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Original Research

ANALYSIS OF THE PROPERTIES OF ORTHOTROPIC COMPOSITES IN TERMS OF THEIR USE IN AIRFRAME REPAIRS

ANALIZA WŁAŚCIWOŚCI KOMPOZYTÓW ORTOTROPOWYCH W ASPEKCIE ZASTOSOWANIA W NAPRAWACH PŁATOWCÓW

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Abstract

The aim of the research was to determine the basic strength properties of orthotropic composites in terms of their use in the repair of aircraft airframes. The objects of the tests were three types of composites reinforced with carbon fibers: produced using the wet method with a thickness of 2.5 mm, commercial with a thickness of 2 mm and commercial with a thickness of 7.3 mm. Specimens cut out from the first two types of materials were subjected to a static tensile test with a force applied in the direction of the fibers and at an angle of 45°, which enabled the determination of tensile strength and modulus of elasticity. Specimens made of 7.3 mm thick composite were subjected to four-point bending and tensile tests to determine Young's modulus, compression and impact strength, also taking into account two directions of load application. The values of stresses and Young's modulus determined in this way indicate much lower strength and stiffness of orthotropic composites apart from the reinforcement fibers' directions, which is the basis for replacing them with quasi-isotropic composites in repairs of aircraft airframes.

Keywords: orthotropic composite, mechanical properties, impact strength

Streszczenie

Celem badań było wyznaczenie podstawowych właściwości wytrzymałościowych kompozytów ortotropowych w aspekcie wykorzystania ich w naprawach płatowców statków powietrznych. Obiektami badań były trzy rodzaje kompozytów zbrojonych włóknami węglowymi: wytworzony metodą na mokro o grubości 2,5 mm, komercyjny o grubości 2 mm oraz komercyjny o grubości 7,3 mm. Próbki wycięte z dwóch pierwszych rodzajów materiałów poddano statycznej próbie rozciągania siłą przyłożoną w kierunku ułożenia włókien oraz pod kątem 45°, co umożliwiło wyznaczenie wytrzymałości na rozciąganie oraz modułów sprężystości podłużnej. Próbki wykonane z kompozytu o grubości 7,3 mm poddano czteropunktowemu zginaniu oraz próbom rozciągania w celu określenia modułu Younga, ściskania oraz wytrzymałości udarnościowej także z uwzględnieniem dwóch kierunków przyłożenia obciążenia. Wyznaczone w ten sposób wartości naprężeń oraz modułów Younga wskazują na znacznie mniejszą wytrzymałość i sztywność kompozytów ortotropowych poza kierunkami ułożenia włókien zbrojenia, co stanowi podstawę do zastąpienia ich kompozytami quasi-izotropowymi w naprawach płatowców statków powietrznych.

Słowa kluczowe: kompozyt ortotropowy, właściwości mechaniczne, udarność

1. Introduction

Composite construction materials have found application in many industries due to their special properties. They are, among other things, a response to the search for new solutions in the field of materials used in the construction of aircraft airframes. The main purpose of their use is weight reduction and optimization of fuel consumption.

Therefore composites replace heavier elements made so far in 60-70% of aluminum alloys [1]. In addition to low weight, other advantages of composite materials include corrosion resistance and chemical stability, thermal and electrical conductivity, as well as low coefficient of thermal expansion [2].

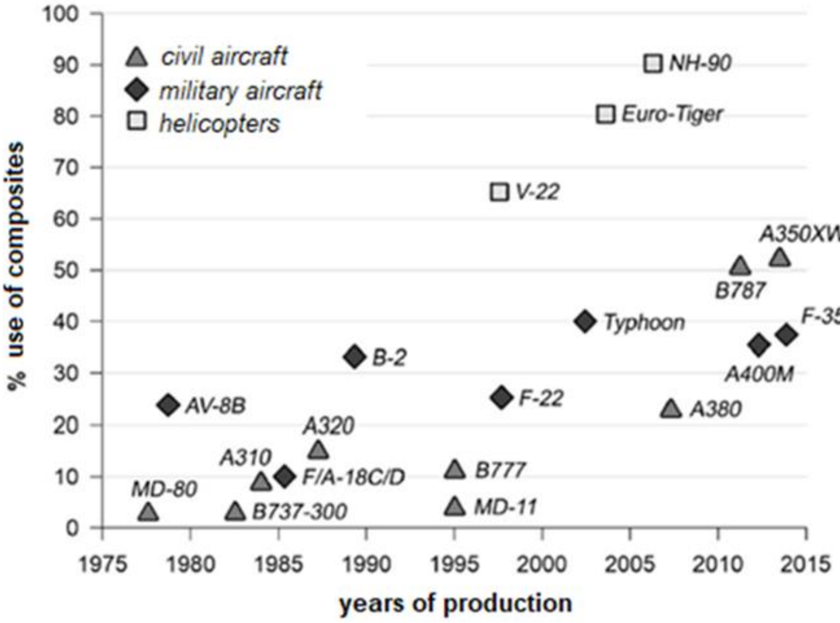


Fig. 1. Mass share of composites in the construction of aircrafts in the years 1975-2015 [5]

Due to their high stiffness, immediate and fatigue strength, composites reinforced with carbon fibers with matrixes based on polymer thermosetting resins (CFRP) are the most widely used in aviation [4]. Reinforcement in this type of composite may take the form of roving strips, fabrics, mats or short fibers, e.g. milled or chopped. A large part of composite materials exposes the properties of an orthotropic material, which means that its properties change in directions perpendicular to each other. Typical types of orthotropic composite reinforcement are shown in Figure 2.

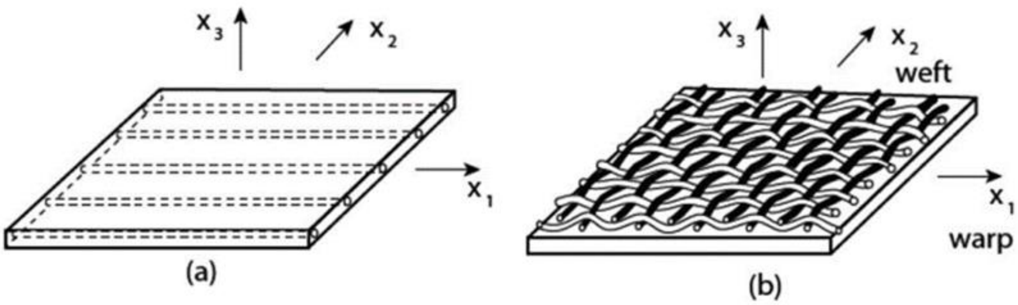


Fig. 2. Directions of orthotropy of the composite reinforced: a) unidirectional, b) fabric [3]

In the case of unidirectional fibers (Figure 2a), the stiffness and strength in the x_1 direction of the fiber are greater than in the x_2 and x_3 directions transverse to it. The fabric presented in Figure 2b is more balanced - it has similar properties in the x_1 and x_2 directions. However, the flat fiber arrangement of 0-90° is the reason for the lower strength in the x_3 direction. Such fabric-reinforced composites, in which the weight of the warp is comparable to the weight of the weft, are the most commonly used type of orthotropic composite [5, 6]. The properties of the composite depend so strongly on the direction of reinforcement orientation due to the fact that the strength of carbon fibers is up to 100 times greater than that of the polymer matrix [7].

The complexity of the internal structure of composite materials is an important factor influencing the fact that elements made of them are subject to damage at various stages of use, which most often include cracks and delamination. Damage can be local or affect the entire element, and it is caused by permanent, fatigue or impact loads. The main operational problems of composites are directly related to their damage - difficulties in detecting low-energy damage (BVID - Barely Visible Impact Damage) [8, 9, 10], in selecting a repair method due to the limited possibility of mechanical processing (cutting [11] and drilling [12, 13]), as well as in the design of joints (especially with the use of mechanical fasteners [14, 15]).

The aim of the research was to determine the strength of polymer carbon composites with orthotropic properties in various directions and to determine their modulus of elasticity. The third type of CFRP composite was also subjected to compression and bending strength tests, as well as impact tests. An attempt was made to analyze the obtained results in terms of the use of orthotropic composite in the repair of airframe structures.

2. Research materials and methods

Composite No. 1

The first stage of the experimental part was the production of a carbon composite. For this purpose, a carbon fabric with a weight of 206 g/m^2, epoxy resin for laminating L285 with a density of 1.19 g/cm^3 and a slow-curing hardener 287 were used. As part of the composite manufacturing process, 12 layers of fabric saturated with a mixture of resin and hardener mixed in a ratio of 100:40 were stacked on top of each other. Excess resin was removed with a roller. The obtained structure was subjected to a force of 40 kN for 30 minutes (pressures of about 0.68 MPa) and then cured for 5 hours in a dryer at 80°C. The effect of the lamination was a composite plate with dimensions close to a square, from which individual specimens were then cut out. Appropriate calculations were carried out (Table 1) in order to theoretically estimate the Young’s modulus of the composite material.

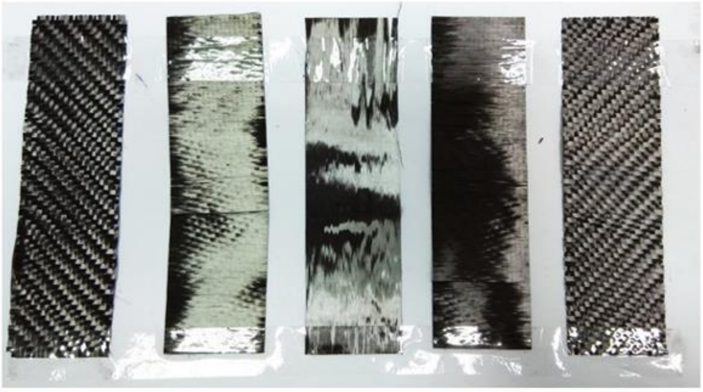
Table 1. Algorithm for determining the Young's modulus of the composite

Plate dimensions	a = 237.8 mm b = 247.4 mm c = 2.492 mm
Carbon fabric weight	$g = 206\ \frac{\mathrm{g}}{\mathrm{m}^2}$
Young’s modulus of carbon fiber	E_w = 230 GPa
Number of layers of carbon fabric	n = 12
Resin density	$\rho_{\dot{z}} = 1.19\ \frac{\mathrm{g}}{\mathrm{cm}^3}$
Young’s modulus of resin	$E_{\dot{z}}$ = 3.15 GPa
Plate weight	m_k = 202.82 g
Plate volume	$V_k = \mathrm{a} \times \mathrm{b} \times \mathrm{c} = 146.61\ \mathrm{cm}^2$
Plate density	$\rho_k = \frac{m_k}{V_k} = 1.38\ \frac{\mathrm{g}}{\mathrm{cm}^3}$
The surface area of plate	$S_k = a \times b = 0.0588\ \mathrm{m}^2$
The surface of area of the worn carbon fabric	$S_t = n \times S_k = 0.706\ \mathrm{m}^2$
Carbon fibers weight	$m_w = S_t \times g = 145.43$ g
Resin weight	$m_{\dot{z}} = m_k - m_w = 57.39$ g
Carbon fibers mass fraction	$w_w = \frac{m_w}{m_k} = 0.72$
Resin mass fraction	$w_{\dot{z}} = 1 - w_w = 0.28$
Resin volume	$V_{\dot{z}} = \frac{m_{\dot{z}}}{\rho_{\dot{z}}} = 48.23\ \mathrm{cm}^3$
Resin volume fraction	$u_{\dot{z}} = \frac{V_{\dot{z}}}{V_k} = 0.33$
Carbon fibers volume fraction	$u_w = 1 - u_{\dot{z}} = 0.67$
Carbon fibers density	$\rho_w = \frac{m_w}{u_w \times V_k} = 1.48\ \frac{\mathrm{g}}{\mathrm{cm}^3}$
Young’s modulus (theoretical) of the plate	$E_{k\ theoretical} = \frac{(E_w \times u_w)}{2} + (E_{\dot{z}} \times u_{\dot{z}}) = 78.21$ GPa

Composite No. 2

The second tested type of composite was a commercial carbon-epoxy composite with a multi-layer reinforcement structure. It consisted of 5 layers shown in Figure 3. The outer layers were in the form of carbon fiber fabrics, and the inner ones - roving, i.e. bundles of continuous, untwisted fibers.

a)



b)

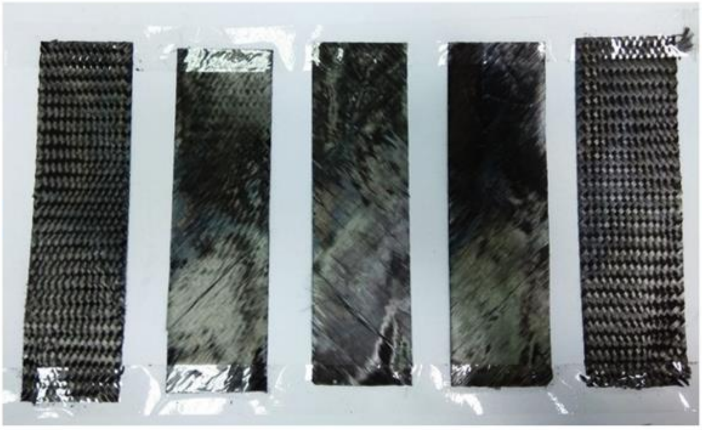


Fig. 3. Individual layers of reinforcement of a composite material with a multi-layer reinforcement structure oriented (a) in parallel (b) at an angle of 45°

Specimens with the dimensions listed in Table 2 were cut out of the composites to carry out a static tensile test using the Hung Ta HT-2402 universal testing machine. The aim of the study was to determine the tensile strength of composite materials (breaking stresses), as well as to determine the actual values of the modulus of elasticity.

Composite No. 3

The third object of research was a composite produced in an autoclave in the Silesian Science and Technology Center of the Aviation Industry Sp. z o.o. based on carbon prepreg GG 204T g/m^2 IMP 503 ZHT, 7.3 mm thick, consisting of 25 layers arranged according to the scheme $[0°]_{25}$. The board was produced at a pressure of 400 kPa and a temperature of 120 °C. For the study of Young's modulus 17 mm wide specimens were cut out of the composite.

Dimensions of specimens for strength tests prepared from the above-mentioned composites are shown in Table 2.

Table 2. Dimensions of specimens prepared for strength tests

Dimension	Width	Thickness
Composite No. 1	25.0 mm	2.5 mm
Composite No. 2	40.0 mm	2.0 mm
Composite No. 3	17.0 mm	7.3 mm

The 3542-025M-025-HT2 (Epsilon) extensometer with a measuring base of 25 mm was used to determine the modulus of elasticity. For better fastening of specimens with a thickness of 2 and 2.5 mm in the handles of the machine, folding handles were laminated to their ends made of 3 layers of glass fabric.

Additional specimens of 60 x 250 mm were cut out of the composite board with a thickness of 7.3 mm using the Water Jet method. The composite specimens were subjected to four-point bending (Fig. 4) on the Zwick Roell Z100 testing machine in order to determine the bending loads and failure stresses.

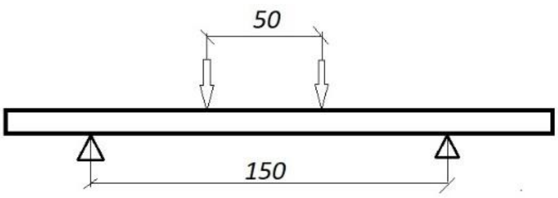


Fig. 4. Scheme of four-point bending

As part of the experiment, the tensile and compressive strength of this composite were also determined. Modulus of elasticity was determined during compression in the x_3 direction (perpendicular to the surface of the material).

In order to test the tensile strength in the x_3 direction, square elements of the composite with dimensions of 16 x 16 mm were bonded into the sockets of steel cylindrical specimens with adhesive DP 420 (Fig. 5). After the joints had hardened, the specimens were axisymmetrically stretched to determine the joint destructive force.

Fig. 5. View of the specimen after testing the strength of the composite in the x_3 direction

To test the modulus and compressive strength in the x_3 direction, 7 cubes of 27 x 27 mm with holes of 10.1 mm in diameter were bonded together (Fig. 6). A specimen with a height of 52 mm was obtained, which was loaded with a force of up to 250,000 N, recording the dependence of the displacement of the machine traverse as a function of force. In addition, the stiffness characteristics of the Instron 8802 testing machine were determined by compressing its plates without a specimen, which allowed to calculate the value of the modulus of elasticity in x_3 direction. Then, the specimen was loaded in a machine with a larger measuring range - the ZDM100000 tensile machine, leading to its destruction.

The impact strength tests of composite No. 3 were carried out on specimens with a square cross-section of 7.3 x 7.3 mm and a length of 60 mm (Fig. 7). The specimens were cut out in the direction of the fibers and at an angle of 45°. The tests were carried out on the impact hammer SW-5 with the speed of 3.8 m/s and the energy of 50 J in the plane of laying the composite layers and in the plane of the cross--section of the composite.

Fig. 6. Cube cut out of 7.3 mm thick composite

Fig. 7. Specimens for impact tests a) in the plane of laying composite layers b) in the cross-sectional plane of the composite

3. Research results

The use of an extensometer made it possible to determine the values of the modulus of longitudinal elasticity of the tested composites. Young's modulus of composites was determined taking into account two basic load variants of composite specimens: variant A - load applied parallel to the direction of the reinforcement fibers and variant B - load applied at an angle of 45° to the reinforcement (specimens cut at an angle).

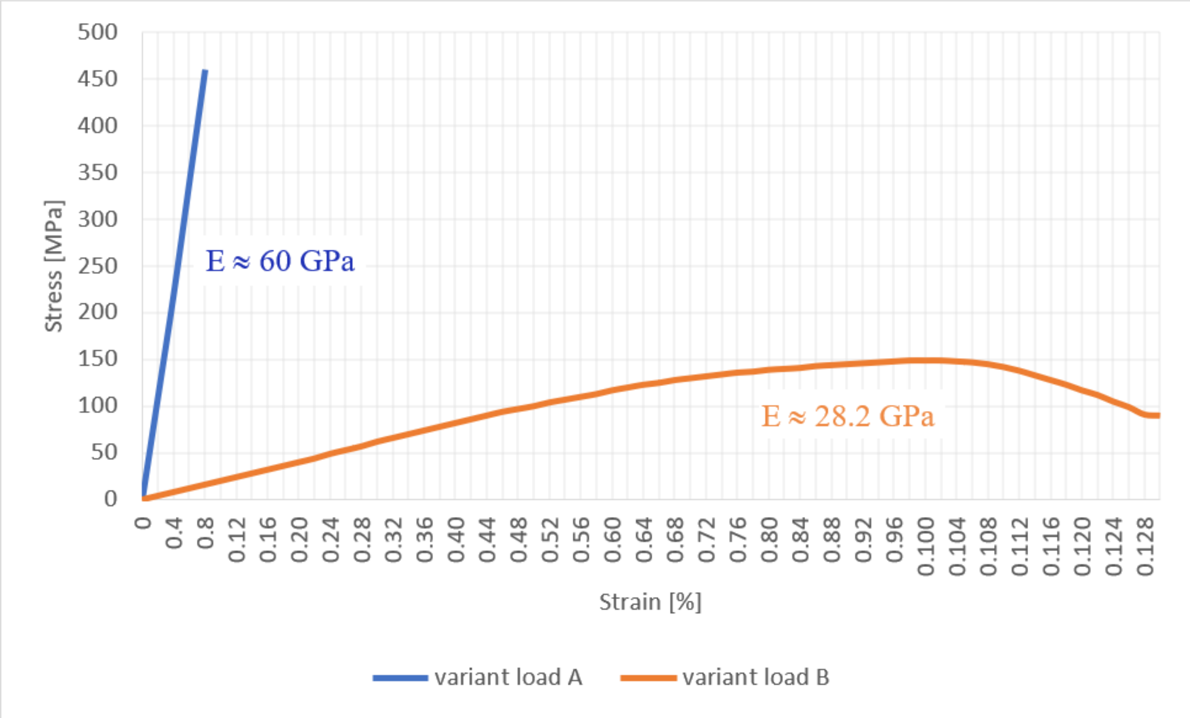


Fig. 8. Curves σ = σ(ε) of composite No. 1

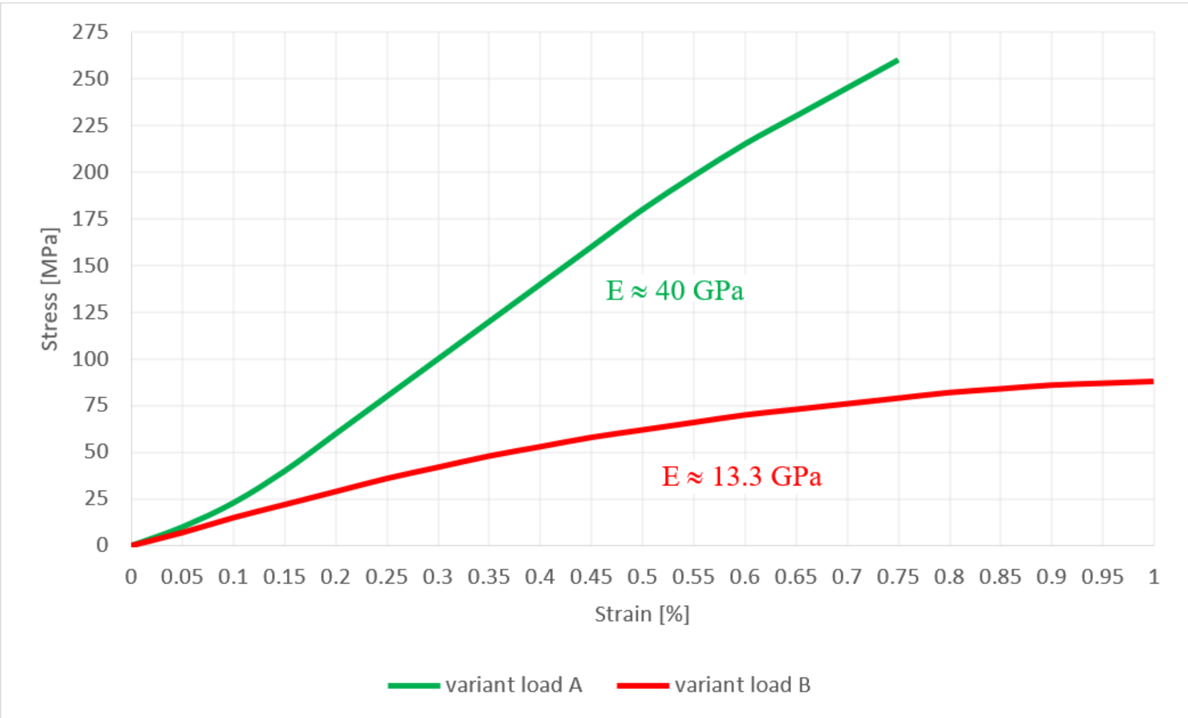


Fig. 9. Curves σ = σ(ε) of composite No. 2

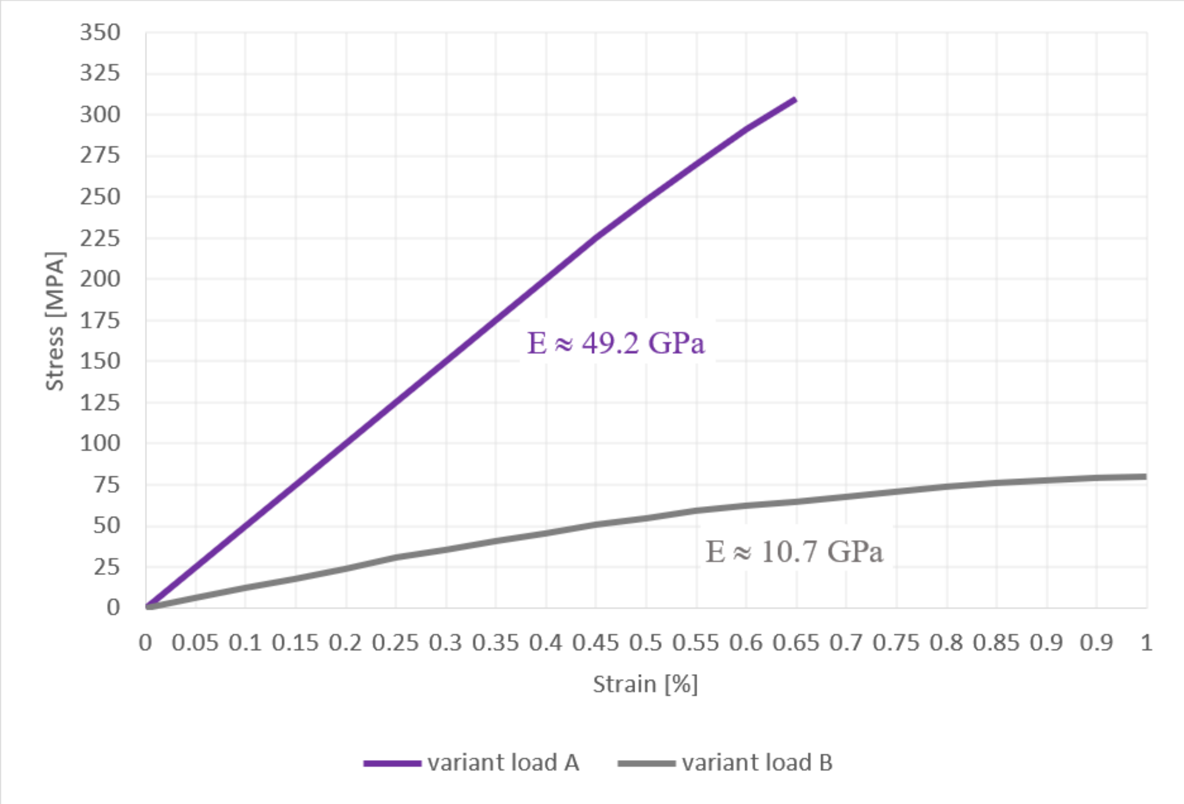


Fig. 10. Curves σ = σ(ε) of composite No. 3

The tensile strength significantly depends on the direction of the load. For loads directed at an angle of 45° (variant B) in relation to the fiber arrangement, the strength is at least twice as low as the strength of the material loaded along the fibers (variant A).

