information about the supplier to assess its qualifications as a future business partner. According to the purchasing process, information is obtained such as: financial status, R&D capacity, supply and flexibility, social and environmental policy. etc. To facilitate the acquisition of this information, the group provides the responsible persons with a special form. The obtained data is stored in a specialized database, provided if a decision is made to continue cooperation with a given supplier.

Step 7: "Initial quality audit"

The preliminary quality audit is carried out on the basis of the document "Supplier's initial process audit questionnaire". Its purpose is to assess the production processes of the selected supplier to demonstrate its ability to produce products of adequate quality. The supplier's factory is visited and the production process is assessed in accordance with the procedure described later in this article. On this basis, a report is prepared, containing a plan of corrective actions, which are monitored up to Step 14, if a decision made at DP1 is to continue cooperation.

DP1: Decision point

After completing all activities related to steps 1-7, in accordance with the "20 Steps Procedure", it is time to make the first decision regarding the continuation of the evaluation of the selected supplier and possible cooperation. In the procedure, this decision point is referred to as DP1. At this stage, the collected information is reviewed, assessed and a decision is made to continue cooperation. During the internal meeting, the Purchasing Department discusses the items to be delivered, discusses the list of suppliers and reviews the profile of the evaluated supplier, and analyzes the results of the preliminary audit. initial cost estimation, logistics solutions, other data (e.g. tools, specification agreements, packaging), RoHS data, possible profits, risk assessment. The plan of steps 8-18 is also reviewed and a decision is made whether to continue cooperation or not to qualify for a given supplier.

Step 8: "Specification review"

The purpose of this stage is to provide the selected supplier with the final and detailed specification of the component and the customer's requirements. The technical specification is checked for completeness. All documented requirements should result from the performance characteristics of a given component and the production process. Suppliers are provided with final drawings, delivery and quality specifications. At the end of this stage, the following documents are created: component specification, RoHS requirements, packaging requirements, quality and reliability requirements and other related specifications. The supplier confirms with his signature the specification and all requirements of the ordering party.

Step 9: "Delivery and contract"

At this stage, preliminary terms of delivery and quality agreement are established. The Purchasing Department determines all variable parameters, such as delivery times and their flexibility as well as quality parameters. Initial terms of delivery and quality agreement are negotiated and agreed.

Step 10: "Pre-production quality plan"

The purpose of this step is to plan and agree on qualitative preventive actions. The quality department defines the optimal quality assurance plan for a given supplier. The supplier must prepare a plan to meet these requirements. The plan must then be approved by the Quality Department.

Step 11: "Samples and test results"

The compliance of the specifications with the initial samples is checked. The test results report provided by the supplier is viewed. If a risk assessment is required, the status of the entire production process is checked. These actions may result in the notification of nonconformities and a request for corrective action.

Step 12: "Component and sampling"

The goal is to establish cooperation between the R&D Department and the supplier to verify the compliance of the specifications and the ability of the supplier's production process. Samples and test results are verified for compliance with the specification. There is also a process capability report prepared by the supplier.

Step 13: "Supplier development"

The concern supports the supplier in the full implementation of the quality assurance plan and preparation for the process audit. Substantive assistance is provided if the supplier's knowledge in this regard is not sufficient. An action plan is prepared to support implementation. At this stage, the final process maps, the MSA quality control and analysis plan, and the documented risk analysis – process FMEA are created. To complete this step, all preventive actions following the pre-audit must be fully implemented by the supplier.

Step 14: "Component homologation "

At this stage, it is checked whether the analyzed component meets the specified requirements. The compliance of the manufactured component with the specification is verified. Tests are performed to check functionality, reliability, safety, etc. The RoHS compliance (if required) and the CE mark (if required) are verified. The result is a homologation report, RoHS certificate (if required) and a CE file.

Step 15: "Testing under production conditions. Homologation."

This step is followed by verification of the feasibility of the assembly and testing of the assessed elements during assembly. Tests are performed under production conditions. It is checked whether an initial qualitative input inspection will be necessary. As a result of these tests, approval for use, approval for the pilot batch and entry inspection procedures are issued.

Step 16: "Supplier process audit".

