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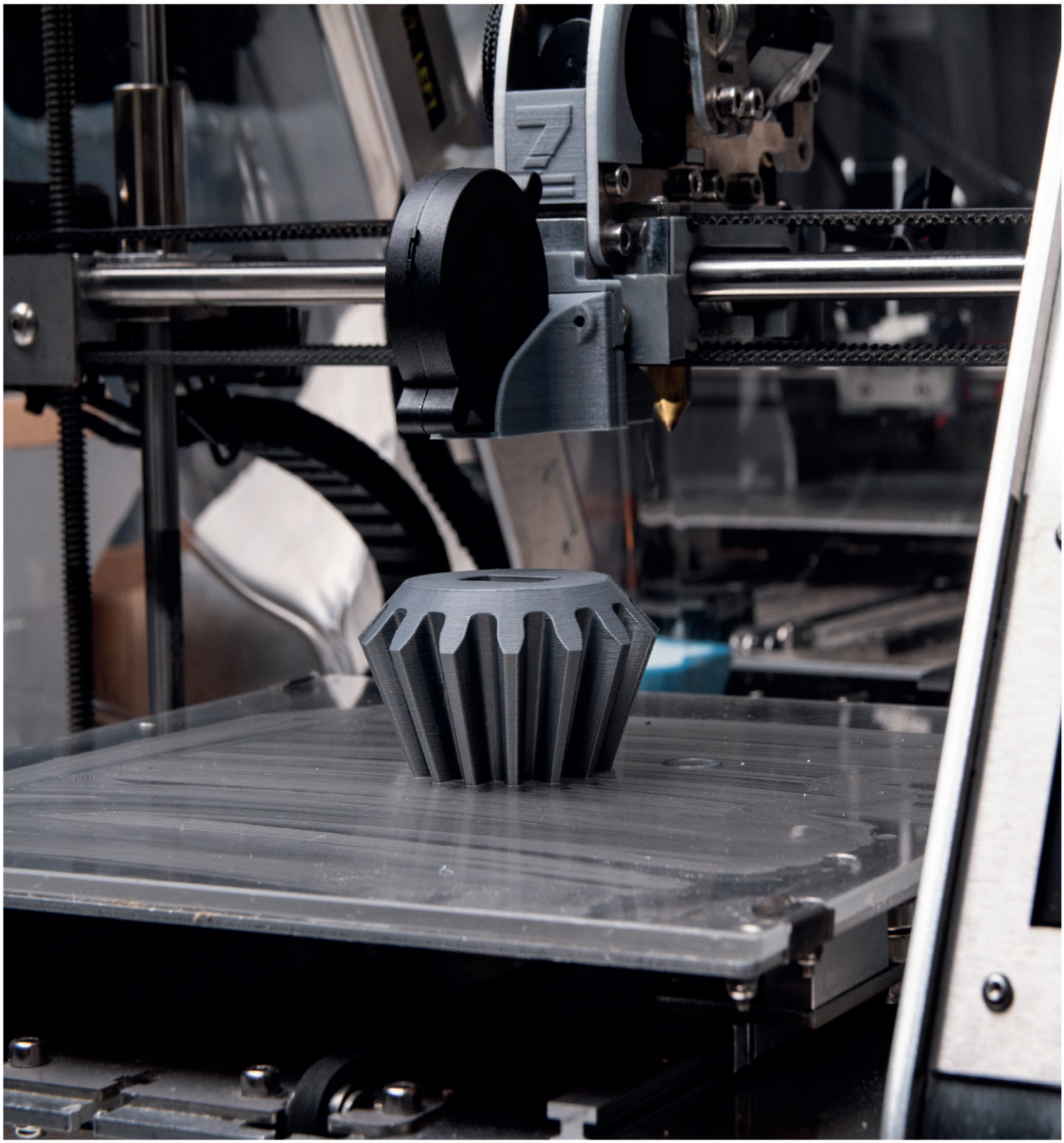

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PERSPECTIVES FOR THE DEVELOPMENT OF ROBOTIZATION IN ENTERPRISES

KATARZYNA ANTOSZ

Dear Authors and Readers,

It is well known that robotization of processes allows to increase the productivity and efficiency of processes, and thus, reduce operating costs. Due to the increasing demands placed on enterprises, robots are constantly evolving and they are used to a growing extent. This fact is confirmed by the available research results which indicate the rise in the needs in the field of robotization and automation of processes, not only in production. In addition, many companies in the current epidemic situation have noticed how extremely valuable it is to maintain production continuity that is guaranteed by working without interruptions. Currently, there are many solutions available for enterprises to take advantage of. Here are a few of them.

Intralogistics is one of the areas that will be subjected to robotization to an even greater extent than before. Mobile robots are increasingly used in this area. However, mobile robots can perform much more functions than handling transport orders. Their use in the creation of a second, parallel production line or rapid expansion of processes may be a key to maintaining the plant's position on a competitive market. Automation with the use of autonomous mobile robots can bring far greater benefits if they are also strategically used in production. Modern mobile robots can be used as autonomous product carriers, including the transport of heavy pallets (automating transport and storage orders as well as delivering components to an assembly area), but they can also successfully act as a mobile production station, constituting a new link in a flexible production line. They are safe in cooperation with a human, with the possibility of quick reconfiguration for new tasks without stopping the main process.