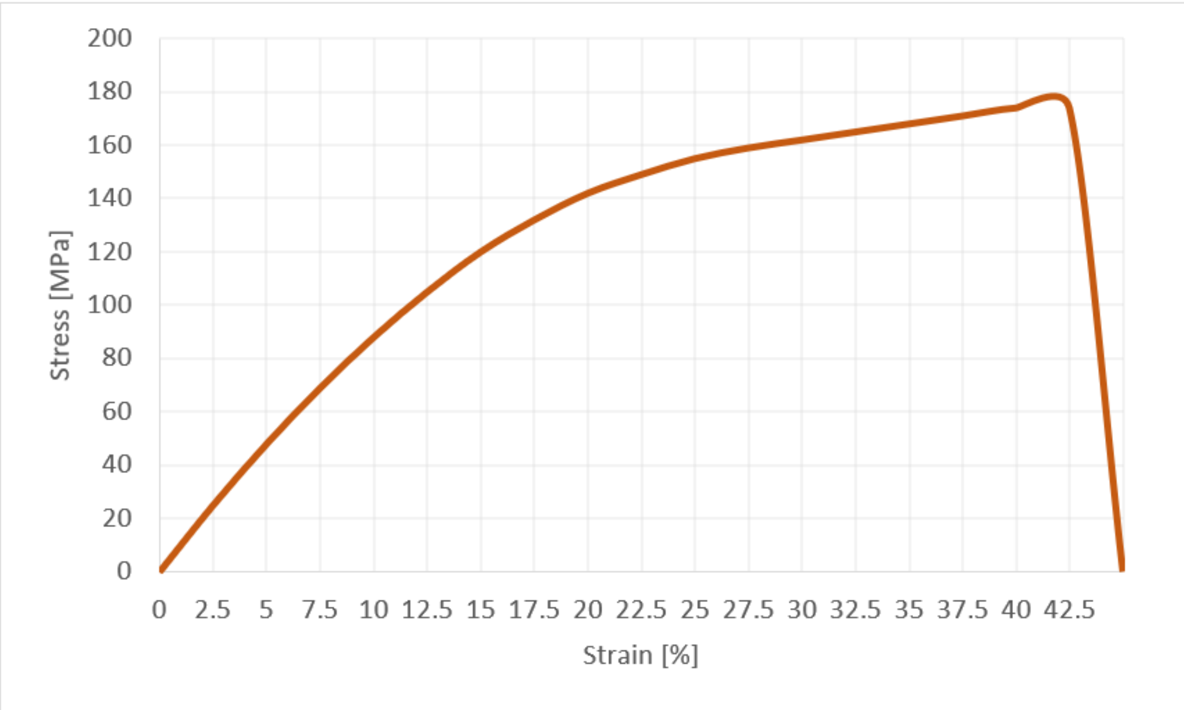


Fig. 11. Curve σ = σ(ε) of composite No. 3 in the load variant B in the entire range of deformations (without using an extensometer)

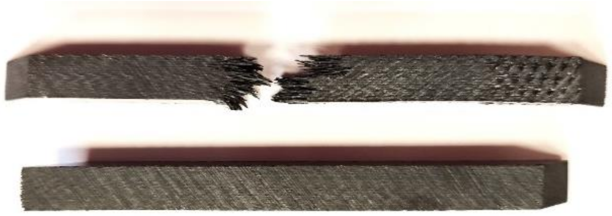


Fig. 12. Destruction of composite No. 3 in variant B

The strength of composites No. 1 and 2 is presented in table 3.

Table 3. Tensile strength of composites loaded in different directions

Load variant	Strength [MPa]	
	Composite No. 1	**Composite No. 2**
A	766.80	344.45
B	148.00	160.51

The result of three measurements of four-point bending of specimens from composite No. 3 is the average value of the destructive force, which was 14.133 kN, which corresponds to the maximum positive and negative normal stresses in the bending specimen of 663 MPa.

$$\sigma = \frac{M_g}{W} = \frac{7166.5 \times 50 \times 6}{60 \times 7.3^2} = 663 \text{ MPa} \tag{1}$$

On the basis of axial-symmetric tensile tests of 5 specimens, the tensile strength of the composite in the direction perpendicular to the arrangement of fabric layers was determined to be 24.04 ± 3.85 MPa. This is the stress level corresponding to the tensile strength of epoxy matrixes.

Based on the obtained two compression curves (specimen compression and machine stiffness characteristics), the value of Young's modulus of the tested orthotropic composite was calculated in the x_3 direction, which is 6240 MPa. Using the ZDM100000 testing machine with a larger measuring range, the value of breaking stress equal to about 340 MPa was determined. The destruction consisted in crushing one element of the specimen (Fig. 13).

Fig. 13. The form of destruction of a compressed specimen element

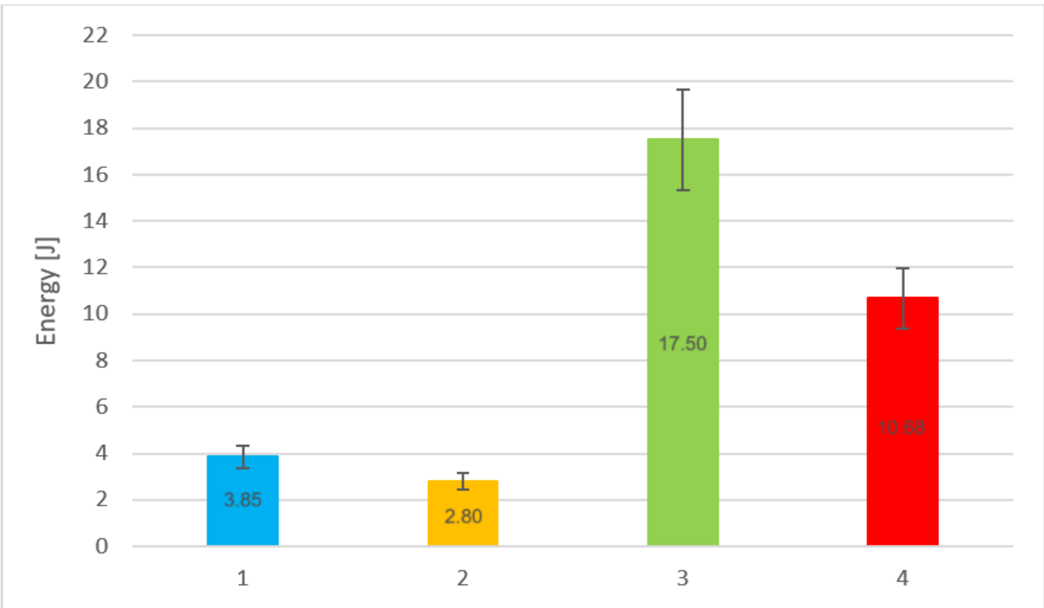


Fig. 14. Values of the energy of destruction of composite no. 3 during the impact test:
1. Load variant A perpendicular to the composite surface, 2. Load variant A perpendicular to the composite cross-section,
3. Load variant B perpendicular to the composite surface, 4. Load variant B perpendicular to the cross section of the composite

Impact tests using the SW-5 impact hammer of composite No. 3 tested in both load variants consisted in hitting both into the surface of the composite as well as into the cross-sectional area. The obtained values of the destruction energy are presented in the diagram in Figure 14.

4. Analysis of the results and discussion

Table 4 summarizes the mechanical properties of the tested composites. The obtained values of the modulus of elasticity and strength correspond by an order of magnitude to the values for carbon fiber-reinforced composites presented by other authors [18].

Table 4. Mechanical properties of the tested composites

Load variant	Composite	Strength [MPa]	Young's modulus [GPa]
A	No. 1	766.8	60.0
B		148.0	28.2
A	No. 2	344.5	40.0
B		160.5	13.3
A	No. 3	663.0	49.2
B		178.5	10.7

The difference between the calculated theoretical value of Young's modulus of composite No. 1 comes from the fact that the analytical calculations assumed that the fibers are perfectly parallel to the load. The experimentally obtained tensile diagrams $\sigma=\sigma(\varepsilon)$ in the direction of fiber orientation show that the stiffness of the composite increases slightly with increasing load. (Fig. 9), which may indicate fiber straightening.

The initial stiffness of the composites in variant B is several times lower than the stiffness in load variant A and clearly decreases with the increase of strain. Researchers in other publications also point out differences in the strength of orthotropic composites depending on the orientation of carbon fibers as a source of possible problems [5].

The failure of the loaded composite in variant A is rapid and cracking occurs in a plane perpendicular to the load. The failure of composites loaded in variant B is characterized by large deformations resulting from the slippage of fibers arranged at an angle of 45°. Therefore, the assessment of the strength of the composites in variant B is less accurate.

The highest strength and stiffness of the wet-produced composite No. 1 resulted from high curing pressures (greater than those obtained in autoclaves), the use of which allowed to obtain a large volume fraction of fibers (about 67%). Research shows that the volume fraction of carbon fibers in the range of 60-70% provides the most optimal mechanical properties [19].

The tests showed that the tensile strength of the composite in the x_3 direction (the direction of laying successive layers of the laminate) is even lower than the tensile strength of epoxy resins. This proves poor cohesion of the epoxy matrix used and poor adhesion to carbon fibers. The lack of reinforcement fibers makes this direction most susceptible to rheological phenomena [14]. The elastic modulus in the x_3 direction is 6.24 GPa, which is consistent with literature data [18].

Exceptionally large differences in the values of the destruction energy of composite No. 3 occur when it is loaded dynamically in different directions. The specimens showed more than four times higher impact strength in load variant B. The maximum impact strength was about 328 kJ/m^2, which is a relatively high value. Exemplary results of other tests of a twelve-layer CFRP composite show a Charpy impact strength slightly above 200 kJ/m^2 [20]. It follows that the impact strength of composites depends significantly on the direction of fiber arrangement in relation to the direction of the impact load.

5. Conclusions

- Large differences in mechanical properties (strength, Young's modulus) of orthotropic composites depending on the load direction make their use in repairs of metal (isotropic) airframe structures unjustified.
- In the case of composite structures, their use would be justified if it concerned fabricated elements made of orthotropic composites, for which the direction of the reinforcement is known. Quasi-isotropic composites seem to be more suitable for repairing metal structures, which can be obtained by rotating successive layers of fabrics against each other.
- The calculation of the Young's modulus of composite materials based on the knowledge of the volume fraction of their components is subject to a large inaccuracy. It results from the fact that the modules of carbon fibers used in fabrics can vary significantly and from the fact that the fibers in fabrics are not perfectly regular.
- Orthotropic composites have the lowest strength properties (tensile strength, Young's modulus) in the x_3 direction (perpendicular to the fabric laying surface). The determined tensile strength in this direction (interlayer strength) is lower than that of typical epoxy resins.
- The highest impact strength is shown by orthotropic composites loaded dynamically in the

variant B. This useful feature of the composite material could be used in the production of collision protection parts, e.g. bumpers.

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Original Research

PROBLEMS OF FORECASTING THE LENGTH OF THE ASSEMBLY CYCLE OF COMPLEX PRODUCTS REALIZED IN THE MTO (MAKE-TO-ORDER) MODEL

PROBLEMATYKA PROGNOZOWANIA DŁUGOŚCI CYKLU MONTAŻU WYROBÓW ZŁOŻONYCH REALIZOWANYCH W MODELU MTO (MAKE-TO-ORDER)

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Abstract

This article presents the problem of forecasting the length of machine assembly cycles in make-to-order production (Make-to-Order). The model of Make-to-Order production and the technological process of manufacturing the finished product are presented. The possibility of developing a novel method, using artificial intelligence solutions, to estimate machine assembly times based on historical company data on manufacturing times for structurally similar components, is described. It is assumed that the result of the developed method will be an intelligent system supporting efficient and accurate estimation of machine assembly time, ready for implementation in production conditions. Such data as part availability, human resource availability and novelty factor will be used as input data for learning the neural network, while the output variable during learning the neural network will be the actual machine assembly time.

Keywords: assembly cycle, machine assembly, forecasting, Make-to-Order, artificial neural networks, input signals, output signals, MatLab

Streszczenie

W niniejszym artykule przedstawiono problem prognozowania długości cyklu montażu maszyn w produkcji na zamówienie (Make-to-Order). Przedstawiony został model produkcji na zamówienie oraz proces technologiczny wytwarzania wyrobu gotowego. Opisana została możliwość opracowania nowatorskiej metody, wykorzystującej rozwiązania z zakresu sztucznej inteligencji, umożliwiającej szacowanie czasu montażu maszyn w oparciu o dane historyczne przedsiębiorstw, dotyczące czasów wytwarzania podobnych konstrukcyjnie elementów. Zakłada się, iż rezultatem opracowanej metody będzie inteligentny system wspomagający skuteczne i dokładne szacowanie czasu montażu maszyn, gotowy do implementacji w warunkach produkcyjnych. Jako dane wejściowe do uczenia sieci neuronowej wykorzystane zostaną takie dane jak: dostępność części, dostępność zasobów ludzkich oraz czynnik nowości, zaś zmienną wyjściową podczas uczenia sieci neuronowej będzie rzeczywisty czas montażu maszyny.

Słowa kluczowe: cykl montażu, montaż maszyn, prognozowanie, produkcja na zamówienie (Make-to-Order), sztuczne sieci neuronowe, sygnały wejściowe, sygnały wyjściowe, MatLab

1. Introduction

One of the key stages in the manufacturing process of customized products is the assembly cycle. An accurate analysis of the assembly time of a particular product that a customer wants to order affects the actual completion of the order within the agreed time, and consequently the shipment of the finished product within the time specified in the contract. Nevertheless, determining this time in a traditional way is in many cases impossible, which prompts the search for methods using the latest scientific and technological advances.

For complex problems that require multi-criteria analysis of large amounts of data, analytical and optimization methods give way to heuristic methods. Although they can be considered more accurate, the time-consuming nature of obtaining results can disqualify them in many situations such as the preliminary design of complex systems or acting in the face of an unexpected crisis. Combining heuristic methods with artificial intelligence in the areas of technological processes and machine assembly can increase the productivity and competitiveness of manufacturing companies [1].

The researchers discussed various aspects of the assembly system. Schedin et al. [2] discusses assembly system design, while Gorski et al. [3] deals with mass customization. The assembly-oriented method of process and assembly equipment included product and process analysis, identification of change drivers and responsibilities, assembly system modeling, technical design of modules, composition and design of the overall assembly system. According to Müller et al. [4], operational tasks in assembly can be divided into manipulation (including: feeding, transporting, blocking), joining (including: pressing, welding, bolting, etc.), commissioning (including: adjusting, setting parameters, function testing), auxiliary processes (including: storing, changing quantities, checking, etc.), and special operations (including: cleaning, reworking, packaging, etc.).

Mital et al. [5] present different assembly methods: manual assembly, automatic assembly (stationary), hard automation, and robotic assembly (soft automation). The estimation of manual assembly time was discussed by Chan et al. [6], who obtained assembly times using the MODAPTS predefined time system. Liu et al. [7] propose an assembly process modeling mechanism based on product hierarchy, and an assembly-by-dismantling approach is used to build an assembly process model.

Unfortunately, the number of publications in the field of assembly time prediction and estimation is very limited. Some attempt to estimate assembly time from data of a complex product was presented by Eigner, Roubanov and Sindermann [8]. An interesting proposal to support assembly time prediction using Markov model and hybrid developments was proposed by Gellert et al. [9]. More recently, an attempt to use artificial neural networks for assembly operation time prediction was presented by Rueckert, Birgy and Tracht [10]. Unfortunately, none of these solutions is not a comprehensive method for predicting the assembly time of complex products realized in nested production.

The research problem that has arisen is that it is not possible to predict machine assembly times at the quotation stage, i.e. at a stage where detailed assembly technology has not yet been developed. The aim of this study is to present the concept of an intelligent system for the prediction of cycle time for the assembly of complex products using artificial neural networks. In particular, the main input and output factors for the prediction of the assembly process duration will be identified and analysed.

The process of forecasting the assembly of complex products implemented in the MTO model is an area of constant improvement and search for new solutions. Modern science focuses on technological and organizational issues of the manufacturing process, leaving somewhat the area of industrial assembly technology in the background. This area of industry is characterized by a high dependence on the human factor, as it focuses its attention on human labor in conditions that are not digitally controlled and do not require advanced machinery and tools [11].

2. Make-to-Order Production

The purpose of custom manufacturing is to fulfill a production order within a specified period of time. The process based on the MTO model begins when an order is received from a customer for a specific product. Only after the order is received is the raw materials needed to fulfill the order ordered (or their reservation if they are in stock) ordered [12]. Production planning, purchase of materials or scheduling of production tasks in the short term take place on the basis of orders received. Since production is "triggered by orders," these systems are also known as pull systems [13]. Long-term planning is done on the basis of projections of sales plans. Custom manufacturing strategy characterized by long delivery times, low storage costs and a large variety of finished goods. For material demand planning, most often ERP-class information systems are used which can additionally serve as a source of data for analysis and decision-making related to production control [14], [15].

This production strategy is found in unit production and small batch production. A typical finished product is non-standard in nature and unique. The product can be individually designed to the customer's needs, configurable from available variants, or assembled from finished blanks only after the order is received. The production order is triggered at the start of the design process or at the start of assembly according to customer specifications. The main advantage of MTO is the ability to fulfill an order with the exact product specifications required by the customer.

The industries where MTO's manufacturing strategy is most commonly found are machinery, construction, IT or exclusive product manufacturing [16].

In the literature you can find a division of MTO strategies into several subcategories and varieties [17-21]:

- assembly to order (ATO) - involves using off-the-shelf (previously manufactured or purchased) semi-finished products and assembling them into the final finished product ordered by the customer. The assemble-to-order (ATO) strategy is appropriate for those situations where fast response is highly valued.
- configure to order (CTO) - is a special case of the ATO strategy. Individual semi-finished products are divided into subsets, and the customer selects items from these subsets. For example, a computer is configured by selecting a processor from several options, a monitor from several options, etc. The difference between a CTO system and an ATO system is important at the level of inducing demand,
- finish to order (FTO) - involves producing a not-quite-finished product (semi-finished), e.g., pre-extrusion of aluminum profiles - and then finishing (e.g., heat treatment, painting) the finished product according to the customer's order,
- engineering-to-order (ETO) design - involves designing and manufacturing the finished product according to customer specifications. When ordering a finished product, the customer also orders the process of designing that product to meet his individual needs.

For a comprehensive overview of custom manufacturing strategy knowledge and related issues, see the items [22-23].

3. Assembly of complex products

One of the main steps in the manufacturing process is assembly, which is a key stage in the production of customized products, where products are assembled according to customer needs. Time standards are among the of the most important indicators of the efficiency of the manufacturing process. Knowing the exact assembly time of a machine greatly increases the probability of completing all stages of production within the set time, and consequently, shipping the finished product on the date agreed with the customer. Nevertheless, the determination of this time by traditional methods is, in many cases, impossible, which urges the search for techniques using the latest scientific and technical achievements and technology.

The production process for the MTO model, from approved order to shipment of the finished product is labor-intensive and complicated (fig. 1). The process from receiving specifications to shipping the finished product is time-consuming. The received specifications are sent to the design departments, where the machine is designed and the material list is prepared. The bill of materials goes to the production preparation department, where it is imported into the system and then the process of ordering parts in the procurement department begins. The entire assembly process takes approximately two months. After this time, the process of testing and starting the machine as well as quality control begins. After positive receipt of the machine, a shipping specification is prepared and the process of packing the machine and shipping it to the customer begins.