This stage is to confirm that the supplier can deliver his products in accordance with the group's requirements. An audit and assessment of the correct production processes at the supplier is performed, including verification of the correct implementation of the quality assurance plan (Step 10). Unsatisfactory results are reported in the CAR report (required corrective actions) and the supplier is given a deadline within which he must prepare a corrective action plan.

Step 17: "Contract finalization. Component approval"

During this step, all conditions are finalized and agreed. Supply chain is planned. The terms of the contract are negotiated and agreed, this applies to the schedule, its flexibility, procurement procedures and quality parameters are established. The logistics arrangements are also being finalized. The results are purchase order acceptance and contract finalization. It is also confirmed that the component meets the production and use requirements. If so, its status is changed to "approved" in the BOM.

DP2: Decision point

At the end of the "Supplier Qualification" phase, it is time to make another documented decision about the fate of the supplier participating in the qualification process. During the Procurement meeting, relevant information is reviewed and analyzed, and then a decision is made to proceed with the "20 Steps Procedure". During the decision meeting, the following are discussed: verification of completeness of the specification. Pre-production quality assurance status. Process audit results, component / application test results. Approvals CE marking, RoHS compliance, contract and agreement review, ordering procedure and logistic solutions, financial justification review, corrective actions required, start of production, decision to continue The result is a DP2 report approving the introduction of the component into production and listing the delivery on the list suppliers.

Supplying phase

Step 18: "Production start"

The purpose of this stage is to initiate production and start deliveries. An order and a transport order are placed.

Step 19: "Ongoing business assessment"

At this stage, the supplier and component production are monitored and managed. The reliability of deliveries is controlled. An entry inspection is performed. Line rejects are monitored. The implementation of improvement projects is checked. The results of these activities are reports on the ongoing evaluation, analysis and implementation of improvement projects.

Step 20: "Supervision"

This is the last step of the "20 Steps Procedure". This step includes overseeing the implementation and results of corrective actions by the supplier as per the audit results.

The result is an update of the results of the process audit.

4. Supplier auditing system

4.1. Supplier pre-audit

The first audit during the implementation of the "20 Steps Procedure" discussed above takes place at Step 7 of the "Selection" phase. It is an initial audit aimed at assessing a potential supplier, confirming its ability to meet the requirements, especially those related to ISO 9001: 2015. It is necessary to be sure that the supplier has an effective management system and controls its production processes, and that the manufactured elements meet all the concern's requirements.

The questionnaire is based on the following standards: ISO 9001: 2015, ISO / TS 16949 and QS 9000.

The purpose of the pre-audit is to understand the potential supplier's system of operation, to check that there are correct management methods throughout the organization and to identify possible critical points.

The table below (Tab. 2.) presents the system of awarding points for individual criteria:

Table 2. Scoring system for audit questions (source: internal corporate documentation).

Answer	Points	Justification	Corrective actions
No	0	Required but not included in the management system	Yes
Yes, but	1	Included in the management system but implementation needs improvement	Yes
Yes	2	Effectively used in the management system	No

Upon completion of the audit, on the basis of the scores obtained, the potential supplier is qualified to one of two groups. The classification system is presented in the table below (Tab. 3.).

Table 3. System of classification of suppliers (source: internal corporate documentation).

Score	Status	Criteria	Comments
A	Acceptable	> = 75% as the average level for all sections and a minimum of 1 point for each question	Supplier confirming compliance with audit requirements. Also demonstrating high self-discipline and excellent process management.
B	Not acceptable	<75% as the average level in all sections or not a minimum of 1 point was obtained for each question	The supplier does not meet the requirements

The audit is performed by sampling, the purpose of the auditors is not to find non-conformities, but to demonstrate compliance on the basis of random spot checks in the areas examined. The following sections are assessed:

Management – in this area, the maximum number of points that a potential supplier can obtain is 20. The questions concern the following issues: “Does the supplier have a current ISO 9001 or similar certificate (e.g. ISO / TS 16949), issued by an accredited organization, in terms of products/services?"; "Have internal and external quality targets been set based on customer feedback and other data?"; "Is there a quality cost measurement system that monitors the costs of internal nonconformity, prevention, and control and testing?"; "Have objectives been analyzed and action taken if objectives have not been met (internal objectives and consistent actions also need to be considered)?"; "Have specific improvement projects been implemented and are they properly measured and verified in terms of effectiveness?"; "Were internal audits carried out according to the schedule and were the causes of nonconformities analyzed and corrective actions taken?"; Are there periodic management reviews with the active participation of the management? ”; "Is there a system for checking the causes of nonconformities (internal and external) and have appropriate corrective actions been taken to eliminate them?"; "Is the effectiveness of corrective actions adequately verified (including goals, trends, PDCA method, etc.) to prevent duplication?"; "Was there a system for identifying training needs and were all the people whose activities influencing the quality trained?".

Quality planning – the maximum number of points that can be obtained in this section is 8. Questions related to this area are as follows: "Is the process of implementing a new product started, which covers the following issues: customer requirements review, customer and supplier relations, feasibility studies, tool planning, FMEA, identification/control of critical points, MSA, control plans and diagrams, sample identification, evaluation of process capability and usage of appropriate statistical methods, evaluation of product lifetime, management of the above changes? ”; "Is the organization able to conduct an FMEA?"; "Can the potential supplier perform statistical process capability studies and use statistical process control methods?"; "Is there an effective system for approving/evaluating components and, if necessary, production processes prior to production at the supplier's facility?".

Purchasing – a maximum of 6 points can be achieved in this section. The questions are: "Is there an effective system for ongoing monitoring of the supplier's production capacity and is a quality management system required?"; "Is there a defined process for obtaining and evaluating samples from the supplier?"; "Are suppliers required to inform the organization of any changes to the delivered product?".

Production control – in this section, the maximum number of points to be earned is 20. The questions are as follows: "Are there workplace procedures and instructions available?"; "Do the procedures (or control plans) contain requirements for production, inspection, testing, start production, approval and product, process and tool changes, with recorded results?"; "Have special processes been identified and appropriate metrics identified?"; "Are the appropriate statistical methods (SPC) required by the control plans in place?"; "Are materials, products and relevant components kept in segregated and labeled uniform batches at all production levels, including final storage?"; "Is the product traceable from procurement to the delivery to the customer?"; "Do the inspections and tests carried out at each stage have a clearly marked status?"; "Is there an effective system for handling the product, its storage, packaging, delivery and protection?"; "Is the working environment clean and well-organized"; "Is there an effective system for monitoring product output quality through statistical audit of ready-to-ship products?".

Calibration and maintenance - in this section it is possible to receive a maximum of 6 points. The questions are: "Is there a system that ensures that the appropriate measurement and test equipment is properly calibrated, on time, in accordance with international standards and MSA (Measurement Systems Analysis)?"; "Is there a planned maintenance system for all equipment, including schedule, defined criteria, frequency and responsibility and records?"; "Is there a spare parts management system for key production equipment, including their identification and availability?".

4.2. Supplier process audit

A process audit can be initiated by both the customer and the supplier. The decision to audit a given supplier is made on the basis of strategic data analysis. The current supplier who has made significant organizational changes or moved production to another location is also subject to audit. The supplier may request a reassessment of the management system in order to increase the scores or change the category awarded in an earlier audit. Suppliers whose manufacturing and delivery history shows low quality of material / components and / or services are also subject to audit. The same also applies to suppliers who have not been audited in the last three years.

The objectives of a process audit are as follows:

- deepening the supplier's understanding of the customer's processes and expectations;
- improving the supplier's operations based on the analysis of statistical variability of input and output data from each process area;
- applying statistical techniques to the supplier's products and processes;
- maintaining an appropriate management methodology throughout the supplier's organization, which also has a significant impact on the level of quality costs.

The form includes a sheet that summarizes the nonconformities identified during the audit and an appendix with specific requirements that can be used to document the necessary corrective actions during post-audit meetings.

The scoring system is as follows (Tab. 4.).