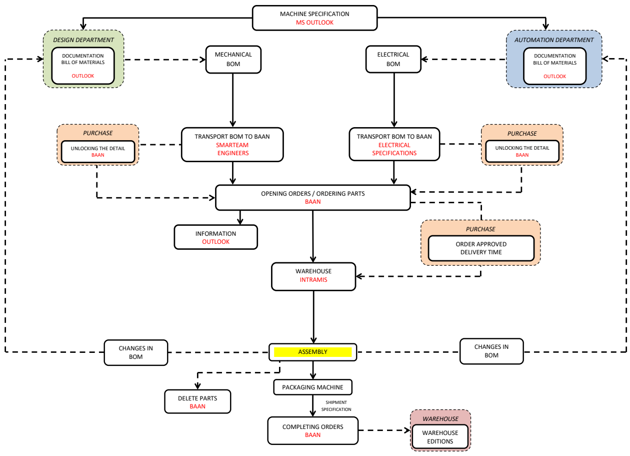

Fig. 1. Diagram of the production process in the MTO model

The assembly process of machine is shown in figure 2. The production process of the company from which the data is taken is carried out in production nests. The assembly of the machine begins with the frame, on which mechanical components, pneumatics, and the electrical board and cabinet are assembled one by one using an overhead crane and a forklift. At the final stage, covers are installed.

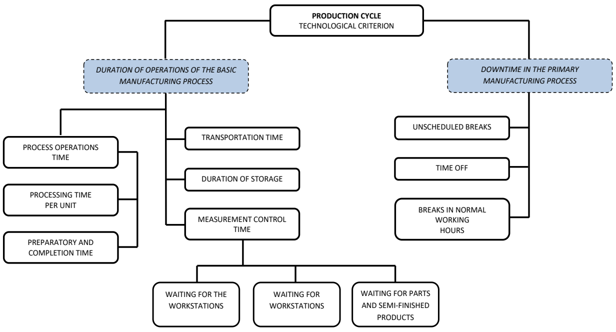

Fig. 2. Assembly manufacturing process

Table 1 shows the list of assembly components along with the with assembly times using one type of machine as an example. The process of building a machine can be divided into stages: construction of the frame, assembly of the components and assembly of the components into the previously prepared frame.

Table 1. List of assembly components with their assembly times

No.	Component name	Assembly and adjustment time (h)
1	Preparation time for machine components and subassemblies	24
2	Cleaning and threading of frame parts after painting	8
3	Installation of electrical trays	8
4	Assembling the machine frame	6
5	Arming the doors of electrical cabinets	4
6	Full tray conveyor	20
7	Empty tray conveyor	20
8	Unit for transporting and stacking full trays	8
9	Transport of trays and products	8
10	Alignment unit	4
11	Linear unit with full and empty tray	10
12	Cleaning unit	8
13	Tipping module for empty feeders	3
14	Installation and disassembly of the pneumatic system	14
15	Adjusting the machine after startup	12
16	Initial and final assembly of covers	26
17	Corrections due to independent errors	16

Preparation time for machine components and subassemblies before and during assembly includes:

- transporting the machine components + normals from the warehouse and receiving them,
- distribution of the machine elements on racks to facilitate their identification (subdivision into subassemblies),
- transport of components to and from the paint shop.

4. Factors affecting the assembly time estimation process

According to data from the assembly department of one of the unit/small batch manufacturing companies in the machinery industry, the key elements affecting the assembly cycle are human resources, part availability, bench availability, tool availability and the novelty factor (fig. 3). A complete database containing the above information was compiled from various databases and reports (ERP system, Power BI).

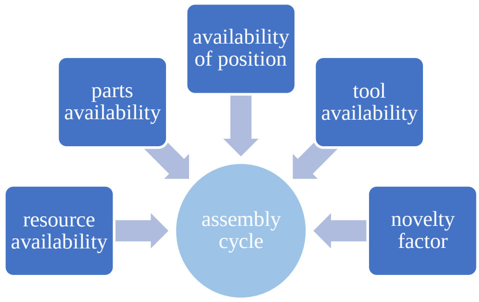

Fig. 3. Graphical interpretation of factors affecting machine assembly time

4.1. Availability of components of complex products

The biggest influence on the time of the entire assembly is the availability of parts to start the planned process at a specific moment. This fact is of great importance, since the lack of components (parts) increases the time of the entire process, and also introduces unnecessary chaos in production.

With part availability of less than 100%, it is difficult to plan the work so that the entire finished goods process is efficient. If this factor is not met, the start of assembly will be delayed, or if we start assembly there will be downtime during assembly due to waiting for parts, and we must take this into account as well. The delays are usually a few days, but this affects the entire production flow. One can then try to make up for those few days by shifting to a different stage of production or starting production with oversized working hours, but this also brings additional costs to the company. That's why 100% availability of parts to start machine assembly is such an important element.

Part availability data (input) determines the product assembly time (output). The parts availability factor can be estimated by comparing the dates of planned to actual delivery of parts: the planned start of assembly and the date, confirmed by suppliers, of actual delivery of parts to the warehouse.

4.2. Resource availability

The availability of human resources in production load planning often assumes a factor of seasonality of work, holiday periods and random events or sick leave. Employees are also selected for a particular production order because of their qualifications. The appropriate selection of an employee increases labor productivity and thus reduces product assembly time. Unfortunately, unplanned employee absenteeism (resulting, among other things, from sick leave or so-called "on-demand" leaves) is a difficult to predict factor that has a significant impact on the process. Consequently, there is always a difference between the normative and actual effective working time of an employee, which is difficult to predict at the stage of estimating the production cycle [24].

The resource availability factor can be determined from the planned and actual budget used by employees for the machine for a specific task and operation according to the recommended assembly technology (tab. 2).

Table 2. Hourly budget of employees

Task	Description	Budgeted	Total	Consumption
623	Mechanical Assembly	350	314,91	
624	Electrical Assembly	260	200,1	
625	Tooling	8	0	
628	Packing & Loading	16	0	
669	Other Activities	8	31,48	

Depending on the composition of the brigade and the sophistication of the workers, the assembly time may be shorter or get longer (in the case of new workers, for example, the time may increase).

4.3. Availability of an assembly station with appropriate instrumentation

Some assembly stations are equipped with tools/equipment that are designed only for a specific type of product and can only be assembled at these stations. This is also an impediment to predicting the assembly time of products, as the waiting time for a given workstation to be freed up for a particular type of product may be prolonged - which consequently causes postponement of the assembly process of subsequent products.

Disorganization of production as a result of lack of free space on the shop floor is a difficult planning situation, since it is impossible to start assembling a product using any substitute solutions. It is also a hindrance in forecasting the time of product assembly, as the waiting time for the release of a given workstation for a particular type of product can be prolonged, which causes a delay in the completion of the process of assembling subsequent products. An important element in the entire assembly process is the release of the assembly station at the right time, so that the assembly of the next product can begin at the right moment and there are no delays in further stages of the process.

Each production hall has its own limited space, and in small batch production, where specific assembly stations are designated, dedicated to specific products, it is very important to complete the assembly of a machine in a timely manner, so that the assembly of the next machine can begin at the planned time.

4.4. Availability of tools and assembly tooling

A factor that determines the efficiency of the execution of the assembly process is the availability of tools and assembly tooling dedicated to the execution of specific technological operations. In many cases, the number of tools and tooling used to manufacture specific products is less than the number of assembly stations and/or the number of products of a given type being assembled simultaneously. Consequently, situations may occur in which the lack of specific tools or tooling may prevent the timely execution (and thus delay) of the assembly process.

4.5. Novelty factor

By the factor of novelty we can define changes in the construction of the machine, which lengthen, but also shorten in some cases, the assembly time. Changing the components of a machine at the construction stage can significantly hinder its subsequent assembly due to the new assembly technology, or shorten the assembly time when, for example, the components for assembly come from the supplier already in an assembled subassembly.

The novelty factor was divided into two items:

1. New items - are calculated from the comparison of details (items) new from the material list to the quantity of all items from the material list. New items in the system are marked with a special code, which makes it easy to verify the number of new details entering the system for a given machine.
2. Changed items - are calculated by the number of items that have been changed from the initial revision (A) to the final and final revision (B) of the material list to the number of all items in the material list.

These changes are recorded in the system and downloaded as an A/B revision comparison report (tab. 3).

Table 3. Comparison of A/B revisions from the bill of materials

Engineering Item 1	: RM0930000-M-0081				Engineering Item 2	: RM0930000-M-0081			
Revision	: A				Revision	: B			
Status	: Approved by Production				Status	: Approved by Production			
Component	**Pos.**	**Type**	**Quantity**	**Unit**	**Component**	**Pos.**	**Type**	**Quantity**	**Unit**
28-198132	16	E-Item	1,0000	pcs	28-199676	19	E-Item	1,0000	pcs

In table 4, we can see what items were added and/or removed from the first revision of the bill of materials from the final version.

Table 4. Value of A/B revision - items changed

REVISION	ITEMS DELETED „-”	ADDED ITEMS „+”
A/B	**2**	**6**
B/C	**0**	**1**
C/D	**0**	**2**
FINAL A/D	**2**	**9**

As can be seen from table 4, the sum of details changed: deleted and added is 11 items. Two items were removed from the initial list - revision A, and nine details were added to the material list - revision B. This amount is compared to the amount of all items in the material list, and then we get the percentage of novelty factor - items changed.

5. Input data for modeling the assembly time estimation process

Based on simulation studies, input signals that have a direct impact on the estimation of assembly time were selected for testing the network (fig. 4).

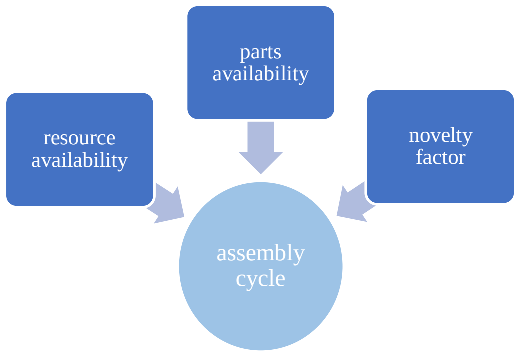

Fig. 4. Graphical interpretation of factors directly influencing machine assembly time

Figure 5 shows sample results from one type of machine, showing the variation of part availability, resource availability and novelty factor. The machine assembly time will depend on these results. The larger the deviations, the more difficult it is to verify the estimated machine assembly time. Therefore, using neural networks, we can create a model that will give us information at the output about the estimated assembly cycle of a given machine type [25].

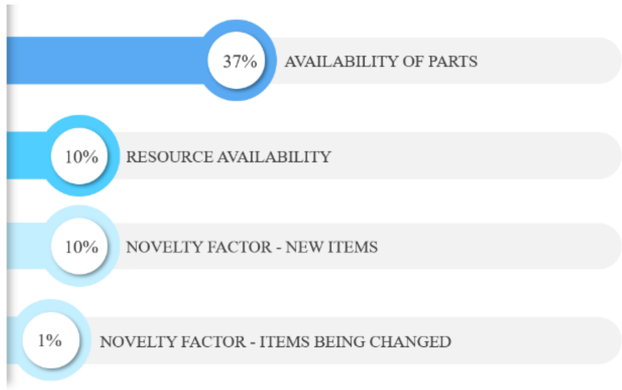

Fig. 5. Deviations of the factors of the example machine

6. Output elements of the modelled process

The purpose of neural network modeling is to predict the course of a nonlinear technological process using trained neural networks. Its analysis can contribute to the creation of an enterprise decision support system [26]. With the help of neural networks, we want to be able to estimate the assembly time of a machine so that the deadlines confirmed to the customer are met and the response to a new request goes to the customer in the fastest possible time.

The Neural Network library (fig. 6) in the MatLab computing environment can be used to model the process. At the stage of learning the neural network, it is necessary to indicate the chosen learning algorithm (Levenberg-Marquardt algorithm, Bayesian regularization or scalable coupled gradients algorithm), the number of hidden layers in the modeled network and the number of neurons in each hidden layer. In addition, the analyzed data set should be divided into learning, test and validation. Most often, they are determined in proportions of 70%:15%:15%. The selection of the best model is made on the basis of an analysis of the quality measures of the obtained networks - the mean square error (MSE) and the correlation coefficient (R). MSE is calculated according to formula (1):

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(y_i' - y_i^*)^2 \qquad (1)$$

where:
n - the number of cases analyzed, $y'i$ - the actual value of the assembly time for the i-th case, $y*i$ - the predictive value of the assembly time for the i-th case obtained as a result of the network.

The correlation coefficient (R) is calculated according to formula (2):

$$R(y', y^*) = \frac{cov(y', y^*)}{\sigma_{y'}\sigma_{y^*}} \quad R\epsilon < 0{,}1 > \qquad (2)$$

where:
cov(y′,y∗) - covariance between the variables y′ and y∗, *σy′* - standard deviation of the actual assembly time values, *σy** - standard deviation of the predictive assembly time values.

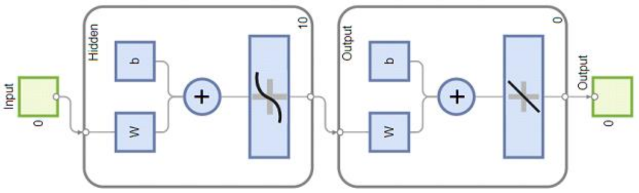

Fig. 6. The network model in the Neural Network library in MATLAB

Once a good quality network is obtained, the next step is to generate the model into the Simulink computing environment (fig. 7), so that the machine assembly time can be predicted. After inputting the following data into the model: availability of parts, human resources, availability of the assembly station and availability of tools after running the model, the output will receive the estimated machine assembly time.

The result of the model in the form of the estimated machine assembly time will then be able to go to the customer in response to their inquiry in a short period of time.

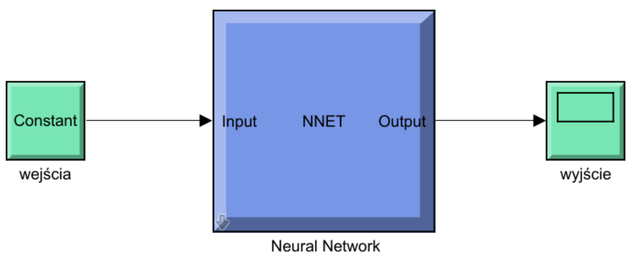

Fig. 7. Model in the Simulink computing environment

7. Summary and conclusions

An artificial neural network can be successfully used to determine and estimation of time in the assembly process. The development of a model using SSN can be based on the following steps: developing training sets and test sets and finding the best SSN structure. Preliminary results conducted on simulation data made it possible to determine what input factors should be considered for the model. The assembly process was analyzed and the features (attributes) that affect the time norm were selected.

By inputting into the model, the inputs of part availability, human resource availability and novelty factor after running the model, a predicted/estimated machine assembly time will be generated at the output of the model. The developed method will be able to be used in enterprises as an intelligent system to support efficient and accurate estimation of the assembly time of machines not yet ordered (tendered).

This will allow to increase the accuracy of enterprises' work, claims in meeting given production completion dates, and will increase competitiveness in the market. The system will be ready for implementation in production conditions for small batch and unit production. Knowing the exact assembly time of the machine significantly increases the probability of completing all stages of production within the set time, and consequently, shipping the finished product within the time agreed with the customer.

The next stages of work will be based on building and testing the model in the MatLab environment. Neural networks will be tested in various variants. The best model will be selected based on the analysis of quality measures of the obtained networks: mean square error and correlation coefficient. After selecting the highest quality neural network from all analyzed networks, a model will be generated in the Simulink computing environment that can be used to predict machine assembly times.

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Original Research

ANALYSIS OF THE STRENGTH OF ASSEMBLY JOINTS – WELDED JOINTS OF VARIOUS CONSTRUCTION MATERIALS

ANALIZA WYTRZYMAŁOŚCI POŁĄCZEŃ MONTAŻOWYCH – POŁĄCZEŃ SPAWANYCH RÓŻNYCH MATERIAŁÓW KONSTRUKCYJNYCH

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Abstract
The aim of the article was to present issues related to the strength analysis of one of the types of assembly joints - welded joints, taking into account the influence of selected factors: technological - welding method, construction - type of joints and material - type of joined material. The following welding methods were used (in accordance with the PN-EN ISO 4063 standard): arc welding in the shield of inert/active gases MIG/MAG (131/135), manual metal arc welding with a coated electrode MMA (111) and gas welding (oxyacetylene welding) (311).Butt joints and lap joints were made of CuZn37 copper alloy (PN-EN 1652), S235JR unalloyed structural steel (EN 10025) and 1.4301 acid-resistant steel (EN 10088). Welded joints samples were made with appropriate parameters, according to the welding methods. Strength tests of welded joints on MTS BIONIX 370.02 testing machine, in accordance with the PN-EN 1465 standard were provided. Based on the obtained test results, it can be seen that the value of stresses is affected by both the welding method and the type of joint structure, while the type of material to be welded should also be taken into account.

Keywords: welded joint, welding method, strength

Streszczenie
Celem artykułu było przedstawienie zagadnień związanych z analizą wytrzymałościową jednych z rodzajów połączeń montażowych – połączeń spawanych z uwzględnieniem wpływu wybranych czynników: technologicznych – metody spawania, konstrukcyjnych – rodzaju połączenia oraz materiałowych – rodzaju łączonego materiału. Zastosowano następujące metody spawania (zgodnie z normą PN-EN ISO 4063): spawanie łukowe elektrodą metalową w osłonie gazów obojętnych/aktywnych MIG/MAG (131/1355), spawanie łukowe elektrodą otuloną MMA (111) oraz spawanie gazowe acetylenowo-tlenowe (311). Wykonano połączenia doczołowe i zakładkowe stopu miedzi CuZn37 (PN-EN 1652) oraz stal niestopowa konstrukcyjna S235JR (EN 10025) oraz stal kwasoodporna 1.4301 (EN 10088). Próbki spawane wykonano przy odpowiednich parametrach, stosownie do metody spawania. Badania wytrzymałościowe połączeń spawanych przeprowadzono na maszynie wytrzymałościowej MTS BIONIX 370.02, zgodnie z normą PN-EN 1465. Na podstawie uzyskanych wyników badań można zauważyć, że na wartość naprężeń ma wpływ zarówno metoda spawania, jak i rodzaj konstrukcji połączenia, przy czym należy uwzględnić także rodzaj spawanego materiału.

Słowa kluczowe: połączenie spawane, metoda spawania, wytrzymałość

1. Introduction

Joining is one of the most common technological processes in the engineering industry. In the technology of the assembly process in almost all industries, the type of assembly joints plays a very important role (Ferenc, 2007; Mistur & Czuchryj, 2005; Siwek, 2002). Technological progress makes it possible to combine materials with different properties, which is why various assembly joints are used in the assembly process, both permanent and temporary. The permanent joints include joining materials by welding, soldering and bonding (Ferenc, 2007; Mistur & Czuchryj, 2005; Siwek, 2002). These processes differ in the state of aggregation of the base materials and the binder at the point of joints, the type of bonds formed between the joined material and the binder, and the type of thermal and/or mechanical energy provided to create the joint (Ferenc, 2007; Łabanowski, 2018; Siwek, 2002). Moreover, depending on the type of joints, they are characterized by specific features specific to the joining method and geometric features of the joints (Łabanowski, 2018). They often enable the creation of a joint of dissimilar materials (Ciechacki & Szykowny, 2011; Łabanowski, 2005).

One of the methods of making assembly joints that has been widely used is welding (Ferenc, 2007; Łabanowski, 2018; Mistur & Czuchryj, 2005; Siwek, 2002), and over the years the technology of making this type of joints has developed significantly along with the development of techniques and devices (Bucior et al., 2017; Frydrych et al., 2011; Kozak, 2012; Nur, 2010). The accuracy and strength of welded joints are influenced by many factors: technological, structural and material (Bucior et al., 2017; Frydrych et al., 2011; Łabanowski, 2005; Rudawska & Sosnowski, 2013; Rudawska et al., 2017). In order to improve the quality of the joints made, both welding methods and their parameters are subject to continuous research, also in the aspect of making welded joints in various environments (Frydrych, 2012; Frydrych et al., 2013).

The work focused on determining the stresses of welded joints of three types of construction materials: copper alloy sheets, unalloyed structural steel and acid-resistant steel (material factor) in two structural configurations: lap joints and butt joints (construction factor). These joints were made using three welding methods, i.e. MIG/MAG welding, manual metal arc welding and gas welding (technological factor). The comparative criterion was the failure force of the welded joints.

2. Materials and methods

2.1. Materials

Three types of materials used for structural elements of mining equipment were used in the tests: CuZn37 copper alloy (PN-EN 1652), S235JR unalloyed structural steel (EN 10027) and 1.4301 acid-resistant steel (EN 10088). Materials were used to make the welded joints, provided by one of the company dealing with the repair of industrial structures, using the welding methods presented in the work. Selected properties of the listed materials are listed in Table 1.

Table 1. Mechanical properties of welded materials

Properties	Type of material		
	CuZn37[1]	S235JR[2]	1.4301[3]
Minimum yield strength R_e, MPa	$R_{p0,2}$ 180	Re 235	Re 205
Tensile strength R_m, MPa	300-370	360-510	515-700
Minimum elongation A_{min}, %	48	18	45

[1] https://emetal.eu/mosiadz/mosiadz-ISO
[2] PN-EN 10027-1: 2007: Systemy oznaczania stali - Część 1: Znaki stali.
[3] https://stalespecjalne.com.pl

CuZn37 brass is the most popular two-component alloy susceptible to plastic processing. S235JR steel can be welded without restrictions, without subsequent heat treatment and without preheating (https://tenslab.pl). S235JR steel is not susceptible to cold cracking, regardless of thickness and information on cold cracking of selected steel grades is described in the works (Kozak, 2012; (Frydrych, 2012; Frydrych et al., 2013). 1.4301 acid-resistant steel is very well weldable. The welding process should be followed by solution annealing if the carbon content remains at the upper level (https://stalespecjalne.com.pl).

2.2. Geometric characteristics of welded joints

For the analysis, lap and butt welded joints of the three materials mentioned in point 2.1 were made. The diagram and dimensions of the joints are shown below in Fig. 1 and Fig. 2 and in Table 2.

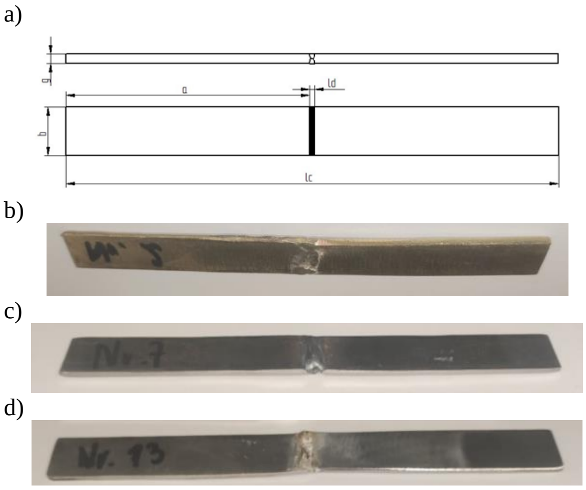

Fig. 1. Welded joints: a) diagram of butt welded joint used in the tests, b) made of copper alloy, c) made of unalloyed structural steel, d) made of acid-resistant steel

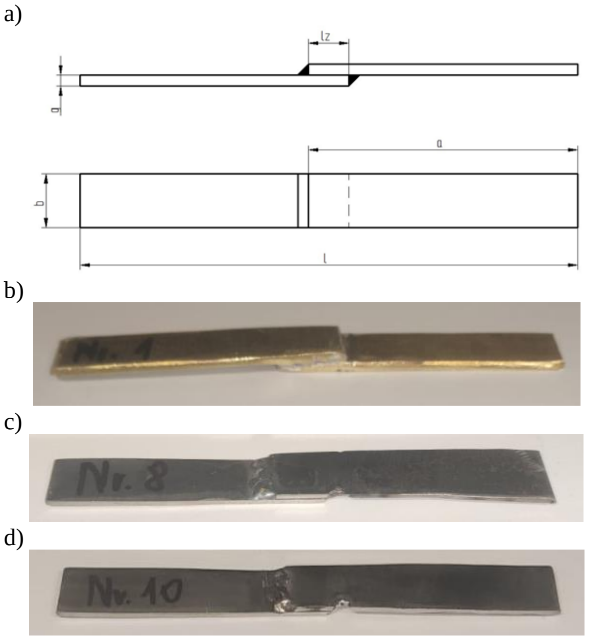

Fig. 2. Welded joints: a) diagram of the lap welded joint with double weld used in the tests, b) made of copper alloy, c) made of unalloyed structural steel, d) made of acid-resistant steel

Table 2. Mechanical properties of welded materials

Dimension designation	**a [mm]**	**b [mm]**	**g [mm]**	**l_c [mm]**	**l_d [mm]**
Joint type	butt welded joint				
Dimension	80	20	2	162	2
Dimension designation	**a [mm]**	**b [mm]**	**g [mm]**	**l [mm]**	**l_z [mm]**
Joint type	lap welded joint				
Dimension	80	20	2	140	20

2.3. Methods of preparing welded joints

Three methods were used to make the welded joints: the MIG/MAG method (131/135), MMA arc welding (111) and gas welding (311) (PN-EN ISO 4063). The welded joints samples were made manually by a welder with industrial experience and appropriate qualifications in the company's department dealing with the repair of industrial structures made of the materials presented in the work, using available equipment (Table 3).

When making welded joints, the following parameters of the welding process were used, listed in Table 3.

Table 3. Parameters of welding

<table>
<tr><th rowspan="3">Materials</th><th colspan="3">Method of welding/welding parameters</th></tr>
<tr><td>MIG/MAG welding</td><td>Manual Metal Arc welding (MMA)</td><td>Gas welding</td></tr>
<tr><td>131/135</td><td>111</td><td>311</td></tr>
<tr><td>1.4301
S235JR</td><td rowspan="2">- Migomat STEL MAX 503 IP54 ATX
- gas: Ar 82%, CO_2 18%
- wire: SG2, φ 1,2 mm
- gas flow: 10 l/min
- current intensity:150 A</td><td>- Migomat STEL MAX 503 IP54 ATX
- Electrode BASEWELD 50E-7018, φ 2 mm x 350 mm (low-hydrogen covered electrode)
- welding load voltage: 18 V</td><td rowspan="2">- oxyacetylene blowpipe
- gas: technical oxygen, technical acetylene</td></tr>
<tr><td>CuZn37</td><td>-</td></tr>
</table>

2.4. Tests

Three methods were used to make the welded joints: the MIG/MAG method (131/135), MMA arc welding (111) and gas welding (311) (PN-EN ISO 4063). The welded joints samples were made manually by a welder with industrial experience and appropriate qualifications in the company's department dealing with the repair of industrial structures made of the materials presented in the work, using available equipment (Table 3).

The welded joints were subjected to strength tests, in which the failure force of the welded joints was determined. Strength tests of welded joints on MTS BIONIX 370.02 testing machine, in accordance with the PN-EN 1465 standard were provided. Strength tests were carried out at a temperature of 23±1°C and air humidity of 34±1%. The tests were carried out until the welded joint sample cracked and the values of maximum stresses were given.

Strength tests were carried out on 5 joints made by the welding methods mentioned in point 2.3 for three materials. In the case of S235JR unalloyed structural steel and acid-resistant steel 1.4301, 3 series of 5 welded joints were made, a total of 15 welded joints for each type of material, and in the case of CuZn37 copper alloy, 2 series of welded joints, 5 joints each (the total of welded joints was 10).

3. Results

3.1. Strength test results

The results of strength tests of butt welded joints are shown in Fig. 3 and of lap welded joints in Fig. 4.

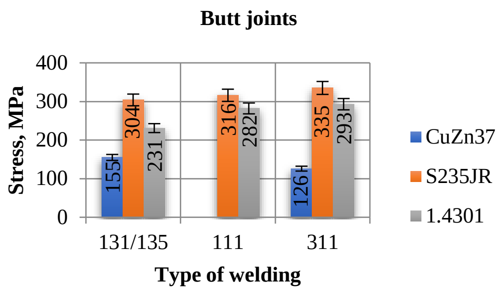

Fig. 3. Stress of butt welded joints

Based on the results summarized in Fig. 3, it can be seen that the highest stresses occurred in the case of butt welded joints of S235JR unalloyed structural steel, and this applies to each of the three welding methods used. The smallest stresses were shown by butt welded joints of CuZn37 copper alloy, with lower values obtained after using the gas welding method (126 MPa) than using the MIG/MAG welding method (155 MPa) by about 19%.

The difference in the stress value of butt welded joints of unalloyed structural steel (S235JR) and acid-resistant steel (1.4301) for individual joining methods is: method 135/136 - 24%, method 111 - 21% and the method 311 - 23%

Considering the welding method, both in the case of butt welded joints of unalloyed structural steel and acid-resistant steel, the highest stress values were obtained using the gas welding method (311).

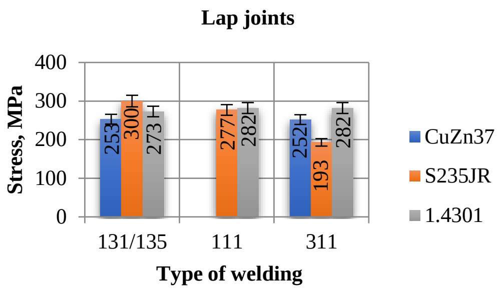

Fig. 4. Stress of lap welded joints

Based on the summarized results (Fig. 4), it can be seen that:

- in the case of lap welded joints of the copper alloy, no differences in stress values were observed (method 131/135 - 253 MPa and method 311 - 252 MPa),
- a similar relationship was observed in the case of acid-resistant steel for the 111 and 311 welding methods (282 MPa), while a lower stress value of welded joints was obtained after using the MIG/MAG method - 273 MPa, and this difference is insignificant and amounts to only about 3%,
- in the case of welded joints of unalloyed structural steel (S235JR), the highest stresses were obtained in the case of using the MIG/MAG welding method (300 MPa), while the lowest - for joints made using the gas method (193 MPa), the difference between these values is 36%.

3.2. Basic descriptive statistics

A basic descriptive statistics was presented in Table 4 and Table 5 and the tables were performed on the results from the strength test. Basic statistics is the basis for further analyzes and inferences.

Table 3. Parameters of descriptive statistics of butt welded joints stress [MPa]

Type of material	**Basic descriptive statistics**									
	No. of tests	Mean	Median	Mode	Mode size	Range	Variance	Standard deviation	Skewness	Kurtosis
	Welding method									
MIGMAG welding method (131/135)										
CuZn37	5	155	155	multiple	1	4	2.50	1.58	0.00	-1.20
S235JR	5	304	304	multiple	1	4	2.50	1.58	0.00	-1.20
1.4301	5	231	231	231	2	3	1.30	1.14	0.40	-0.18
MMA method (311)										
S235JR	5	316	316	317	2	4	2.80	1.67	-1.09	0.53
1.4301	5	282	282	283	2	3	1.70	1.30	-0.54	-1.49
gas welding method (311)										
CuZn37	5	126	125	125	2	4	2.30	1.52	1.12	1.46
S235JR	5	335	335	336	2	4	2.80	1.67	-1.09	0.54
1.4301	5	293	293	multiple	2	3	1.50	1.22	-1.36	2.00

Table 4. Parameters of descriptive statistics of lap welded joints stress [MPa]

Type of material	Basic descriptive statistics									
	No. of tests	Mean	Median	Mode	Mode size	Range	Variance	Standard deviation	Skewness	Kurtosis
	Welding method									
MIGMAG welding method (131/135)										
CuZn37	5	252	253	multiple	1	5	4.30	2.07	-0.24	-1.96
S235JR	5	300	300	302	2	4	3.20	1.79	-0.05	-2.32
1.4301	5	273	273	multiple	1	5	3.70	1.92	0.59	-0.02
MMA method (111)										
S235JR	5	277	277	277	2	3	1.30	1.14	0.40	-0.18
1.4301	5	282	282	283	2	3	1.70	1.30	-0.54	-1.49
gas welding method (311)										
CuZn37	5	252	252	multiple	2	3	1.50	1.22	-1.36	2.00
S235JR	5	193	193	multiple	1	5	4.30	2.07	-0.24	-1.96
1.4301	5	282	282	283	2	4,	2.80	1.67	-1.09	0.54

Comparing the type of material and type of construction of welded joints, the correlation coefficient r (X,Y) for the MIG/MAG method was +0.99, which means that regardless of the type of construction of the joint, a similar dependence of stress values was observed depending on the type of joined material. Higher stress values obtained for butt welded joints correspond to higher stress values of lap welded joints, regardless of the type of material. In the case of welded joints made by the MMA method (111), the Pearson correlation coefficient r was -1, which means that the higher strength of butt welded joints is accompanied by the lower strength of lap joints. However, when considering gas welded joints (311), the correlation coefficient was - 0.37, which means a rather weak relationship between the type of joints and the type of welded material.

3.3. Discussion of the results

Based on the results presented in Fig. 3 and Fig. 4, it was noticed that:

- considering the MIG/MAG method (131/135): (i) comparable stress values were obtained for butt joints and lap joints of unalloyed structural steel, which means that in the case of this steel, the type of joint structure will not affect the obtained stress values, (ii) in both structural cases of welded joints of both copper alloy and acid-resistant steel, differences in stress values depending on the type of joint were observed, with higher stress values obtained for lap joints,
- analyzing the MMA method (111): (i) in the case of welded joints made of acid-resistant steel, there are no differences in the stress values of butt joints and lap joints, (ii) considering the stress values of welded joints of unalloyed structural steel, the stress values were higher for butt joints by about 12% than for lap joints.
- considering the gas welding method (311): (i) in the case of copper alloy welded joints, significant differences in stress values obtained by butt joints (123 MPa) and lap joints (252 MPa) are observed, and this difference is 50%, (ii) welded joints of unalloyed structural steel are also characterized by significant differences in stress values depending on the structure, with a higher stress value for butt joints (335 MPa) than lap joints (193 MPa), and this difference is 42%,
- among all welded joints, the highest stress value was obtained for joints of unalloyed structural steel welded using the MIG/MAG method (335 MPa), and this value exceeded the minimum yield strength Re (235 MPa) and approached the lower limit of tensile strength, i.e. 360 MPa (Table 1), which means that after exceeding the yield point, a significant increase in plastic deformation occurs in the stretched material,
- in the case of butt welded copper alloy joints, the stress value (155 MPa – MIG/MAG method and 125 MPa – gas welding method) did not exceed the minimum yield strength, i.e. 180 MPa, while this value was exceeded in the case of lap joints, regardless of welding methods.

In the work (Rudawska et al., 2017) results of strength tests of butt and lap welded joints (with single and double welds) of S235JR steel made with the use of arc welding with a coated electrode. Based on the obtained results, it was noticed that the highest strength was obtained for butt welded joints. On the other hand, the highest transferred force and the highest value of elongation were achieved by lap welded joints with a double weld. In this article, too, greater strength is obtained for butt welded joints than for lap joints.

In addition to the indication in this work that the type of construction of joints and the type of welded material as well as the welding method affect the strength parameters of welded joints, other factors should also be taken into account when making welded joints. In the work (Bucior et al., 2017) it was indicated that an important element is also the surface treatment (especially of thin sheets) for the welding process.

4. Conclusions

Based on the obtained test results, it can be seen that the value of stresses and deformations is affected by both the welding method and the type of joint structure, while the type of material to be welded should also be taken into account. The literature confirmed that weldability is a material, technological and design feature at the same time.

- For copper alloy welded joints, the type of joint construction type is more important than the welding method, and lap joints are preferred for this material.
- In the case of welded joints of unalloyed structural steel, higher stress values were obtained for butt welded joints, regardless of the welding method.
- Considering the welded joints of acid-resistant steel, in most variants of both corruption and welding methods, similar values were obtained, only in the case of butt welded joints made using the MIG/MAG method, the stress value is noticeably lower than the others and amounts to 231 MPa.

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Original Research

USE OF AUGMENTED REALITY FOR SMALL PARTS ASSISTED ASSEMBLY

WYKORZYSTANIE RZECZYWISTOŚCI ROZSZERZONEJ DO WSPOMAGANIA MONTAŻU MAŁYCH CZĘŚCI

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Abstract

The use of augmented reality (AR) for assisted assembly of small parts remains a current and dynamically developing issue in industry and the technology sector. Because AR technologies and related applications are constantly advancing, it is necessary to pay sufficient attention to this topic. This article provides a simplified view of software application design and architecture. We are focusing on a 45mm x 45mm x 42mm component consisting of 42 parts. In the article, we gradually show how to properly create an application with a main, and working environment in which we can create animations from a database of 3D models. In the end, we performed a product assembly test with and without the use of the AR application, for one piece and a production batch. In conclusion, we can state that the applications have an impact on the training of the workforce and the ways through which new workers are prepared to work in an industrial environment. Improved education and training programs based on AR can help integrate new workers into production processes faster and more efficiently. Considering these perspectives and the dynamics of the AR technologies development, our article raises awareness of current trends and innovations in this field, as it can have a significant impact on the efficiency and competitiveness of various industries.

Keywords: AR application, assisted assembly, Unity, architecture of application

Streszczenie

Wykorzystanie rzeczywistości rozszerzonej (AR) do wspomaganego montażu małych części pozostaje aktualnym i dynamicznie rozwijającym się zagadnieniem w przemyśle i sektorze technologicznym. Ponieważ technologie AR i związane z nimi zastosowania stale się rozwijają, należy poświęcić temu zagadnieniu odpowiednią uwagę. W tym artykule przedstawiono uproszczony pogląd na projektowanie i architekturę aplikacji. Skupiamy się na komponencie o wymiarach 45 mm x 45 mm x 42 mm składającym się z 42 części. W artykule stopniowo pokazujemy jak poprawnie stworzyć aplikację zawierającą środowisko główne oraz środowisko pracy w którym możemy tworzyć animacje z bazy modeli 3D. Na koniec wykonaliśmy test montażu produktu z aplikacją AR i bez niej, dla jednej sztuki i partii produkcyjnej. Podsumowując, można stwierdzić, że aplikacje mają wpływ na szkolenie siły roboczej i sposoby przygotowania nowych pracowników do pracy w środowisku przemysłowym. Ulepszone programy edukacyjne i szkoleniowe oparte na AR mogą pomóc w szybszej i skuteczniejszej integracji nowych pracowników z procesami produkcyjnymi. Mając na uwadze te perspektywy oraz dynamikę rozwoju technologii AR, nasz artykuł podnosi świadomość aktualnych trendów i innowacji w tej dziedzinie, gdyż może to mieć istotny wpływ na efektywność i konkurencyjność różnych branż.

Słowa kluczowe: Aplikacja AR, montaż wspomagany, Unity, architektura aplikacji)

1. Introduction

Augmented reality (AR) represents an innovative approach that affects many industries, with one area with great potential being the production and assembly of small parts. Assembly of these small components is often a difficult task that requires high precision and expertise of the operators. However, with the AR technology development, new possibilities are opening up to improve this process. This article will focus on the use of augmented reality for the assisted assembly of small parts and explore how AR can increase the efficiency, accuracy and quality of production in this specific industry Kaščak (2019).

Currently, 11.5 million people in the U.S. work in assembly departments, representing 8.8% of the workforce, and this number continues to grow. Global assembly is projected to face a shortfall of 7.9 million workers by 2030, resulting in an unrealized economic impact of $607.1 billion if current initiatives do not change. Brazil is projected to need 1.7 million assembly workers by 2030, while Indonesia could face a labor shortage of 1.6 million. The United States is already struggling with a shortage of high-skilled manufacturing workers, and this shortage is expected to increase significantly over the next decade, reaching 383,000 by 2030, the equivalent of more than 10% of the high-skilled workforce. As a result, of the effort to eliminate the shortage of qualified personnel, the manufacturing industry, which has traditionally developed rather slowly, is rapidly moving to integrate AR technologies. Global AR/VR spending will reach $160 billion by 2023, up significantly from $16.8 billion in 2019, and AR/VR spending could grow at a cumulative annual growth in spending of 78.3% over the five years. Commercial uses of these technologies, which are expected to see the largest investment in 2023, include training ($8.5 billion) and maintenance ($4.3 billion) Pettyjohn (2023). With the increasing number of businesses adopting AR/VR technologies for various use cases, the AR/VR market is expected to grow. These technologies will play a key role in expanding human resources. Current advances in hardware and software—initiatives and efforts by tech giants such as Google (ARCore), Apple (ARKit 3), and Microsoft (HoloLens)—will open up more opportunities and push AR/VR toward widespread adoption. Hardware will account for more than half of all AR/VR spending. Spending on system integration services will grow at the highest rate (94.8% annually), overtaking consulting services and application development, while software costs will grow by 70% annually. Strong growth in spending on AR hardware, software and services (135.5% per year) will lead to a significant overshoot in total AR spending by the end of 2023. The rise of AR/VR use in enterprises will be a direct result of the increase in production volume as companies implement new technologies to increase productivity, safety and achieve high accuracy. Interest in AR continues to grow exponentially. Now it's also powered by artificial intelligence, which allows cameras to "understand" the world and overlay digital content on top of it. Combined with ever more powerful and lighter devices, the coming years will be crucial for augmented reality development Poetker (2019).

1.1. AR and assisted assembly

The use of Augmented Reality (AR) for small parts assisted assembly is a promising and innovative field that has the potential to fundamentally impact various industries, especially manufacturing and service. With AR technologies development the door opens for new ways to increase the efficiency, accuracy and quality of the small components assembly Radianty (2020).

One of the significant ways how AR positively impacted assembly is providing assembly guidance for production and service operators in real-time. With the help of AR glasses or mobile applications, operators can get interactive 3D models, animations, instructions and procedures right at their workplace. In this way, the need for traditional written instructions is minimized and operators are able to assemble parts more accurately and efficiently Antosz (2019).

In addition, AR enables visual inspection of product quality during assembly. Operators can use AR to display the optimal image of the product and compare it with the real product to detect possible errors or flaws in the assembly. In this way, product quality increases, and the risk of errors is minimized Gatial (2023).

Interactive assembly tools and virtual assembly of parts are other important aspects of the use of AR in small parts assembly. Operators can create a virtual environment where they can store and examine individual components before actual assembly. This makes it possible to detect potential problems or conflicts between components before assembly begins.

In addition to these direct benefits of AR, this technology also offers effective solutions for the education and training of new assembly workers. Simulated assembly training in an augmented reality environment reduces the time needed to acquire skills and experience, thus contributing to a faster and more efficient introduction of new workers into production Heinzel (2017).

AR also has the potential to recognize and track parts throughout the manufacturing process, improving inventory monitoring and optimizing processes. Improved communication between operators and technical support or other manufacturing departments is another benefit that AR brings through the ability to share insight and information in real time.

All in all, the use of augmented reality in the small parts assembly promises to revolutionize the industrial environment. With the help of this technology, it is possible to increase the efficiency of assembly, improve products quality, save costs for training workers, and increase communication within the production processes, thereby contributing to competitiveness and innovation in industries Kaščak (2022).

1.2. Literature review

The papers collectively suggest that augmented reality (AR) can be used to assist in the assembly of small parts Okamoto Jr. (2016) proposes an AR system that recognizes parts and guides users through the assembly process using virtual graphic signs. Dupláková (2021) describes the use of AR in the assembly process to speed up and facilitate assembly while preventing errors. Ojer (2020) presents a projection-based AR system for assisting operators during electronic component assembly processes. Ceruti (2017) proposes an innovative methodology using virtual and augmented reality to support assembly, including the development of a knowledge-based system and the production of a virtual user manual. These papers collectively demonstrate the potential of AR for assisted small parts assembly.

This article focuses on an augmented reality application for assisted assembly that allows technicians and assembly workers to streamline their work and minimize assembly errors. It uses augmented reality to display 3D models and other visual information directly on physical objects in real time. In this way, the technician can visualize how the device or part of it should look after assembly and what are the optimal steps that should be taken during assembly Milgram (1995).

The application may also contain step-by-step instructions and other assembly information. In this way, technicians and assemblers gain confidence in the assembly and can assemble faster and more efficiently, reducing the cost and time required to carry out the assembly. The application thus helps to increase productivity and improve assembly quality Luo (2018).

2. Methodology

As can be seen from the analysis so far, the main goal is to focus on a specific product consisting of a number of small parts. For our purposes, we chose a cam switch. It consists of 42 parts, of which 23 parts are different assembled in a 45mm x 45mm x 42mm cube. Currently, the cam switch assembly is carried out manually during the entire process in production, based on the technological procedure indicated in paper form.

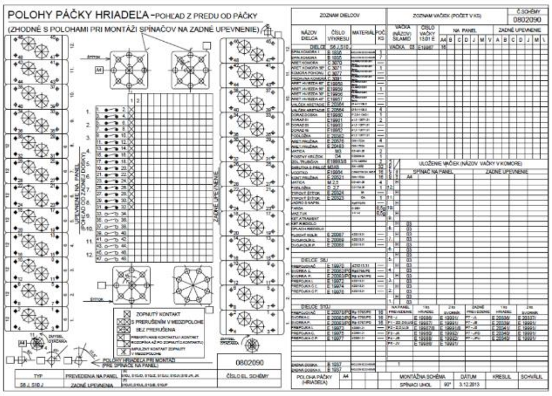

Fig. 1. Production drawing with technical specification

The picture below shows the final product and the switch in its disassembled state.