Table 4. Scoring – process audit (source: internal corporate documentation)

Answer	Points	Justification	Corrective actions
No	0	Required / high risk but not included in the management system	Yes
Yes, but	1	Included in the management system but implementation requires improvement	Yes
Yes	2	Works effectively in the management system	No
N/A	-	Not applicable	-

The auditor records his observations in the questionnaire. Nonconformities will be included in the audit summary, as long as the answer to a given question obtained less than 2 points and requires corrective action. Auditor comments may also be attached to responses that scored 2 points, but are not seen as a requirement for corrective action. Such comments are recorded in the appropriate column and may become a source of corrective action if the full specification is not provided or the requirements are not met prior to the commencement of deliveries.

As a general rule, all questions must be assessed. The exception is when the question does not entirely relate to the assessed organization. Example: the supplier produces components in the assembly technique, then SPC is not expected and scores NA (not applicable), if the supplier has a small production company and cannot afford to implement SPC, but the production characteristics require this technique, then scores 0 points. The decision to consider certain aspects as NA must be made during the audit preparation phase and must be agreed with the team prior to the audit and recorded on the evaluation sheet and as a commentary to the question in the report.

The decision to accept responses to certain questions as NA must be made during the audit preparation phase and agreed with the audit team prior to the audit and recorded as a comment on the evaluation form next to the relevant question. It is important that the audit team evaluates and scores any question that has not been allocated to the NA category. If for some reason the audit cannot be completed, a further visit is necessary so that all questions are assessed.

When questions are asked about information on procedures, the questions are usually assessed against whether there are instructions and whether they are adequate ("Do the procedures / work instructions / control plans list requirements for inspection, test and record results?"). If the instruction is inadequate or non-existent, a score of 1 or 0 is given. If the instruction is adequate but not implemented, the scoring will be on the question: "Do workers act in accordance with work instructions or other relevant requirements?".

Additional explanations of the scoring rules:

- 0 points are awarded when a requirement exists but is not addressed in the management system or not implemented, or there is a serious failure in the management system, or there is a high risk to the customer.
- 1 point is awarded when the issue is in the management system, but its implementation requires improvement or the requirement is not consistently implemented.
- 2 points are awarded when a requirement is fully met and perfectly performed.

Nonconformities must be assigned to specific questions (otherwise they may duplicate in the summary). If the same nonconformity occurs for two different questions, the audit team must decide which one it has the greater connection with and rate the question with 1 or 0 points. The latter question, which also corresponds to the same nonconformity, will be scored 2 points unless any other nonconformity is found which affects the scoring. The described situation stems from the assumption that the supplier is not punished twice for the same failure. Comments appear when there is no evidence of nonconformity or a threat to the customer is discovered.

The classification system is similar to the pre-audit, but the classification criteria have been slightly tightened. The rules are illustrated in the table below (Tab. 5.).

Table 5. Rules for the classification of suppliers (source: internal corporate documentation)

Score	Status	Criteria	Comments
A	Acceptable	>= 80% in all sections except a minimum of 85% for section 3.0.	Supplier confirming compliance with audit requirements. Also demonstrating high self-discipline and excellent process management.
B	Unacceptable if immediate improvements are not planned and implemented	<80% in all sections except <85% for section 3.0.	The management system processes reflect significant nonconformities in the aspects assessed. The supplier cannot be considered for new / additional ventures if he fails to implement effective improvement actions within the appropriate timeframe.

The part of the form that contains the audit questions is divided into 9 sections. The thematic division and the maximum number of points that can be obtained in each section are presented in the table below (Tab. 6.).

Table 6. Thematic sections of the audit questionnaire (source: internal corporate documentation)

Section	Assessed area	Points
1.0	Strategy and planning	22
2.0	Purchasing	12
3.0	Production supervision	32
4.0	Monitoring and measurement	22
5.0	5.1 Identification and traceability 5.2 Raw material management 5.3 Personnel and training	12
6.0	Maintenance	10
7.0	Calibration	14
8.0	Supervision of documents and records management	12
9.0	Corrective actions and improvement	20
	Total	**156**

The questionnaire contains several dozen detailed questions that would be difficult to quote in full. Therefore, the topics of individual sections are presented in the summary below:

1.0: annual quality objectives, quality costs, specific improvement processes and their measures, quality plans, supervision of the specification and its changes, supervision of changes in products and processes, FMEA and corrective actions;