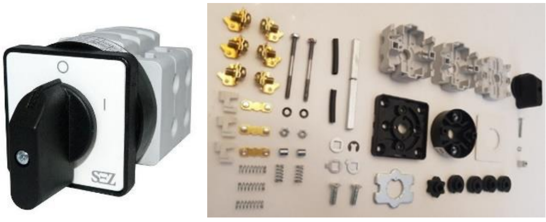

Fig. 2. Cam switch

The total assembly consists of 5 steps:

1. Description
2. Manual assembly
3. Testing
4. Visual inspection
5. Packaging

The total assembly process of 1 piece of cam switch takes 3 minutes 50 seconds, and 20% of the total time is assumed for the permitted deviation. According to the assigned order, the employee will receive a manual in which the adjustment of the lever positions for the main shaft, for a specific type.

Fig. 3. Current assembly workplace

As can be seen from Fig. 3, the manual assembly workplace consists of a work table, boxes with components, preparations for assembly and a technical manual (Fig. 1). The basic production procedure does not change, but the designs change due to the switch closing requirement and according to the type Kovbasiuk (2023).

2.1. AR application creating process

The first thing to do when creating an application is to build a CAD model of the assembled part, consisting of all components. For the application requirements, we created a model in Autodesk Inventor and then saved each component as a separate model in *.obj format. We used 26 models to create the database and animations.

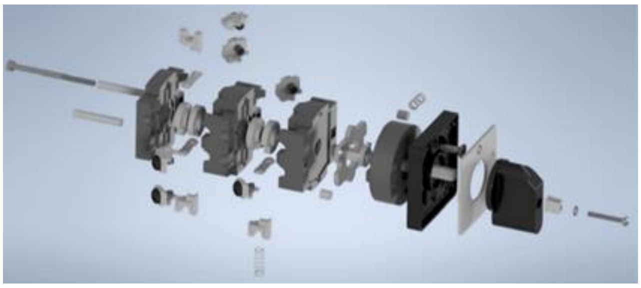

Fig. 4. 3D cam switch model

These 3D models need to be imported into the Unity development tool in which the AR application will be created. At the beginning, we need to create a basic manual of how the application will look. What will be its structure, what will it contain, how many layers will it consist of and what online/offline interactions should it offer. We can say that we will create a simplified architecture of the assembly application.

The architecture of an augmented reality (AR) application depends on many factors, including the purpose of the application, the target platform, and the type of device that will be used to display the AR content. In general, an AR application should include these basic elements:

- Sensors and devices: An AR application should use sensors and devices to capture input data, such as cameras, motion sensors, and ambient sensors.
- Data processing: The data captured by the sensors should be processed and analyzed to find out where the user is, where he is looking and what he is doing.
- Visualization: The AR application should be able to display AR content on the device display so that it appears as part of the real environment. This process involves combining AR content with surrounding objects and adjusting perspective, lighting and other factors.
- Interaction: The user should be able to interact with the AR content, for example by hand movement or voice command. The application should be able to record these interactions and adapt to them.
- Synchronization: The application should be able to synchronize AR content with other devices and applications within the network to share experiences among users.

Considering the complexity of these requirements, it is advisable to have a high-quality architecture in the AR application, which will enable simple and effective data processing, visualization, and interaction with them. It is also important to choose the right platform and device that will be used to display AR content and ensure their optimal functioning.

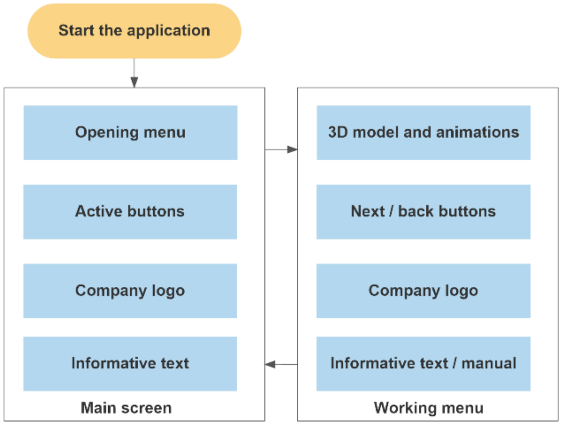

Fig. 5. AR application architecture

The presented AR application was created in the Slovak language modification, as it was solved based on the specific requirements of the company. As a first step in the Unity environment, we will define the appearance of the initial main menu in which we will set the main links. We achieve this by creating user buttons through the User Interface, where we define the button's shape and their interaction. The click is felt when in contact with the display surface or in the ARCamera interface.

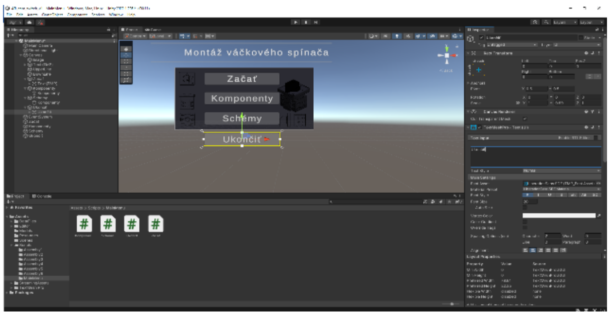

Fig. 6. Main Menu in Unity software

After defining the buttons area, the creation of User Interface links with the help of scripts to the main scenes takes place.

Script to run the application.

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using UnityEngine.SceneManagement;