2.0: supplier assessment, monitoring of the current supplier assessment, procedures for corrective actions in the supplier classification process, purchase specifications, delivery approval system, supply change management system;
3.0: work procedures and instructions, process diagrams, on-site instructions, working according to instructions, special processes, measures and criteria for starting production (startup), organization of the work environment, statistical methods, process capability, control cards, warehouse and logistics procedures, packaging process control;
4.0: input product verification procedures, traceability, inspection and test procedures, output inspection, product audit data analysis, inspection records;
5.1: identification and traceability system;
5.2: homogeneous batches stored separately, adequate storage and FIFO;
5.3: identification of training and training needs, personnel competences;
6.0: maintenance system planning, frequency of maintenance, maintenance records. identification and availability of key spare parts, consideration of TPM methods;
7.0: inspection, measurement and testing of measuring equipment; conditions for carrying out calibration, appropriate criteria; calibration in accordance with international standards; calibration at the appointed dates, as required; appropriate storage of measuring equipment; appropriate actions after the discovery of uncalibrated equipment;
8.0: document control system, engineering and process control and change management system, withdrawal of invalid documents from use, supervision of records, retention time of records, availability of records;
9.0: corrective actions, procedures to identify the causes of nonconformities, analysis and implementation of corrective actions, management of complaints, verification of the effectiveness of corrective actions, use of nonconformity reports for preventive actions, use of information on corrective and preventive actions during management review.

A positive audit result is valid for two years. After this period, the audit results expire and a new audit is required. Result B, obtained as a result of the audit, indicates the need to immediately prepare a corrective action plan. If, after performing corrective actions, the supplier process audit results are still unacceptable, an alternative supplier should be sought.

Upon completion of the audit, the supplier must receive a written report prepared by the audit team, which is an official record of the audit activities. The report should contain the results of the process audit and impose the requirement to carry out the necessary corrective actions to remove or correct the identified weaknesses. Ideally, the report should be submitted to the supplier at the end of the audit, or presented to the supplier within two weeks after the end of the audit.

5. Supervision over the implementation and corrective actions of suppliers

Upon receipt of the report, the supplier should respond with a corrective action plan within 30 days. A process audit is not considered complete until the supplier has identified the most effective and practical solutions to nonconformities identified during the audit and identified the methods of implementing these solutions. The supplier is responsible for initiating corrective actions for all detected nonconformities. This means indicating the causes of nonconformities, taking corrective actions and long-term corrective actions. The supplier should indicate the extent to which this problem has had an impact on its past business and what will be required to correct it. Corrective actions whose success will depend on revolutionary changes in the supplier's resources or drastic changes in the behavior or capabilities of individuals are unacceptable. The supplier is responsible for the preparation of a written response to the lead auditor within the agreed time, including all corrective actions. An initial corrective action plan should be prepared within 30 days of receiving the final report. Reports on the implementation progress of corrective actions should be sent to the lead auditor on a quarterly basis.

Upon receipt of the corrective action report, the audit team leader is required to assess the adequacy of the supplier's response and ensure that corrective actions have been defined for each nonconformity. Additional information should be provided by the supplier, thus confirming that it is working on schedule and that the problems are minimized as the corrective action progresses.

It is possible to conduct a surveillance audit to verify the effectiveness and adequacy of corrective actions that cannot be verified by telephone calls or written documentation. Such an audit does not require the presence of the entire audit team, can be carried out in one day and should focus on corrective actions.

Depending on the need, periodic supervision visits can be carried out to ensure that the results of the process audit have not decreased. Another process audit may be necessary if there is a deterioration in the quality of the supplier's performance.

6. Analysis and evaluation of the supplier qualification process and proposals for improvement activities

The analysis of the supplier qualification process, carried out above, indicates the possibility of introducing changes of an improving nature in order to improve the course of the process. As part of the consultations with representatives of the concern, no information was obtained on the effectiveness indicators of the supplier qualification process.

Undoubtedly, the first improvement action, that should be proposed, is to establish measures of effectiveness (efficiency) of such a process, to set goals for these measures in a given period, and to constantly monitor trends, thanks to which the introduction of other improvement actions could be assessed in terms of their adequacy. Such measures could be, for example:

- ratio of the number of suppliers qualified for each of the categories at the assumed time of the procedure to the number applying for the supplier status;
- ratio of the number of suppliers whose status has decreased to the global number of suppliers on the qualified list for a given assortment.