public class Zacat : MonoBehaviour
{
    public void StartGame()
    {
        SceneManager.LoadScene("Assembly1");
    }
}
```

After clicking on the selected button, a script will run that will connect us to the scene of the first assembly process (Fig.7). First, we will set up the display of the working menu of the application. This consists of informational text for the individual actions of the "Ďalej", "Späť", "Home Icon" and "Refresh Icon" buttons. In addition to the main camera during assembly operations, it is also necessary to create an ARcamera interface. With this setting, we chose the technical drawing of the cam switch as the basic working marker. The marker is imported into the Vuforia Developer portal database and interacts with the application being created via a unique license key. Markers can be changed according to the library of created models.

Fig. 7. Work Menu in Unity software

To create an animation of the first assembly operation from inserting 2 screws into the locking chamber, open the Animator Controler and define the assembly process operation: moving the screw along the Z coordinate to the green area.

After performing the operation, we will use the "Ďalej" button, which will start the script and link to the "Assembly2" scene - Assembly operation 2. It will place the arresting chamber on the rear attachment.

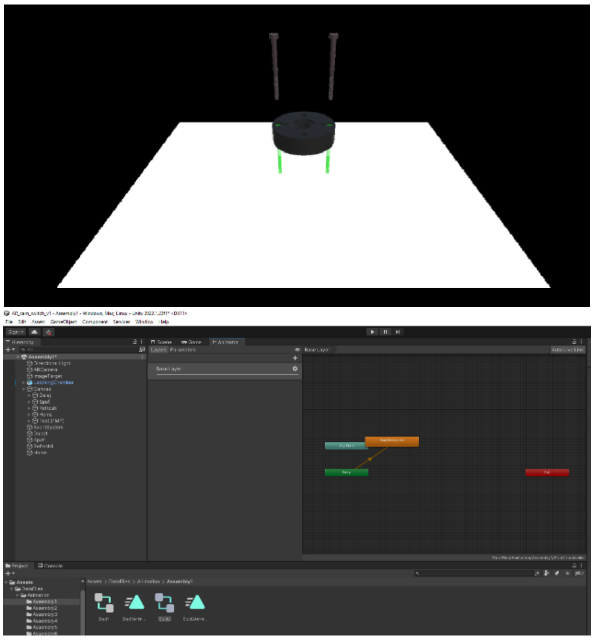

Fig. 8. Setting the animation scene

To create scenes in the application, we will use the models database from the library. Since it is a "*.obj" format, i.e. j. colorless model, it is necessary to define a texture for each depicted element. We create individual textures from the "assets" database or upload them as our own color.

Fig. 9. Library of 3D models and materials

By repeating these procedures and working with an animator, we will create a complex application consisting of 26 scenes with 35 animations defined in the technological assembly procedure.

3. Results

The application is universal from the point of view of the main and working menus. What will change during individual assembly operations is the view of ARCamera, the description of the operation and the animation loaded from the database. The application created in this way represents a universal tool that can be implemented in industrial conditions.

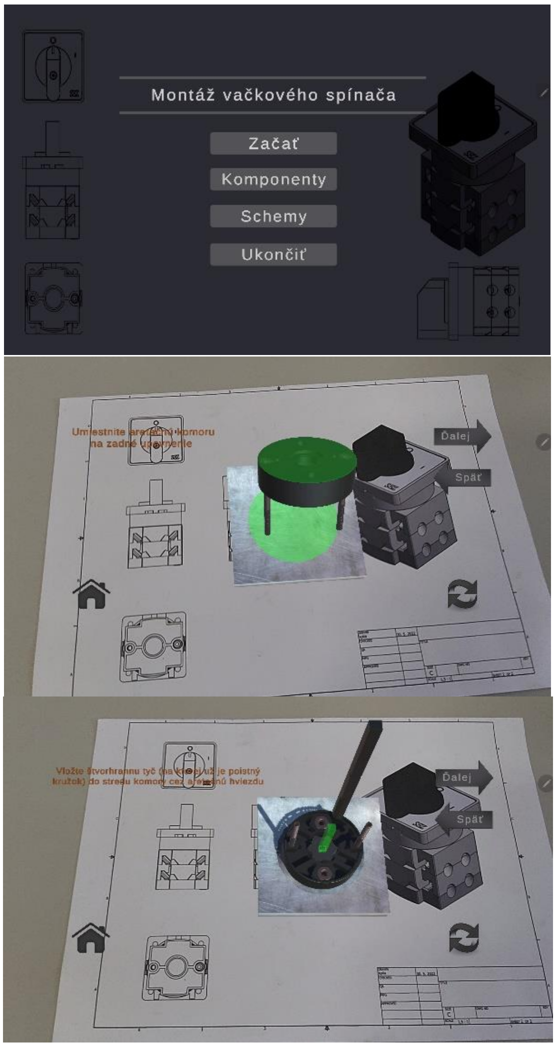

Fig. 10. Screenshots of the AR app for assisted assembly

The interesting thing about the proposed application is that we use a technical drawing as a marker (area for depicting the application), but the design allows us to use specific text or a QR code as a marker. This opens the possibility of printing an order form containing the QR codes of the products, and after scanning the code, a specific product is selected and the required application is launched online.

To verify our application, we measured the assembly time without and with the AR application for 1 piece and 10 pieces. The results can be seen in Table 1.

Table 1. Assembly time measurement with and without AR application

	Assembly time for 1 piece (s)	**Assembly time for 10 pieces (s)**
Without AR application	230	2053
With AR application	197	1668

The application created by us reduced the assembly time for one piece from 230 seconds to 197 seconds, which represents a 14.3% reduction in time. After 10 repetitions, the assembler's independent learning was also recorded and the expected time of 2300 seconds did not occur but was shortened to 2053 seconds. If we performed repeated measurements using the AR application, we arrived at a reduction in time to 1668 seconds for 10 pieces, which represents a reduction of 18.75%.

Overall, we can conclude that the use of AR applications during assembly accelerates the learning of employees, reduces the rate of errors and supports their intuitiveness.

4. Conclusion

Our proposal of assembly application interaction in augmented reality can bring great benefits to assisted assembly. Some of the main benefits of combining these technologies are mainly:

- Improve accuracy and efficiency: Creating an augmented reality application allows workers to see in real time a virtual version of the product they are working on and compare it to the physical version. This can help improve accuracy and work efficiency.
- Minimizing errors: The application allows us to create a virtual version of the product and test its functionality and assembly before actual assembly in the real world. Linking a real-world model with an augmented reality application allows workers to see virtual elements and compare them with physical ones, which can minimize the risk of errors.
- Increased safety: Linking an augmented reality application with a real-world model can help increase safety at work by allowing workers to see virtual elements and instructions in real time, which could help minimize the risk of errors and accidents.
- Cost reduction: Creating a product virtual version and testing its functionality and assembly before actual assembly in the real world can help minimize the cost and time needed to correct errors.
- Increase productivity: Linking an augmented reality application to a product can help increase worker productivity by allowing them to see virtual elements and instructions in real time, minimizing time spent searching for the right tools and components.

Overall, connecting an augmented reality application with a real product can bring several benefits to assisted assembly, improving accuracy, efficiency, and work safety, and reducing the cost and time needed to correct errors. In the future, the author's collective plans to solve the creation of an online simplified AR application architecture, which will be connected to the database and cloud storage. The client connects to the application, creates a user interface and then just loads 3D models and assembly processes with timing from the cloud. Such a concept represents a solution that can be modified for various companies and is widely used in practice.

Acknowledgments

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Original Research

RELATIONSHIP BETWEEN 3D SURFACE ROUGHNESS PARAMETERS AND LOAD CAPACITY OF ADHESIVE JOINTS AFTER SHOT PEENING

ZALEŻNOŚĆ POMIĘDZY PARAMETRAMI CHROPOWATOŚCI POWIERZCHNI 3D A NOŚNOŚCIĄ POŁĄCZEŃ KLEJOWYCH PO PNEUMOKULKOWANIU

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Abstract

The aim of the article was to investigate whether roughness parameters in a 3D system can be used to assess the load capacity of adhesive lap joints strengthened in the shot peening process. The analyzes were carried out for single-lap adhesive joints made of EN AW-2024-T3 aluminum alloy, whose overlaps were shot peened for 60 to 180 s using balls with a diameter of 0.5 to 1.5 mm with a compressed air pressure of 0.3 to 0.5 MPa. As a result of the regression and correlation analysis, it was found that within the adopted range of input parameters variability, the load capacity of adhesive joints subjected to shot peening is most closely related to the roughness parameter *Sdr*. It has been shown that increasing the value of the *Sdr* parameter contributes to increasing the load capacity of adhesive joints. A mathematical model describing the impact of treatment time, balls diameter and compressed air pressure on the value of the *Sdr* parameter was also built. The model was built in accordance with the the Hartley's PS/DS-P:Ha_3 plan methodology. The obtained results allow to conclude that the *Sdr* parameter can be used to predict the load capacity of adhesive joints after shot peening and thus to assess the strengthening treatment (within the assumed range of input parameters variability). Additionaly, the simplicity and low cost of roughness measurements justify the use of this method in industrial purposes.

Keywords: shot peening, surface roughness, Hartley's PS/DS-P:Ha_3 plan

Streszczenie

Celem artykułu było zbadanie, czy parametry chropowatości w układzie 3D mogą być stosowane do oceny nośności zakładkowych połączeń klejowych, umacnianych w procesie pneumokulkowania. Analizy przeprowadzono dla połączeń klejowych jednozakładkowych ze stopu aluminium EN AW-2024-T3, których zakadki pneumokulkowano w czasie od 60 do 180 s, kulkami o średnicy od 0,5 do 1,5 mm z ciśnieniem wynoszącym od 0,3 do 0,5 MPa. W wyniku przeprowadzonej analizy regresji i korelacji stwierdzono, że w przyjętym zakresie zmienności parametrów wejściowych, nośność połączeń klejowych poddanych pneumokulkowaniu jest najsilniej związana z parametrem chropowatości *Sdr*. Wykazano, że zwiększanie wartości parametru *Sdr*, przyczynia się do zwiększania nośności połączeń klejowych. Zbudowano również model matematyczny, opisujący wpływ czasu obróbki, średnicy kulek i ciśnienia sprężonowego powietrza na wartość parametru *Sdr*. Model zbudowano zgodnie z metodyką planu Hartleya PS/DS-P:Ha_3. Uzyskane wyniki pozwalają na stwierdzenie, że parameter *Sdr* może być wykorzystywany do przewidywania nośności połączeń klejowych po pneumokulkowaniu, a tym samym do oceny obróbki umacniającej (w przyjętym zakresie zmienności parametrów wejściowych), a prostota i niskie koszty pomiarów chropowatości przemawiają za słusznością użycia tej metody w celach przemysłowych.

Słowa kluczowe: pneumokulkowanie, chropowatość powierzchni, plan Hartleya PS/DS-P: Ha_3

1. Introduction

The stress state in the bond-line of single-lap adhesive joints is not uniform. The maximum stresses are recorded in the end part of the overlap. Failure of the adhesive bond begins at the point of stress concentration. Therefore, in order to increase the strength of adhesive joints, efforts should be made to reduce the value of maximum stresses [4, 7].

There are various methods of reducing the stress concentration in the end part of the overlap. One of them is shot peening of the outer surface of the overlap [3, 4, 10]. Shot peening of the outer surface of the overlap leads to the reduction of stresses in the bond-line of joints subjected to stretching [9, 11]. It has been proven that the greatest stress reduction occurs in the case of normal stresses perpendicular to the bond-line surface. Figure 1 shows a comparison of normal stresses perpendicular to the surface of the bond-line in connections not subjected to and subjected to shot-peening. In the case of joints not subjected to shot peening, the maximum values of these stresses are about 78 MPa. On the other hand, in the case of connections subjected to shot peeningg, the maximum stress values are only about 28 MPa [11].

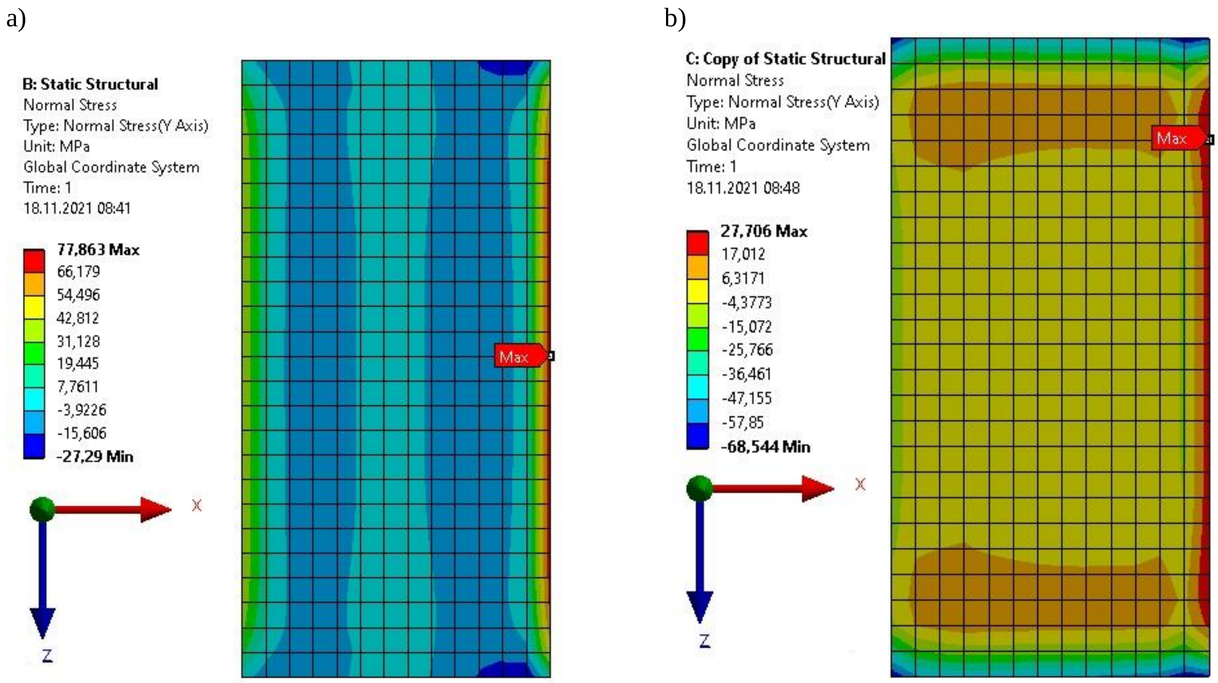

Fig. 1. Comparison of the values of normal stresses perpendicular to the surface of the bond-line in the adhesive connections: a) not subjected to shot peening, b) subjected to shot peening [11]

As a result of reducing the maximum values of normal stresses perpendicular to the surface of the bond-line, the capacity ratio of the bond-line decreases, which in turn translates into an increase in the strength of the adhesive joint [11].

Shot peening, which is one of the types of dynamic burnishing, has great potential for strengthening adhesive bonds. Therefore, it would be useful to identify ways to assess the correctness of this type of strengthening treatment in order to facilitate its implementation in industrial applications.

In general, in order to ensure repeatability of the dynamic burnishing process and maintain the required quality of machined parts, the following methods are used:

- assessment of the degree of surface coverage with imprints resulting from the impact of burnishing elements,
- assessment of the intensity of dynamic burnishing (Almen strip test),
- analysis of the geometric structure of the surface after treatment,
- analysis of the physical properties of the surface layer,
- analysis of the functional properties of the machined elements [8].

It was decided to check whether one of the mentioned methods (analysis of the geometrical structure of the surface after treatment) can be used to assess the strengthening treatment and to predict the load capacity of lap adhesive joints subjected to shot peening. For this purpose, the relationship between the surface roughness parameters of EN AW-2024-T3 aluminum alloy samples subjected to shot peening and the load capacity of adhesive joints made of EN AW-

2024-T3 aluminum alloy after shot peening was analyzed.

2. Experimental details

The subject of the analyzes were adhesive bonds made of aluminum alloy EN AW-2024-T3, bonded with the use of two-component epoxy adhesive Loctite EA 3430 and plates of aluminum alloy EN AW-2024-T3. The dimensions of the adhesive bond and the plate are shown in Figure 2.

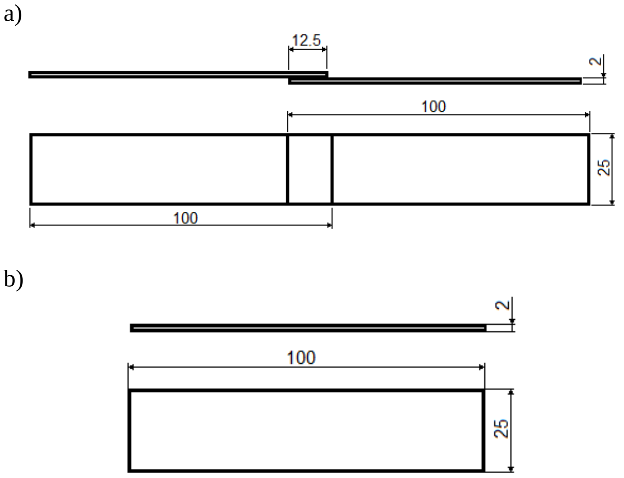

Fig. 2. Scheme of: a) adhesive bond, b) plates for measuring surface roughness

In order to obtain the appropriate degree of development, ensuring greater adhesive strength, the bonding surfaces were subjected to abrasive blasting. The processing was carried out on a New-Tech machine (New-Tech, Wrocław, Poland) with the use of ekeltrocorundum with a grain size of 0.27 mm. Then, the bonding surfaces were cleaned of dust and grease residues with acetone.

The next step was to create adhesive bonds. Bonds were made using two-component epoxy adhesive Loctite EA 3430 (Loctite, Düsseldorf, Germany). The adhesive components were mixed by hand and applied to both bonded surfaces. The bonds were placed in a fixing device ensuring constant pressure. Crosslinking in the device lasted 3 days. The cross-linking temperature was 22 ± 1˚C.

The adhesive bonds and plates made of aluminum alloy EN AW-2024-T3 were subjected to shot peening. The tests were carried out for 11 variants of the shot peening process. Individual variants differed in processing parameters. Treatment parameters were selected in accordance with the Hartley plan matrix for three levels of variability of input factors: shot peening time *t*, diameter of steel balls *d* and compressed air pressure *p* (Table 1).

Table 1. Shot peening parameters

Variant	**Shot peening parameters**		
	Time ***t*, s**	**Balls diameter** ***d*, mm**	**Compersssed air pure** ***p*, MPa**
1	60	0.5	0.5
2	180	0.5	0.3
3	60	1.5	0.3
4	180	1.5	0.5
5	60	1.0	0.4
6	180	1.0	0.4
7	120	0.5	0.4
8	120	1.5	0.4
9	120	1.0	0.3
10	120	1.0	0.5
11	120	1.0	0.4

Shot peening was carried out in a device consisting of a working chamber closed with a cover to which the samples (adhesive joints and plates made of aluminum alloy EN AW-2024-T3) were attached. In the case of adhesive joints, only the overlap zone was treated. The remaining part was protected against the impact of the burnishing elements by caps.

The tests were also carried out for variant 12, meaning samples not subjected to shot peening treatment.

More details on the methodology of preparing adhesive joints and the shot peening process can be found in [12].

In order to determine the impact of shot peening on the load capacity of adhesive bonds, the bonds were subjected to a static uniaxial tensile test. The test was carried out on a ZWICK/ROELL Z100 machine (Zwick/Roell, Ulm, Germany) in accordance with the PN EN 1465:2009 standard [6].

3D surface roughness measurements were carried out for EN AW-2024-T3 aluminum alloy plates. Measurements were performed using a Taylor Hobson Talysurf CCI Lite optical profilometer (Taylor Hobson Ltd, Leicester, England). Table 2 presents the measured 3D surface roughness parameters.

Table 2. Measured 3D surface roughness parameters [2]

3D surface roughness parameters	
Sq	Root mean square height, μm
Ssk	Skewness
Sku	Kurtosis
Sp	Maximum peak height, μm
Sv	Maximum pit height, μm
Sz	Maximum height, μm
Sa	Aritmetic mean height, μm
Sal	Auto-correlation lenght, mm
Str	Texture-aspect ratio
Sdq	Root mean square gradient
Sdr	Developed interfacial area ratio, %,
Spd	Plateau root mean square rouhgness, 1/mm^2
S10z	Ten point height, μm

Measurements of 3D surface roughness parameters were made in accordance with the ISO 25178-2:2021 standard [2]. The obtained results were subjected to statistical analyses.

3. Results and discussion

Tables 3-5 show the average values of the load capacity (P_t) of untreated adhesive joints, the average values of the load capacity of adhesive joints subjected to 11 variants of shot peening, and the corresponding average values of 3D surface roughness parameters. The average values of the load capacity of adhesive joints were determined on the basis of load capacity measurements performed for 8 samples. The average values of the roughness parameters were determined based on the results of three surface roughness measurements.

Table 3. The average values of load capacity of adhesive joints and the average values of surface roughness parameters – part 1

Variant	P_t, N	*Sq*, µm	*Ssk*	*Sku*	*Sp*, µm
1	8166	2.56	0.0262	3.62	12.35
2	7168	1.58	-0.0699	3.69	8.91
3	8226	2.09	-1.0420	3.77	6.53
4	4819	3.91	0.0849	3.11	14.75
5	8781	3.35	-0.5400	3.97	13.68
6	9410	3.42	-0.1653	4.07	14.15
7	7005	1.90	-0.0966	3.61	9.67
8	7097	3.21	-0.0329	2.64	10.46
9	8688	2.93	-0.4494	4.06	10.72
10	9443	3.67	-0.0460	3.57	15.36
11	8633	3.43	-0.2201	3.93	16.09
non-peened	7080	0.41	-0.14107	4.39	3.97

Table 4. The average values of surface roughness parameters – part 2

Variant	*Sv*, µm	*Sz*, µm	*Sa*, µm	*Sal*, mm	*Str*
1	14.58	26.9	2.00	0.0629	0.920
2	10.00	18.9	1.23	0.0519	0.905
3	11.34	17.9	1.68	0.0957	0.926
4	15.70	30.5	3.10	0.1426	0.856
5	23.70	37.4	2.68	0.0871	0.927
6	21.63	35.8	2.65	0.0959	0.906
7	11.50	21.2	1.49	0.0626	0.889
8	14.14	24.6	2.61	0.1144	0.910
9	21.20	31.9	2.32	0.0755	0.907
10	22.21	37.5	2.88	0.0965	0.899
11	22.68	38.8	2.68	0.0856	0.925
non-peened	6.14	8.1	0.33	0.02667	0.025

Table 5. The average values of surface roughness parameters – part 3

Variant	*Sdq*	*Sdr*, %	*Spd*, 1/mm^2	*S10z*, µm
1	0.213	2.180	79.3	20.3
2	0.169	1.401	114.8	14.1
3	0.107	0.566	28.2	13.3
4	0.138	0.938	15.6	19.5
5	0.200	1.928	21.8	25.6
6	0.202	1.972	31.7	26.4
7	0.176	1.517	93.1	15.3
8	0.132	0.860	19.4	16.3
9	0.209	2.085	33.7	24.6
10	0.215	2.214	30.5	27.1
11	0.207	2.062	25.6	26.3
non-peened	0.082	0.334	428.1	4.4

According to the results presented in Table 3, the load capacity of shot peened adhesive bonds is in most cases higher than the load capacity of non-penned bonds. The increase in the load capacity of adhesive joints subjected to shot peening was possible due to the deformation of the adherends (the edge of the overlap was pressed against the adherend). The deformation resulted in constituting compressive stresses in the bond-line. Summing up the stresses from the deformation and from the external load resulted in a reduction of stresses in the bond-line of the joints subjected to shot-peening in comparison to untreated bonds. The mechanism of strengthening of adhesive bonds due to shot peening was investigated and described in more detail in [11].

Figures 3-5 show selected isometric images of the surface after shot peening.

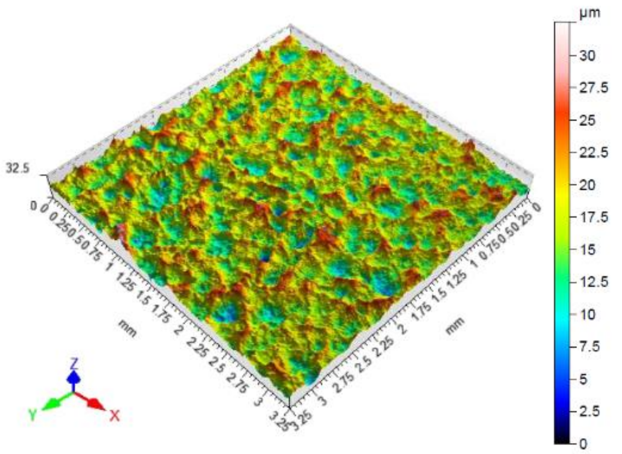

Fig. 3. Isometric image of the surface after shot peening - variant no 10 (t = 120 s, d = 1.0 mm, p = 0.5 MPa)

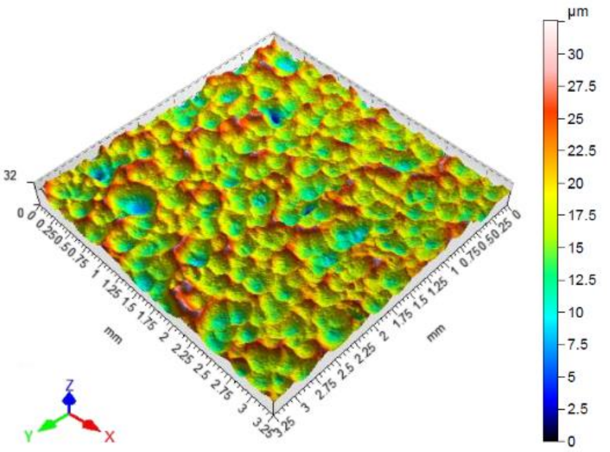

Fig. 4. Isometric image of the surface after shot peening - variant no 4 (t = 180 s, d = 1.5 mm, p = 0.5 MPa)

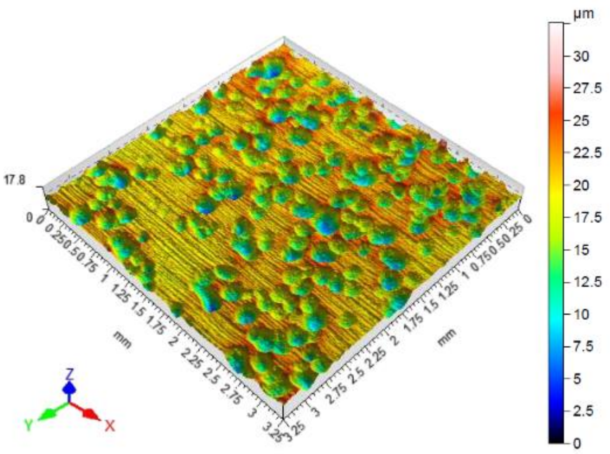

Fig. 5. Isometric image of the surface after shot peening - variant no 3 (t = 60 s, d = 1.5 mm, p = 0.3 MPa)

On the basis of Figures 3-5, it can be concluded that numerous spherical recesses appeard on the surface of the samples subjected to phot peening. Depending on the adopted processing parameters, these surfaces differ in the density of visible imprints resulting from the impact of burnishing elements. Variant no. 10 and 4 is characterized by full coverage with the imprints after shot peening. However, in the case of variant no. 3, incomplete coverage with the imprints can be observed.

The first stage of the analysis was to determine the relationship between the load capacity of adhesive joints after shot peening and 3D surface roughness parameters. For this purpose, one-way ANOVA, regression and correlation analysis were performed. It was assumed that the results of the analysis are statistically significant when the probability values (p-value) are lower than the significance level (α) of 0.05. Probability values determined for one-way ANOVA are presented in Table 6.

Table 6. One-way analysis of variance (ANOVA) results

Parameter	Independent variable	*Pv1**
P_t	*Sq*	0.160
P_t	*Ssk*	0.001
P_t	*Sku*	0.036
P_t	*Sp*	0.296
P_t	*Sv*	0.000
P_t	*Sz*	0.143
P_t	*Sa*	0.261
P_t	*Sal*	0.403
P_t	*Str*	0.042
P_t	*Sdq*	0.019
P_t	*Sdr*	0.087
P_t	*Spd*	0.001
P_t	*S10z*	0.077

* *Pv1* – probability level determined in one-way analysis of variance (ANOVA).

The results of the one-way analysis of variance ANOVA (Table 6) indicate that within the adopted range of variability of the input factors, the independent variables *Ssk*, *Sku*, *Sv*, *Str*, *Sdq* and *Spd* have a significant impact on the dependent variable P_t. This is indicated by the probability values *Pv1*, which in these cases are less than 0.05.

Table 7 shows the results of the regression analysis.

Table 7. Regression analysis results

Parameter	Independent variable	Regression equation	*Pv2**
P_t	*Sq*	$y_{P_t} = 7500 + 154x_{Sq}$	0.623
P_t	*Ssk*	$y_{P_t} = 7623 - 1405x_{Ssk}$	0.044
P_t	*Sku*	$y_{P_t} = 1905 + 1660x_{Sku}$	0.000
P_t	*Sp*	$y_{P_t} = 7157 + 65,6x_{Sp}$	0.370
P_t	*Sv*	$y_{P_t} = 5766 + 127x_{Sv}$	0.001
P_t	*Sz*	$y_{P_t} = 5885 + 70,6x_{Sz}$	0.011
P_t	*Sa*	$y_{P_t} = 7615 + 145x_{Sa}$	0.715
P_t	*Sal*	$y_{P_t} = 9652 - 19286x_{Sal}$	0.032
P_t	*Str*	$y_{P_t} = -15553 + 25920x_{Str}$	0.001
P_t	*Sdq*	$y_{P_t} = 4174 + 21089x_{Sdq}$	0.000
P_t	*Sdr*	$y_{P_t} = 5666 + 1415x_{Sdr}$	0.000
P_t	*Spd*	$y_{P_t} = 8190 - 5,37x_{Spd}$	0.441
P_t	*S10z*	$y_{P_t} = 5221 + 131x_{S10z}$	0.001

* *Pv2* –probability level determined for the independent variable in the regression analysis.

The linear regression equations presented in Table 7 show the influence of 3D surface roughness parameters on the load capacity of adhesive joints. According to the regression equations, within the adopted range of input factors variability, the load capacity of the adhesive joints increases with the increase in the surface roughness parameters. The exceptions are the parameters *Ssk*, *Sal* and *Spd*. Based on *Pv2* values, it can be concluded that the parameters *Ssk, Sku, Sv, Sz, Sal, Str, Sdq, Sdr* and *S10z* have a statistically significant impact on the load capacity of the adhesive joints ($Pv2<0.05$). Therefore, the equations describing the influence of the parameters *Ssk, Sku, Sv, Sz, Sal, Str, Sdq, Sdr* and *S10z* on the load capacity of adhesive joints could be used to predict the load capacity of adhesive joints after shot peening.

Table 8 shows the results of the linear correlation analysis.

Table 8. Results of the linear correlation analysis

Parameter	Independent variable	Linear correlation coefficient R	Pv3*
P_t	*Sq*	0.089	0.623
P_t	*Ssk*	-0.353	0.044
P_t	*Sku*	0.593	0.000
P_t	*Sp*	0.161	0.370
P_t	*Sv*	0.542	0.001
P_t	*Sz*	0.437	0.011
P_t	*Sa*	0.066	0.715
P_t	*Sal*	-0.375	0.032
P_t	*Str*	0.534	0.001
P_t	*Sdq*	0.603	0.000
P_t	*Sdr*	0.635	0.000
P_t	*Spd*	-0.139	0.441
P_t	*S10z*	0.564	0.001

* *Pv3* – probability level in linear correlation coefficient analysis.

The linear correlation coefficients presented in Table 8 are less than 0.7. Therefore, within the adopted range of input factors variability, there is no strong linear correlation between the surface roughness parameters and the load capacity of the adhesive joints. The highest value of the linear correlation occurs in the case of the *Sdr* parameter and amounts to 0.635. This is a positive correlation, which means that the load capacity of the adhesive joints increases with the increase in the value of the *Sdr* parameter. According to the probability value *Pv3*, the influence of the *Sdr* parameter on the load capacity of adhesive joints is statistically significant ($Pv3<0.05$).

The obtained results of the regression and correlation analysis allow to conclude that the *Sdr* roughness parameter can be used to evaluate the strengthening treatment (within the adopted range of input parameters variability).

The *Sdr* parameter (developed interfacial area ratio) is calculated as the ratio of the increase of the surface area of a limited scale inside the defined area to the defined area [2]. The *Sdr* parameter for a perfectly flat surface takes the value of 0. The value of the *Sdr* parameter is particularly important in the case of adhesion and bonding, because a surface with a larger area of development enables a stronger connection with another surface or coating [1].

After showing that within the adopted range of variability, the *Sdr* roughness parameter is most closely related to the load capacity of the adhesive joints, a mathematical model describing the impact of selected parameters of the shot peening on the value of the *Sdr* parameter was build. The mathematical model (1), taking the form of a second degree polynomial, was built in accordance with the methodology proposed in the Hartley PS/DS-P:Ha$_3$ plan:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}{x_1}^2 + b_{22}{x_2}^2 + b_{33}{x_3}^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3, \tag{1}$$

where : y – output factor, x_k – input factors, k = 1, 2, 3, $b_0, \dots, b_k$ – regression coefficients, $b_{kk}, \dots, b_{kj}$ – regression coefficients showing the effects of interaction of input factors, j = 1, 2, 3. The methodology of the Hartley PS/DS-P:Ha$_3$ plan is described in detail in [5].

The input factors were the parameters of the shot peening process: peening time t, diameter of the balls d and compressed air pressure p. The method of coding the input factors is presented in Table 9. The output factor was the value of the *Sdr* parameter.

Table 9. Ranges of volatility and the method of coding input factors

Input factor	Variation units	Method of encoding factor
Processing time t, s	$\Delta x_1 = \frac{180-60}{2}$	$x_1 = \frac{t-120}{60}$
Ball diameter d, mm	$\Delta x_2 = \frac{1.5-0.5}{2}$	$x_2 = \frac{d-1}{0.5}$
Pressure p, MPa	$\Delta x_3 = \frac{0.5-0.3}{2}$	$x_3 = \frac{p-0.4}{0.1}$

The first stage of the mathematical model building was to calculate the values of the the regression equation coefficients and to determine the critical values for the the regression equation coefficients in accordance with the methodology of the Hartley PS/DS-P:Ha$_3$ plan [5].

The calculated values of the equation coefficients were evaluated for statistical significance. The purpose of the assessment was to check whether the calculated coefficients have a significant impact on the result of the equation and whether the equation is useful for estimating the output value (*Sdr* value). The evaluation of the significance of the equation coefficients consisted in comparing the calculated absolute value of the coefficients and the critical value of the coefficients. If the determined critical value of the coefficient was greater than or equal to the calculated absolute value, then the null hypothesis had to be rejected and the alternative hypothesis adopted. Accepting the alternative hypothesis meant recognizing that a given coefficient of the regression equation had a statistically significant impact on the output variable of the equation. Confirmation of the null hypothesis meant, that the given coefficient had no statistically significant impact on the model result and could be removed from the regression equation. The calculated and critical values of the regression equation coefficients and the results of the significance assessment are presented in Table 10.

Table 10. Critical values of coefficients, calculated values of coefficients and significance assessment

Coefficient	Calculated value	Critical value	Significance of coefficient	
b_0	2.026	0.093	$\lvert b_0\rvert > b_{0kr}$	Yes
b_1	-0.061	0.069	$\lvert b_1\rvert < b_{1kr}$	No
b_2	-0.456	0.069	$\lvert b_2\rvert > b_{2kr}$	Yes
b_3	0.213	0.069	$\lvert b_3\rvert > b_{3kr}$	Yes
b_{11}	-0.065	0.108	$\lvert b_{11}\rvert < b_{11kr}$	No
b_{22}	-0.826	0.108	$\lvert b_{22}\rvert > b_{22kr}$	Yes
b_{33}	0.135	0.108	$\lvert b_{33}\rvert > b_{33kr}$	Yes
b_{12}	0.288	0.084	$\lvert b_{12}\rvert > b_{12kr}$	Yes
b_{13}	-0.519	0.084	$\lvert b_{13}\rvert > b_{13kr}$	Yes
b_{23}	-0.102	0.084	$\lvert b_{23}\rvert > b_{23kr}$	Yes

Based on the results of the significance assessment, it was decided to remove two coefficients (b_1 and b_{11}) from the regression equation. After eliminating insignificant coefficients, decoding the equation using appropriate values from Table 9 and ordering, the following regression equation was obtained (2):

$$\begin{aligned} y_{Sdr} = -2.85 + 0.025x_t + 5.312x_d \\ + 3.81x_p - 3.304{x_d}^2 \\ + 13.5{x_p}^2 + 0.01x_t x_d \\ - 0.087x_t x_p \\ - 2.04x_d x_p, \end{aligned} \tag{2}$$

where y_{Sdr} is the surface roughness parameter *Sdr*, x_t is the processing time variable, x_d is the ball diameter variable and x_p is the compressed air pressure variable. The regression equation (2) describe the effects of peening time, ball diameter and compressed air pressure on the surface *roughness* parameter *Sdr*. The obtained model is nonlinear. Tables 11-12 and Figure 6 show the *Sdr* parameter values obtained from measurements and calculated on the basis of the model (2).

Table 11. Results of measurements for the *Sdr* roughness parameter

Variant	Results of measurements		
	y_1	y_2	y_3
1	2.025	2.159	2.357
2	1.186	1.504	1.512
3	0.577	0.558	0.562
4	0.861	0.960	0.992
5	2.041	1.669	2.073
6	1.957	1.732	2.226
7	1.341	1.590	1.619
8	0.795	0.863	0.923
9	2.037	2.121	2.098
10	2.126	2.257	2.258
11	2.039	2.023	2.123

* y_1, y_2, y_3 – values of the *Sdr* parameter obtained in the first, second and third measurement.

Table 12. Results of calculations for the *Sdr* roughness parameter

Variant	$\bar{y}_i$	$S^2(y)_i$	$\hat{y}_i$	$(\bar{y}_i - \hat{y}_i)^2$
1	2.180	0.0279	2.625	0.1977
2	1.401	0.0346	1.545	0.0208
3	0.566	0.0001	0.000	0.3200
4	0.938	0.0047	0.489	0.2013
5	1.928	0.0504	1.786	0.0201
6	1.972	0.0612	1.810	0.0261
7	1.517	0.0234	1.428	0.0079
8	0.860	0.0041	0.516	0.1186
9	2.085	0.0019	1.783	0.0914
10	2.214	0.0058	2.083	0.0171
11	2.062	0.0029	1.798	0.0695

* $\bar{y}_i$ – average value of *Sdr* parameter, $S^2(y)_i$ – variance of experimental results, $\hat{y}_i$ – value of *Sdr* parameter determined using regression equation (2), $(\bar{y}_i - \hat{y}_i)^2$ – variance determined using regression equation (2).

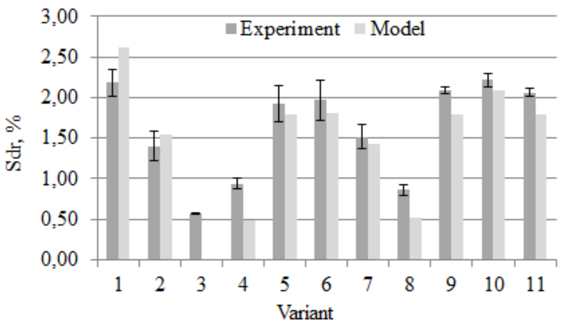

Fig. 6. Results of measurements and calculations for the roughness parameter *Sdr*

The model and experimental values are similar. The linear correlation coefficient is 0.95. Figures 7-9 shows graphs developed from the regression equation (2).

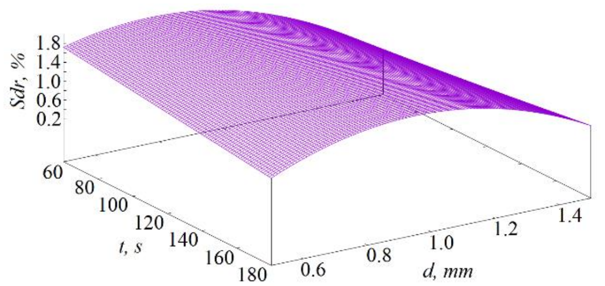

Fig. 7. Graph showing the influence of time *t* and ball diameter *d* on the value of the roughness parameter *Sdr* (*p* = 0.4 MPa)

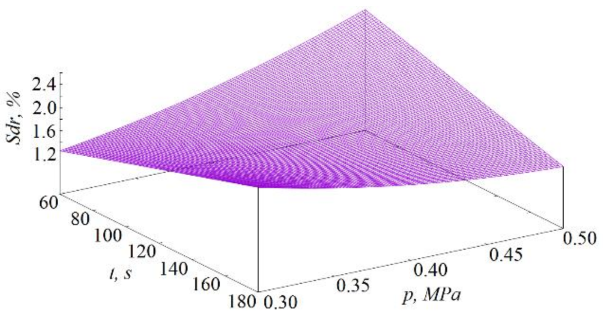

Fig. 8. Graph showing the influence of time *t* and pressure *p* on the value of the roughness parameter *Sdr* (*d* = 1 mm)

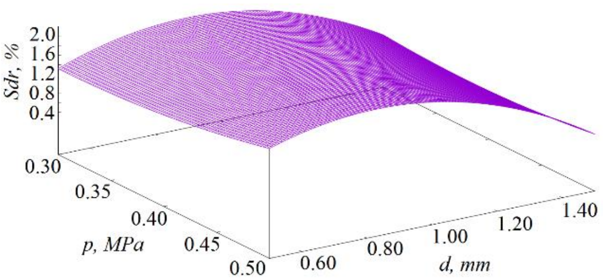

Fig. 9. Graph showing the influence of ball diameter *d* and pressure *p* on the value of the roughness parameter *Sdr* (*t* = 60 s)

Based on the regression equation (2) and the graphs presented in the Figures 7-9, it can be concluded that for the assumed range of input factors variability, the influence of the ball diameter and compressed air pressure on the value of the *Sdr* parameter is non-linear. In the case of the diameter of the balls, the extreme (maximum value of the output parameter) is observed for balls with a diameter of 1 mm. However, in the case of compressed air pressure, the extreme (minimum value of the output parameter) is observed in the case of treatment with a pressure of 0.4 MPa. The complex interaction of the peening time and the diameter of the balls contributed to the increase in the value of the *Sdr* parameter. The complex interaction of machining time and pressure as well as ball diameter and pressure contributes to a reduction in the *Sdr* value.

4. Conclusion

On the basis of the conducted analyzes, it was shown that in the adopted range of variability of the input factors:

- the roughness parameter, which is most strongly correlated with the load capacity of adhesive joints made of EN AW-2024-T3 aluminum alloy after shot peening is the *Sdr* parameter,
- the value of the linear correlation coefficient between the *Sdr* parameter and the load capacity of the adhesive joints is 0.635, which means that with the increase of the *Sdr* parameter, the load capacity increases,
- according with the mathematical model describing the impact of the shot peening parameters on the value of the *Sdr* parameter, it can be stated that the impact of the ball diameter and compressed air pressure on the value of the *Sdr* parameter is non-linear (the maximum value of the output parameter is observed for balls with a diameter of 1 mm, and the minimum value for with a pressure of 0.4 MPa), the complex interaction of shot peening time and ball diameter contributes to an increase in *Sdr*, and the combined interaction of shot peening time and pressure, and ball diameter and pressure contributes to a decrease in *Sdr*.

To sum up, the *Sdr* parameter can be used to predict the load capacity of adhesive joints after shot peening and to assess the strengthening treatment (within the assumed range of input parameters variability). The method of evaluating the strengthening treatment based on the measurement of roughness in the 3D system can therefore be an alternative to the Almen strip test, which was proposed in [10]. Compared to the Almen strip test, roughness measurements are simpler and cheaper, which makes them more attractive to those who would like to use shot peening to strengthen adhesive joints and would seek an effective method to control such strengthening treatment.

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Review

RESEARCH-BASED TECHNOLOGY EDUCATION – THE EDURES PARTNERSHIP EXPERIENCE

EDUKACJA OPARTA O WYNIKI BADAŃ – DOŚWIADCZENIE PARTNERÓW PROJEKTU EDURES

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Abstract

The paper presents the state regarding practices in teaching at partner universities of the EDURES project and current approaches supporting research-based education. It also presents the needs of various groups of stakeholders formulated on the basis of survey results. Moreover, the paper proposes tools and strategies which are useful if research results are implemented in teaching programmes at technical universities (research-based lectures, e-learning, web portal methodologies, wizards, etc). It is finally stated that research-results implementation into teaching processes is possible by the use of various tools and approaches proposed by the EDURES partnership and has the potential to be appreciated by students, academics and external stakeholders.

Keywords: research-based education, technology, digitalization

Streszczenie

Artykuł przedstawia opis zagadnienia dotyczącego nauczania opartego o wyniki badań oraz aktualnie stosowane praktyki partnerów projektu EDURES. Przedstawiono potrzeby interesariuszy na podstawie wyników ankiet. Przedstawiono także narzędzia i strategie użyteczne podczas wdrażania wyników własnych badań w programach nauczania na uczelniach technicznych (wykłady oparte na wynikach badań, e-learning, metodyka portalu badawczego, narzędzia internetowe). Należy stwierdzić, że wdrażanie wyników badań w procesach nauczania jest możliwe przez zastosowanie różnych narzędzi i w oparciu o różne strategie, które zostały opracowane w ramach projektu EDURES i mogą być potencjalnie docenione przez studentów, akademików i zewnętrznych interesariuszy.

Słowa kluczowe: edukacja oparta o wyniki badań, technologia, digitalizacja

1. Introduction

The centuries of technical academia existence have revealed various teaching & learning methodologies which have been implemented, revised, updated many times due to the changes of technology. Nowadays, there are a lot of educational institutions (i.e. higher education institutions such as universities focused on technology) which, in our opinion, are involved in a race together with R&D departments of big technological companies operating in industry. The mission of universities and approaches that are used by academics in the teaching processes nowadays should be adjusted once again to modern challenges such as enormous mobility of people, flow of data, the use of artificial intelligence, etc. Moreover, content of study programmes should enable learners to obtain the skills useful in modern technological environments of firms. These skills must be significantly separated from those which are gained in the technical high schools and strongly focused on shaping scientific skills of higher education learners. This is important because the scientific skills help students to search for the best technological solutions in the real industrial environments by using scientific approaches and methodologies. Rapid transfer of knowledge, that concerns recent scientific achievements of academics, within different forms of classes (e.g. lectures, laboratories) brings various benefits for academics, students and technological companies such as evaluation of achievements by wider audiences, increase of students' satisfaction, faster knowledge transfer to the industry. For this reason, the classes with students should be used efficiently for presenting modern science by using modern approaches. Authors have decided to prepare the paper within the EDURES project which is performed within the ERASMUS+ programme in order to present project team ideas on research-based education. The presented content is mainly adjusted to the mechanical engineering and civil engineering scientific disciplines. These technological disciplines have various research methodologies.

Various teaching methodologies such as problem-based learning (Li Wenli, 2012; https://en.wikipedia.org/wiki/Problem-based_learning 30.08.2023) or project-based learning (https://en.wikipedia.org/wiki/Project-based_learning 30.08.2023) have been studied so far in order to improve effectiveness of teaching and learning. This is crucial due to the acceleration of technological developments worldwide and actual requirements of customers. An example of such action is Aalborg University in Denmark, where students work in groups applying problem oriented methods in preparing projects of a high academic standard according to the pedagogical model of the University - the Aalborg model for problem based learning (https://www.en.aau.dk/about-aau/profile/pbl 22.09.2023).

In addition existence of various papers should be mentioned. For instance, the study of Soledad Ramirez-Montoya et al. is focused on providing perspectives on the future of educational programs by analysing trends in educational programs' designs, students and professors' needs for innovative education (Soledad Ramírez-Montoya María et al., 2021). Another paper authored by Gębczyńska-Janowicz proposed utilization of virtual reality in education (Gębczyńska-Janowicz Agnieszka, 2020).

However, research-based teaching and learning seems to be important area of development due to acceleration of implementation of innovative solutions and technologies in various industries. It should be noted, in this context, that improvements of teaching methodologies have been the crucial point of research activities so far. Shou et al. found that combining scientific research projects with experimental teaching has a significant impact on teaching effects and can improve students' interest in experiments (Qingyun Shou et al., 2014). Paper of Brenner and Adamovic provides an overview of approaches that might be considered in order to successfully integrate European research projects into engineering teaching method (Brenner Werner et al., 2020). The study (Marshall Jill et al., 2018) compares a project-based cornerstone course with the traditionally- taught introductory course in civil engineering. The mentioned paper also points that interviewed students indicated that they recognized and appreciated that the project-based course enabled them to do real engineering. Moreover, the paper of Mariken et al. explores how to strengthen the research-teaching nexus (TRN) in university education, in particular, how to improve the relation between policy and practice (Elsen Mariken et al., 2009). It is stated that if a university chooses to strengthen the research-teaching nexus in undergraduate curricula, students are more often involved in the role of participants in research. Another research gap regarding TRN was filled out by Clark and Hordosy (Clark Tom et al., 2019). They, inter alia, presented how the nexus can also often serve to exclude students as much as it includes. On the other hand Munthe E. et al. analysed research-based teacher education. They inter alia analysed the role of inquiry and research in abovementioned area (Munthe Elaine et al., 2015). The paper proposed by Brew et al. takes into account issues not only for the education of teachers, but also for the introduction of research-based learning in higher education (Brew Angela et al., 2020). It should be stated in the conclusion following opinion of Iivari and co-authors of paper (Iivari Netta et al., 2020) that research-based education needs to be updated and it is a main reason for the study which is presented within this paper in the technology-related journal.

2. EDURES partners practices in the area of teaching programmes at technical universities

2.1. General structure of programmes at EDURES partner universities

The typical teaching programmes of the Rzeszów University of Technology offers full-time and part-time studies. Full-time studying is possible during week days (Monday – Friday) while the part time classes are organized within weekends. Teaching programme is nowadays formulated as a set of semesters divided into modules. The modules are planned as separate courses in the selected area. For instance, a module may concern CNC machine tools programming, fundamentals of mechanics, machine technology basics, etc. Usually, last semesters are mostly focused on a diploma thesis preparation. In the EU zone there are usually 2 or 3 cycles at bachelor, master and doctoral level respectively. For instance, at Rzeszów University of Technology the first cycle consists of 7 or 8 semesters depending on the type of studies (full time or part time). The second cycle (master degree) is shorter and lasts 3 semesters. Number of modules per one semester may vary. However, a number of ECTS points is always the same and equals 30 points per every semester. Number of the ECTS points is linked to the planned number of hours that are assigned to student workload (i.e. 1 ECTS point is assigned to 25 – 30 h). Module coordinators should assign workload to the specific forms of classes. Selected modules are completed by students within the examination procedures. Other modules are passed on the basis of simpler tests, projects, presentations, etc. Modules may be divided into typical forms of classes such as lectures, laboratories, exercises, projects, etc.

Regarding the structure of studies at the National Technical University of Athens (NTUA), it is organized into distinct academic semesters, with each semester carrying a value of 30 credit units. The courses offered within the various Schools are designed to span a single semester. The entirety of studies across all Schools encompasses ten semesters, divided equally between five in the fall and five in the spring. The tenth semester is dedicated to the completion of the diploma thesis. On average, each semester involves the coverage of 30 credit units and spans a duration of 18 weeks. Among these weeks, 13 weeks are exclusively allocated for instructional purposes, 2 weeks are set aside for breaks during Christmas and Easter, and the final 3 weeks of each semester are designated for the administration of examinations related to the courses taught during that semester. In the fall semester, the week following the conclusion of final exams is designated as a period for vacations or potentially specialized educational activities. The NTUA plans and organises its educational programme following some main principles. More specifically, to maintain and to enrich the basic five-year diploma degree course structure, which is equivalent with the master's degree, with a strong theoretical background in the applied sciences and technology with an appropriate range and number of courses, and high standards in the diploma thesis. Furthermore, there is a continued emphasis on enhancing studies, with a focus on fostering coherence and profound academic depth. This approach is designed to effectively address both present and future development requirements. It involves a systematic adjustment to the educational approach of active learning, ensuring a methodical alignment. Furthermore, there is an intention to bridge the gap between theoretical studies and practical application, whether it is within a professional context or oriented towards research. Ultimately, this concerted effort seeks to introduce novel vistas in the realm of scientific and technological education (26.09.2023, https://www.ntua.gr).

Finally, continuing the abovementioned, concerning the assessment of the instructional process at the NTUA, surveys (similar to the ones at the Rzeszów University of Technology) are utilized with the purpose of identifying any deficiencies in the provided education and consistently enhancing its caliber. This proactive approach aims to implement fresh teaching methodologies that amplify student engagement through various means, such as expanding and refining practical laboratory work, incorporating multimedia tools, employing electronic questionnaires for evaluation, granting access to digital libraries and resources via faculty members' personal web pages, and fostering improved interaction between academic staff and students. The questionnaires are distributed to students between the 7th and 10th week of each semester by the School Offices, during courses. They are optional and anonymous, and are offering vital information for achieving the above aims.

Recognized as a scientific institution in Germany, the Furtwangen University (HFU) stands out for its excellence across the following domains (https://www.hs-furtwangen.de/en/who-are-we/profile-mission-statement, 30.08.2023; https://www.hs-furtwangen.de/en/programmes 30.08.2023):

- high quality and innovation in teaching,
- strong practical focus through collaboration with industry,
- international focus,
- applied research and education,
- continuing education and lifelong learning,
- cooperation and motivation,
- social responsibility and safeguarding of the future.

The Furtwangen University offers various bachelor's and master's programs at nine faculties. The bachelor's program lasts seven semesters, master's degree program lasts three semesters and is completed in a master's thesis during the third semester. Modules comprise one or more courses evaluated through written exams, practical work, etc. Main examination period, similarly to other partners of the EDURES project, is set at the end of semester.

OECD library indicates that the Italian Higher Educational System operates in an competitive framework of science, innovation and knowledge economy, which, however, faces some challenges. For instance, among G20 economies, Italy had the 5th-highest penetration of machine-to-machine (M2M) subscriptions in 2017 (OECD, 2017b). Italy also accounted for almost 4% of the world's top 10% most-cited scientific publications in 2016. (OECD, 2017b). (26.09.2023, https://www.oecd-ilibrary.org).

The Italian University System is organized in three cycles. Within these cycles academic qualifications, that can be obtained, are associated with each cycle. They allow students to progress with their studies, to participate in public recruitment competitions and to enter the workplace and careers in the professions. University study courses are structured in credits. A university credit (CFU) is usually equivalent to 25 hours of study by a student, including individual study in the total. The average quantity of academic work performed by a full-time student in one year is by convention measured as 60 CFUs. The CFU system is equivalent to the ECTS system. Degree and master's degree study courses that share goals and educational activities are gathered in 'classes' (degree classes). The education contents of each degree course are determined autonomously by each single university: they are obliged to include certain educational activities (and the corresponding number of credits) fixed at a national level. These requisites are established in relation to each class. The qualifications in the same class all have the same legal value (26.09.2023, https://www.cimea.it).

To what is considering the University of Ferrara which operates close to Centoform (the EDURES project partner), it offers a bachelor's degree program in Mechanical Engineering by the Department of Engineering, which is an open access, with a course of study organized into three years of study. The educational activities of the degree program take place at the Scientific-Technological Pole of the University of Ferrara. The normal duration of the course of study is three years. The degree is awarded after the successful completion of all activities in the curriculum studies and the acquisition of 180 credits (26.09.2023, https://www.unife.it/en).