After introducing process effectiveness indicators, as well as examining their trends for a period of at least twice the average time of supplier qualification, improvement projects can be implemented, based e.g. on the Six Sigma methodology, i.e. consisting of the phases of defining the issue to be improved, making appropriate measurements, aimed at assessment of the actual state, making detailed analyzes to indicate the stages of the project, their products and acceptance criteria. The next phase is the phase of implementing the adopted solutions. The last phase is the phase of supervision, implementation control, along with the possibility of comparing the values of the measures and their trends, the status before the changes were introduced with those after the introduction.

As a result of the analyzes, the proposed improvement projects could be:

- simplification of the "20 Steps Procedure" – the procedure is very tedious, time-consuming and detailed. It provides a large amount of information about a potential supplier. However, it is not known whether such a large amount of information is used by the group. In the measurement and analysis phase of the improvement project, it could be proposed to reduce the supplier information that statistically has the smallest impact on the correctness of the decisions made in step DP1 and DP2. This is of course only possible when there is a sufficient amount of comparative data. which, with the use of an effective statistical tool, would indicate the directions for carrying out activities related to the re-engineering of the analyzed business process [6][7][8][9]
- introducing an electronic system of surveying potential or already qualified suppliers, operated, for example, via a web browser. The analyzed materials indicate a very precise and unambiguous formulation of the requirements for suppliers, however, getting to know all the issues that make it possible to properly disclose data to the concern is very time-consuming. It requires the supplier to read more than a few hundred pages of documentation. The introduction of the possibility of providing data by filling in electronic questionnaires, equipped with a context menu, drop-down lists, an extensive hint system (help), could reduce interpretative differences in terms of the group's requirements, as well as faster and more effective cooperation between the sales departments of suppliers (or customer service) and the group's central Procurement Department. The artificial intelligence methods can be also used for procurement process improvement [10].
- by expanding the IT system proposed above with the ability to track the supplier's profile in the group's system, i.e. quick access to the results of audits, data on agreed corrective or preventive actions, the ability to quickly enter information about current implementations, the ability to simulate the status that the supplier can obtain after introducing the anticipated changes to the system and production processes [11]. An interesting solution would also be the introduction of benchmarking lists so that the supplier could compare his status – the results achieved in individual criteria – with the average obtained by other suppliers of the indicated assortment.

7. Conclusions

The described concern, gaining experience in cooperation with various organizations, both suppliers, customers and partners, during several dozen years of operation in the business reality, has developed, among others, rules defining the processes of dealing with suppliers. They were built back in the times, when the standards the company uses today did not exist in their present form. Using best practices, this global organization anticipated most of the wording that can be found in ISO 9000, 14000, TS and other standards. Of course, it should be remembered that standardization bodies did not work in isolation from the business reality. Bearing in mind the size of the organization, as well as the scope of operation in 150 countries around the world. one can confidently put forward a thesis that the concern and the rules prevailing in it could have a significant impact on the management systems used today in global corporations and could be reflected in the normative acts concerning management systems.

The presented system of supplier evaluation and qualification seems to indicate a rather cautious approach of the concern to the admission of new suppliers of components or semi-finished products.

Criteria. used in this area are very critical, but formulated in a very clear and transparent manner, understandable both for the company's auditors and for current and future suppliers. The "20 Steps Procedure", as well as the principles of auditing, are very precise and leave no doubts of an interpretative nature. This does not mean, of course, that the concern will not develop the presented methods of conduct as part of its improvement activities. In accordance with one of the principles of quality management: the concern provides an excellent tool for improving the supplier organizations and in return gains reliable, effective and loyal suppliers.

As presented in the analysis section, the supplier evaluation methodology used is very detailed and generates a large amount of information. Future considerations could concern analyzes related to the identification of the most significant data, the behavior or trends of which would indicate methods of qualifying and dealing with suppliers. In the current geopolitical situation, data that have not been taken into account so far may turn out to be particularly important, but may have a critical impact on the continuity of the supplier's customer processes [12] [13].

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