2.2. Preparation of learning outputs

Learning outputs are usually prepared in the area of knowledge, skills and social competences. Teachers usually have a freedom in the case of module outputs definition. However, outputs which are assigned to the field of study (teaching programme) are defined for all modules and teachers have to assign module learning outputs to programme learning outputs.

There are different approaches used by the teachers but usually at least one module learning output is defined to the specific form of class work (e.g. one learning output which concerns knowledge may be assigned to the lecture or learning output which concerns skills may be assigned to laboratory or social competence may be assigned to laboratory or other form of class work).

There are specific verbs which are used to describe the learning outputs goals. These learning outputs should be clearly stated and understood by academia and stakeholders. The learning outputs which are defined within curricula should be also reachable and the entire course should be consistent. There might be a challenge or even a problem in the process of learning outputs preparation for teachers who are not experienced and also for those who were used to other system requirements in the past.

2.3. Currently used didactic methods

Most teachers in the EDURES partnership use typical didactic methods. In the case of lectures, lecturers present the content within oral presentations with the support of boards and projectors. Nowadays lectures may be performed in the university classrooms or on-line. Laboratory is a specific type of classes that requires the use of equipment - test stands, computers, machines, etc. Students work in smaller groups in this case. Projects usually require utilization of calculations regarding specific topics (e.g. construction of machine) and are performed on the basis of some input data given by a teacher. In some cases, laboratory classes and projects are difficult to be distinguished due to various approaches used within class, which are typical for both class types. It can be observed that practical forms of class organization and learning activisation has a great potential and are appreciated by students.

Academic teachers require practical knowledge about active learning methodologies; many universities have established learning and teaching centers to address this need. In the United States, such centers have been operational for over a decade, e.g. ABLconnect at Harvard University, The Yale Poorvu Center for Teaching and Learning, the Center for Teaching & Learning at UC Berkeley, Georgia College and State University, Boston University (https://ablconnect.harvard.edu/, https://poorvucenter.yale.edu/, https://www.gcsu.edu/ctl, https://www.bu.edu/ctl/, https://teaching.berkeley.edu/home 22.09.2023). This practice is also gaining popularity in Polish universities, e.g. Center for Modern Education at Gdańsk University of Technology, the Center for Didactic Improvement and Tutoring at the University of Gdańsk, the Center for Didactic Excellence at Wrocław University of Science and Technology (https://cne.pg.edu.pl/, https://cddit.ug.edu.pl/, https://cdd.pwr.edu.pl/ 22.09.2023). Rzeszów University of Technology is also undertaking initiatives in this direction, recently hosting regular meetings and methodological workshops for academic teachers on modern education. In 2023, the Center for Didactic Excellence formally commenced its operations also at this University.

Various comparisons of the teaching methodologies revealed that partners of the strategic partnership in the EDURES did not have worked out strategy of the recent research-results implementation into teaching processes. Structures of programmes have revealed various similarities and differences, inter alia, described above. Research results implementation activities have been performed by individual teachers mostly.

3. Analysis regarding the best practices and trends in research-based education

3.1. Advantages of research-based education

Research-based education focused on utilization of ongoing or recent results can be characterized by various advantages.

Authors would like to indicate the following advantages of research-based education:

1. Students have the actual knowledge in the areas of research which are crucial for academia.
2. Students pay attention to the discussed topics due to a novelty of taught problems.
3. Dissemination of research results to the companies which employ graduates is extended and ideas developed in universities may be easily transferred to the industry (in particular influence on local companies may be increased).
4. Students who perform their own investigations based on the research results of academics may have a better understanding of real research gaps and challenges of science.
5. Academic community is encouraged to publish high quality research results.
6. Classes may be understood as much more attractive because topics and scope of classes must be updated and adjusted to the changing state of the art resulting from research achievements.
7. Level of classes is adjusted to the requirements of the higher education system.
8. The dissemination of research results may lead to acceleration of innovative ideas - both in teaching and research area.

3.2. Research activities of students

Students usually conduct research within scientific groups, in the process of diploma thesis writing or within classes (i.e. laboratory classes). Scientific groups, mentioned also in further part of the paper, are usually started and run by students who are significantly active persons and want to obtain new knowledge and additional skills. In the case of the diploma thesis writing, mainly in the case of master theses, students are encouraged to conduct research or deeper scientific analysis.

Research conducted within classes depends on learning outputs defined by teachers and may be a modern and attractive form of classroom activities. One such approach is the problem-based learning (PBL), that offers the opportunity to undertake research work and conduct scientific research within a given subject and education course. It allows for the analysis and resolution of real-world problems in collaboration with the economic environment. Within the classes, students can carry out research work conducted as part of university projects and orders, thus staying close to current research problems. In the model developed at Aalborg University, classes conducted with the PBL methodology are the main stream of education every semester (these subjects are assigned 15 out of 30 ECTS points). Students also acquire the knowledge necessary for formulating research problems and conducting team projects, including classes on soft skills covering, among others, interpersonal communication, conflict resolution, project management, and time management. The outcome of this work can be scientific articles written jointly by students and academic researcher.

Introducing the latest scientific research results into the educational process is also possible through scientific interest groups, sometimes operating within the structures of units of individual universities. It allows students to engage in scientific activities, providing them with an opportunity to learn research techniques and methodologies. Within these groups, students can collaborate on research projects, discuss the latest scientific developments, and explore innovative solutions to contemporary problems. This involvement not only fosters a passion for learning and discovery but also allows students to develop practical skills and gain experience in their field of interest, preparing them for future research endeavors and professional challenges. The results of such involvement may include participation in scientific conferences and authorship of joint publications.

3.3. Implementation of research in teaching

The general idea regarding research-results implementation is based on the need for access to the current research results by academic community and partners. The word ‘current’ has a special and crucial meaning in this methodology. The abovementioned methodology is shaped in order to teach teachers how to disseminate research results effectively in order to achieve advantages for technological knowledge and innovation acceleration. This methodology also encourages to search for the benefits resulting from ‘publication’ of research results not only in journals but also to own students.

The EDURES methodology suggests various forms of research results implementation in teaching processes.

The exemplary approaches are as follow:

1. Utilization of open access journal articles into teaching process.
2. Creation of digital platforms which enable to disseminate research results of academia amid academic community members.
3. Starting internal scientific discussions.
4. Implementation of current research results into e-learning environment and possibility of their updating in the future.
5. Asking industrial partners for their opinion regarding current industrial problems and implementing their suggestions into teaching on the basis of own achievements.

Research results implementation methodologies will potentially be one of crucial points in the future of education.

4. Surveys and their results

The confirmation of the need to conduct classes with university students based on didactic materials including the results of scientific research are the results of the surveys that were conducted among students, employees of universities, graduates, and employers. The survey was carried out as part of the Intellectual Output 1 entitled *‘Guide for educators regarding the utilization of research results in technology education’* of the EDURES project. The responses to the selected questions included in the above-mentioned surveys are presented below (Figs. 1-7). The following graphs show the selected results of the survey conducted for graduates.

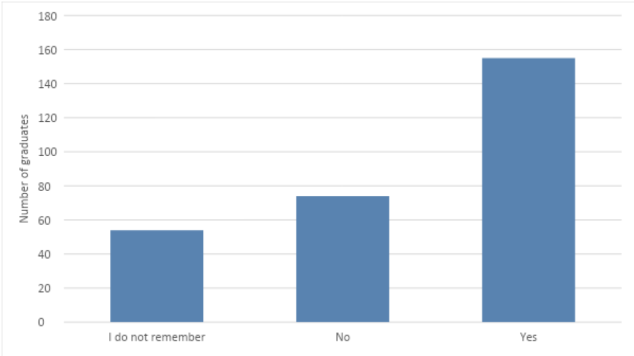

Fig. 1. Question: Did you know about any research conducted at your university during your studies?

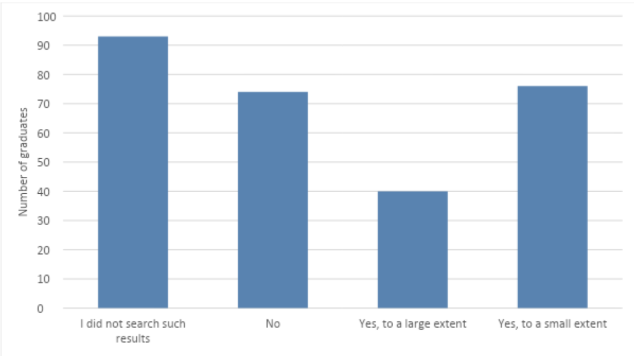

Fig. 2. Question: Did you have access to research results (papers of academics, experiments and test stands, scientific groups, and their achievements) of the university you graduated from?

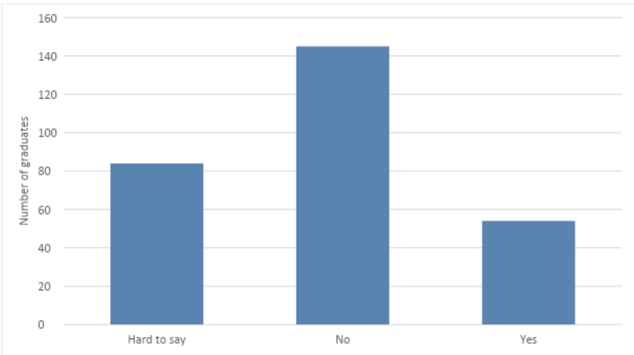

Fig. 3. Question: Did research results of your university enable you to develop your career?

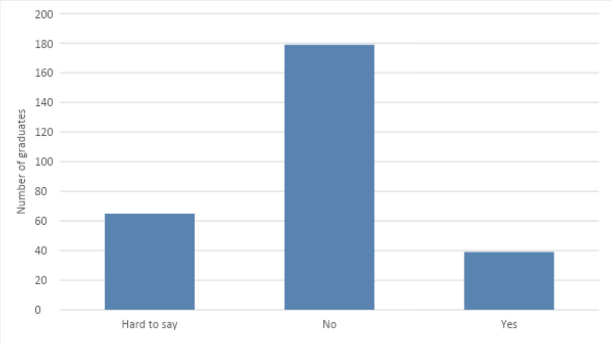

Fig. 4. Question: Did research results of your university enable your firm to develop something new?

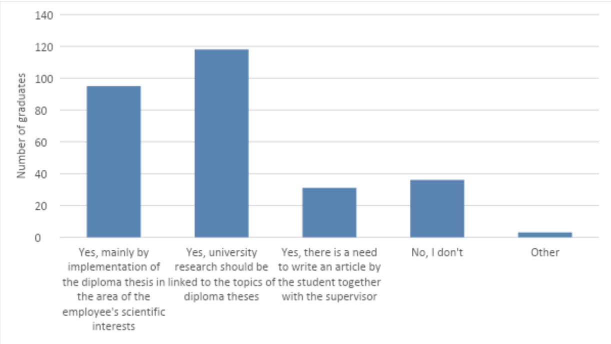

Fig. 5. Question: Do you think that conducted research could be used in diploma theses?

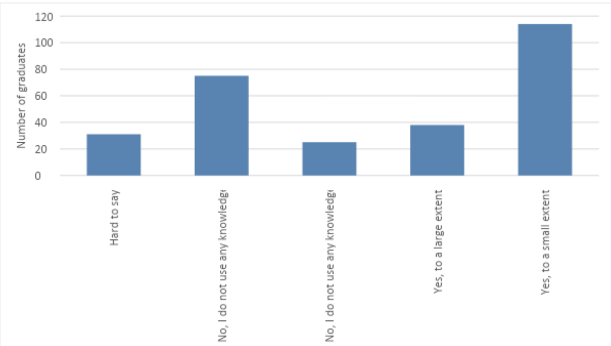

Fig. 6. Question: Do you use the knowledge and skills resulting from scientific research in your current workplace?

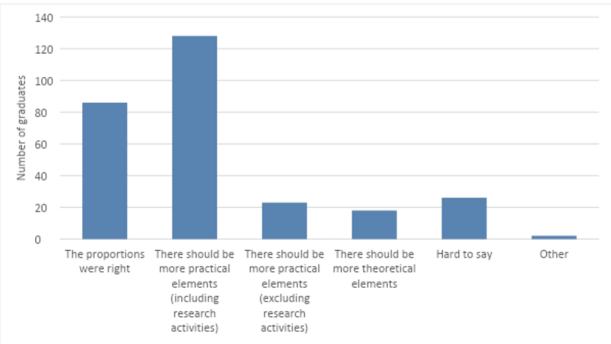

Fig. 7. Question: How, from the time perspective, do you evaluate the relationship between practical, theoretical classes and these which build scientific knowledge and skills of students at your university?

Based on the analysis of the presented results of the surveys, the following conclusions may be issued:

1. Most graduates knew about research conducted at their university during their studies. However, there is also a large group of respondents who have no such knowledge.
2. Most respondents did not search for any research results of the university they graduated from. There is also the large group of graduates who did not have the access to such results or have it to a small extent.
3. Most graduates indicated that research results of their university did not enable them to develop their careers.
4. Most respondents said that research results of their universities did not enable their firms to develop something new.
5. The largest group of graduates indicated that research could be used in diploma theses. Most respondents said that research activities should be linked to the topics of diploma theses.
6. The largest group of respondents think that they use the knowledge and skills resulting from scientific research in their current workplace to a small extent. Moreover, there is the large group of graduates who do not use any knowledge and skills resulting from scientific research in their professional work.
7. Most respondents think that there should be more practical elements, which also include research activities, during their studies.

In turn, from the analysis of the surveys for employers, the following conclusions may be raised:

1. Most employers expect research qualifications from graduates of technical universities.
2. Most respondents think that they should have an influence on the teaching programs and research of higher education institutions.
3. Most employers would encourage their employees to study at a university which offers research skills to students.
4. Large number of employers think that research qualifications are obtained when studying at technical universities. Moreover, graduates of technical universities have extended knowledge, skills, independence, and problem-solving attitude according to respondents.
5. The most respondents are interested in knowledge of their employees graduating from higher education institutions regarding innovations/patents/publications produced by local universities.
6. Most employers do not know any research results produced at regional universities that

have a strong impact on manufacturing firms or know only a few of them.

The detailed survey results for all groups of respondents are presented on the EDURES website. The results of the conducted surveys, despite the large number of graduates who are aware of scientific research conducted at universities, clearly indicate the need to base the didactic process also on the results of research conducted at universities. The obtained answers confirm that the latest research results should be reflected in teaching. Therefore, new teaching materials should be developed and/or modification of currently used materials should be made. New and/or modified materials should incorporate more of the results of ongoing research. Proposals for such materials were created within the EDURES project, and selected ones are presented in the following sections of this article.

5. Lectures including the results of scientific research

The results of the surveys, which are presented in the section and on the EDURES project website, confirm the need to conduct classes based on the results of scientific research. Therefore, as part of the Intellectual Output O3 entitled *'Development of pilot lectures using EDURES methodologies'*, the EDURES project partners developed nine completely new lectures including, among others, the results of their scientific research. These lectures concern, among others: selected aspects of the cryogenic cooling on the milling process of products made of titanium (Figs. 8-10), coordinate measuring technique, surface roughness measurements and additive manufacturing. In the case of the lecture on the metrology of geometric quantities, attention was paid to, among others, on factors influencing the results of coordinate measurements and various methods of distributing measurement points on curvilinear surfaces of products that can be used in the automotive and

Fig. 8. The topic of one of the lectures prepared by the EDURES project partner – Furtwangen University

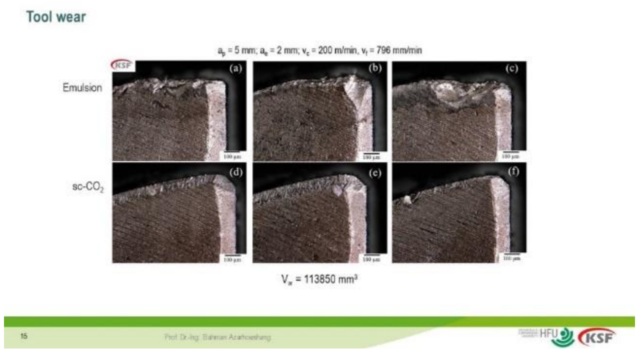

Fig. 9. Wear of cutting tools under cryogenic cooling compared with the conventional cooling (emulsion)

Fig. 10. Experimental setup of cryogenic milling of titanium

aviation industries. The lecture regarding coordinate metrology was based on the results of works published, among others, in articles (Magdziak Marek, 2019a; Magdziak Marek, 2019b).

The full list of the lectures developed, mainly regarding the manufacturing and quality control stages of a production process, is available on the EDURES project website and is as follows:

1. Productivity increase through spark erosion conditioned diamond/CBN grinding wheels.
2. Sc-CO2 Milling of Titanium.
3. Ultra-short pulse laser machining for creating profiles, textures, and functional surfaces.
4. Mechanical Properties of Composite Materials.
5. New Trends and technologies in additive manufacturing: theory application and modelling.
6. An Introduction to the Atomic Force Microscopy (AFM).
7. The use of computer aided technologies (CAx systems) in selected areas of technological research for manufacturing and civil engineering.
8. Comparison of conventional and modern CNC technologies.
9. Quality control and surface texture measurement.

6. E-learning courses including the results of scientific research

Based on the above lectures, which are the results of the Intellectual Output O3 of the EDURES project, the e-learning courses were developed as part of the Intellectual Output O4 entitled *'Digital platform with implemented EDURES teaching content'*. These courses were prepared by using the Moodle e-learning platform after analysis of e-learning platforms available for project partners. The figures 11 - 14 show parts of the course on e.g., coordinate metrology. The course includes four lessons, a database of videos and a forum that allows the exchange of opinions on the issues raised during the course. The films present the use of modern measuring systems and metrological software cooperating with them during, among others, measurements of free-form surfaces of products. The proposed elements of the coordinate measurement strategy can be used in industrial conditions to improve the accuracy of measurements and shorten the time of their implementation. The practical application of the information contained in the developed e-learning course is consistent with the conclusion drawn based on the analysis of the results of surveys conducted among entrepreneurs who are interested in the knowledge of their employees in the field of research results published in scientific journals.

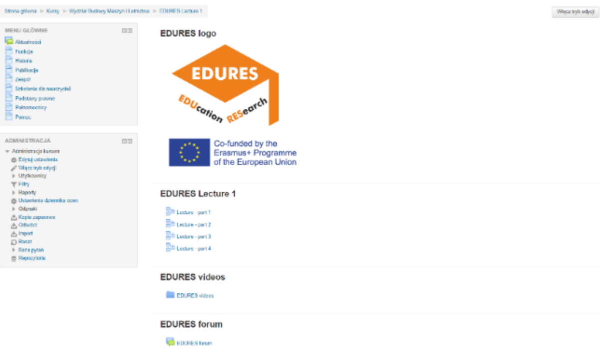

Fig. 11. The structure of one of the e-learning courses on the metrology of geometric quantities

Fig. 12. The fragment of one of the lessons of the developed course

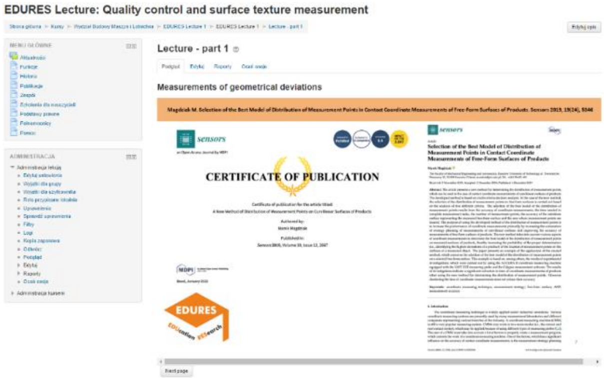

Fig. 13. The course is fully based on the results of scientific research

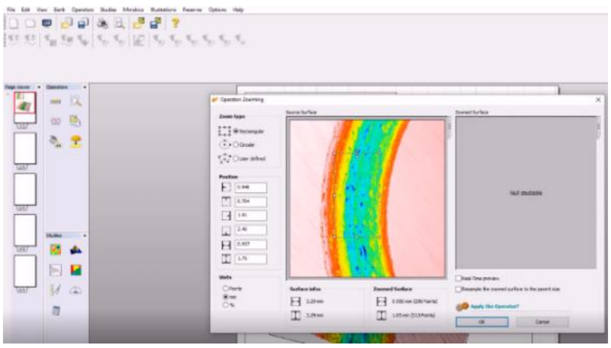

Fig. 14. One of the videos that are part of the e-learning course on surface roughness measurements

7. Research portal

As part of the Intellectual Output O2 entitled *'Development of the digital platform methodologies for utilization of research results in technology education'* of the EDURES project, survey research was conducted to develop the structure of a research portal enabling the popularization of research results. The figures 15-21 show selected results of research carried out at the Rzeszów University of Technology.

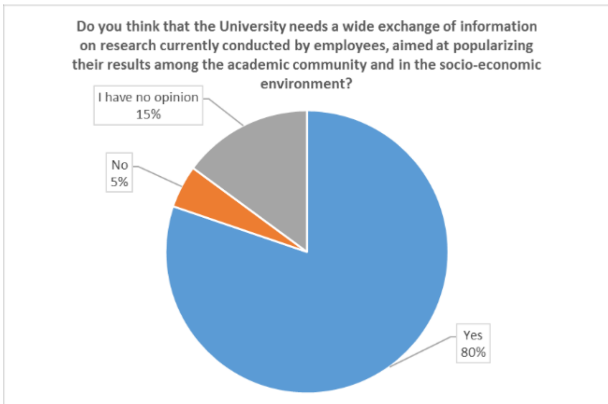

Fig. 15. Question: Do you think that the University needs a wide exchange of information on research currently conducted by employees, aimed at popularizing their results among the academic community and in the socio-economic environment?

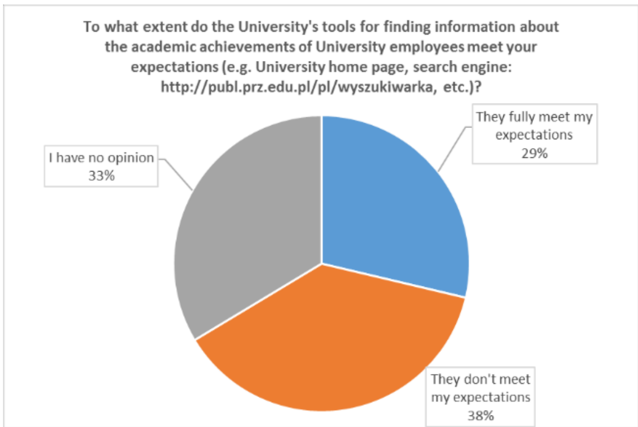

Fig. 16. Question: To what extent do the University's tools for finding information about the academic achievements of University employees meet your expectations (e.g. home page, search engine)?

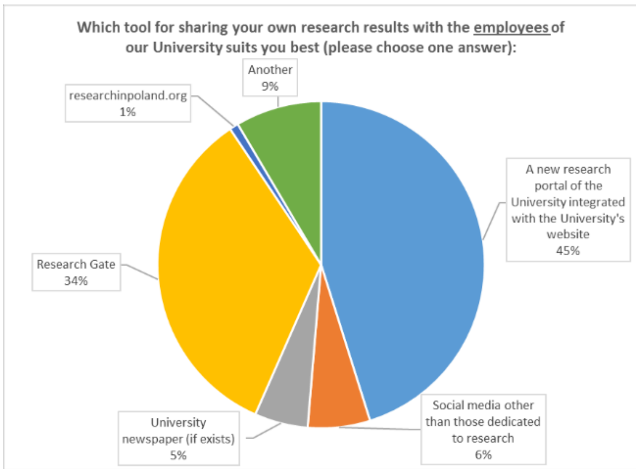

Fig. 19. Question: Which tool for sharing your own research results with the employees of your University suits you best (please choose one answer)?

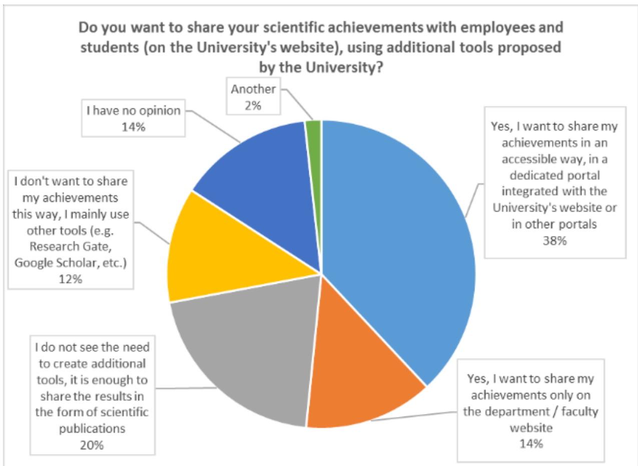

Fig. 17. Question: Do you want to share your scientific achievements with employees and students (on University's website), using additional tools proposed by the University?

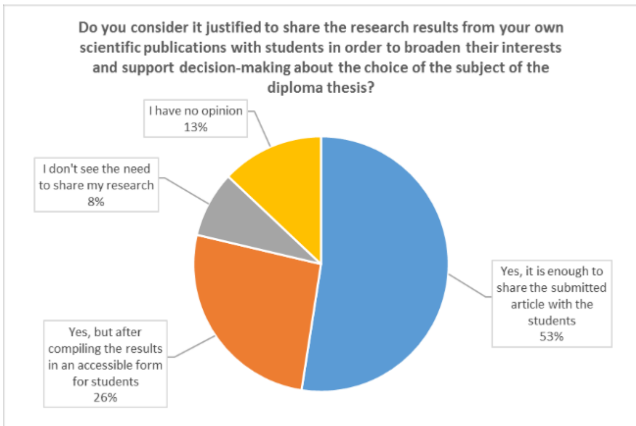

Fig. 20. Question: Do you consider it justified to share the research results from your own scientific publications with students in order to broaden their interests and support decision-making about the choice of the subject of the diploma thesis?

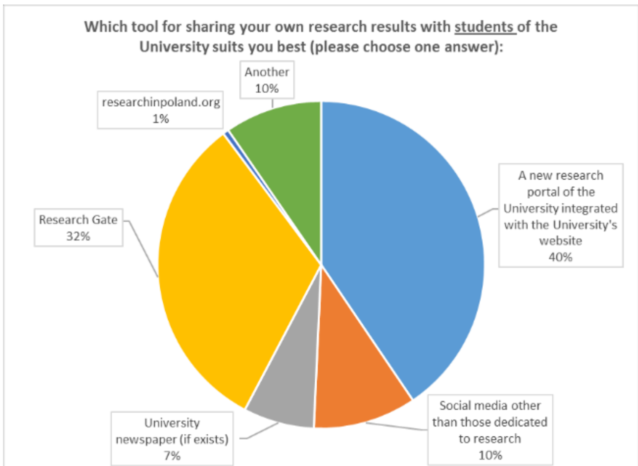

Fig. 18. Question: Which tool for sharing your own research results with students of the University suits you best (please choose one answer)?

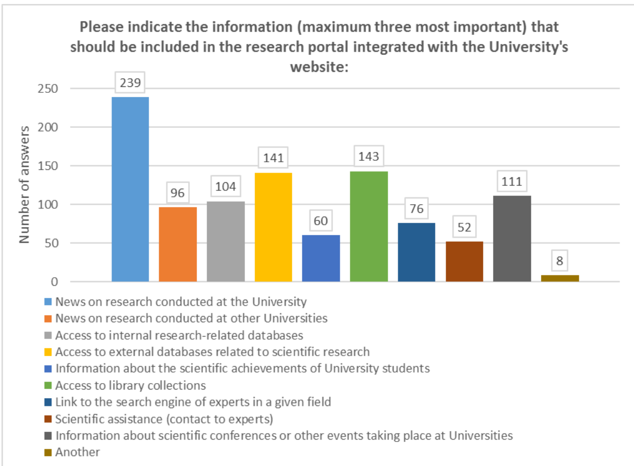

Fig. 21. Survey request: Please indicate the information (maximum three most important) that should be included in the research portal integrated with the University's website

Based on the analysis of the survey results, the following conclusions can be drawn:

1. Most of the respondents believe that it is necessary to exchange information on research conducted by university employees.
2. Most of the respondents are not satisfied with the tools that enable searching for information on scientific achievements of university employees.
3. Most employees of the Rzeszów University of Technology are willing to share their scientific achievements with students and other employees.
4. 40% of respondents want to share the results of their research with students via a research portal integrated with the university's website.
5. 45% of respondents want to share the results of their research with university employees via a research portal integrated with the university's website.
6. Most of the respondents believe that it is justified to share the results of their research with students to, among others, expanding their interests.

The results of the surveys clearly indicate the need to create a research portal enabling the sharing of research results with the academic community. Therefore, on their basis, the structure of the research portal was proposed, which includes the following elements:

1. News from scientific disciplines: this section concerns the latest news from the scientific disciplines which are run at the university.
2. Students' research: the section concerns the latest news from the scientific groups of students.
3. Scientific databases: the section should give an access to the scientific databases available at the university – mainly the databases shared by the university library.
4. Scientific help: the section gives an access to reference managers, software, manuals, and different instructions.
5. Perfect thesis: this part of the portal should give some instructions for students developing their theses at the university, including procedures, required documents, access to the topics, writing hints, etc.
6. Collaboration link: access to chat, forum, communication platforms.
7. Talk to professor: the direct access to communication tools enabling to discuss the scientific problems with professors and experts.

7. Conclusion

It has been proved that research-based education can have a significant impact on the entire teaching process in higher education institutions. Presented results of the surveys informed us that students of our universities pay attention to the interesting classes which are based on scientific achievements. The presented methodologies will help to organize the teaching process and increase the number of interesting presentations within lectures regarding the recent research results, number of scientific experiments, practical tasks in laboratories which form the modern skills of learners (e.g. skills which are based on the digital tools usage), etc. It can be also stated that the attention should be paid on the use of different digital platforms such as e-learning platforms or existing web portals for the aims of recent scientific achievements and knowledge transfer to the audiences. Especially platforms such as web portals play a crucial role for local stakeholders of knowledge who do not have direct access to the scientific databases and e-learning platforms. It shall be finally stated that it is worth implementing research results in teaching processes and universities should look for some solutions in this area. Selected tools such as: research-oriented work books for teachers, web portal methodologies, revision of e-learning platforms capabilities, lectures with implemented research results, smart web tools (e.g. thesis wizards) have been proposed by the EDURES partnership to be utilized and continuously developed in the future. The EDURES team has been presenting current project results which are the part of the paper on the project webpage placed (https://www.edures.prz.edu.pl 30.08.2023).

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