Many enterprises use other industrial robots that learn and do not require complicated programming, which solves many problems. More and more new types and models are created. Nowadays, industrial robots are used for both simple, monotonous, but also dangerous for humans, as well as more and more complex works requiring speed and precision. First of all, they are used for palletizing cardboard boxes or packages, loading and unloading, welding and processing (grinding, drilling, milling, etc.), as well as painting and varnishing, sealing or applying adhesives. Interestingly, it is increasingly profitable to use industrial robots not only for mass production but also for unit production.

In the coming years, it will be more and more common to combine artificial intelligence with machine learning and the automation of processes in which robots are involved. This will apply to all departments of an enterprise, from invoice processing to asset management. Entrepreneurs will notice these effects quickly: more tasks handled, fewer or completely eliminated errors, less workload on employees. Thanks such hyperautomation, it is also possible to create the so-called "digital twin" of an institution or company, which will allow you to track processes in real time. It is a set of tools for building process models, their verification and extension based on the data from event logs, describing the actual course of business events. This solution will allow you to notice what you would not be able to see with the naked eye.

However, automation and new technologies are changing the labor market. Unfortunately, some professional groups will have to adapt to the changes. Many tasks performed by professionals such as office workers, drivers, officials are likely to be performed by robots. However, questions arises: will new professions appear instead? How will the labor market handle it? It is worth remembering, however, that a robot does not have either human locomotive abilities or a specific energy level. Therefore, the best solution is to achieve a perfect balance between digitized tasks and those performed by people. This will allow not only to increase the effectiveness and efficiency of processes, but also to have competent, reliable and committed employees.

ANALYSIS OF THE PROPERTIES OF RFSSW LAP JOINTS OF ALCLAD 7075-T6 ALUMINUM ALLOY SHEETS UNDER STATIC AND DYNAMIC LOADS

Analiza właściwości połączeń zakładkowych blach ze stopu aluminium 7075-T6 Alclad zgrzewanych metodą RFSSW w warunkach obciążeń statycznych oraz dynamicznych

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A b s t r a c t: This paper presents research regarding refill friction stir spot welding (RFSSW) of EN AW-7075-T6 Alclad aluminium alloy sheets, and the joint behaviour under static and dynamic loads. Single-point lap joint of sheets with different thicknesses, which corresponds to those used in aircraft fuselage structures, i.e. upper sheets with a thickness of 1.6 mm and lower sheets with a thickness of 0.8 mm, were analysed regarding the failure mechanism in static shear testing. It has been shown that a properly made joint is destroyed as a result of tension in the lower plate. The lower plate at the edge of the weld is structurally weakened by the HAZ, but also geometrically due to plastic deformation during the welding process, which has been demonstrated by metallographic investigations as well as by the FEM numerical model. Single-row RFSSW welded joints with different spacing of the welds and a riveted joint were impact tested. It has been shown that welded joints are characterized by a greater stiffness, which is higher when the spacing of the welds is smaller.

K e y w o r d s: RFSSW, aircraft fuselage skin, aluminium alloy, drop-weight impact test, FEM, impact resistance

S t r e s z c z e n i e: Praca przedstawia badania połączenia zakładkowego RFSSW blach ze stopu aluminium EN AW-7075-T6 Alclad pod wpływem obciążeń statycznych oraz dynamicznych. Jednopunktowe połączenie zakładkowe blach o różnej grubości co odpowiada połączeniom stosowanym w konstrukcjach kadłubów lotniczych tj. górna blacha o grubości 1.6 mm oraz dolna blacha o grubości 0.8 mm, poddano analizie mechanizmu zniszczenia w próbie statycznego ścinania. Wykazano, że poprawnie wykonane połączenie ulega zniszczeniu na skutek rozciągania dolnej blachy. Dolna blacha przy krawędzi zgrzeiny jest osłabiona strukturalnie przez strefę wpływu ciepła, ale także geometrycznie poprzez deformację plastyczną powstałą podczas procesu zgrzewania, co wykazano na podstawie badań metalograficznych jak również przy użyciu modelu numerycznego MES. Jednorzędowe połączenia zakładkowe poddano badaniom udarności. Badano połączenia zgrzewane RFSSW o różnym rozstawie zgrzein oraz połączenie nitowane. Wykazano, że połączenia zgrzewane charakteryzują się większą sztywnością, która jest tym większa im mniejszy rozstaw zgrzein.

S ł o w a k l u c z o w e: zgrzewanie RFSSW, pokrycia kadłubów lotniczych, badania dynamiczne z użyciem młota opadowego, MES, odporność na uderzenia

Introduction

A relatively new technology for joining construction materials, especially unweldable metals, is the friction stir welding method. Refill Friction Stir Spot Welding (RFSSW) is a derivative of this process and combines many advantages, so it may soon become an alternative to traditional joining methods.

One of the areas of industry where the RFSSW welding method can be widely used is the aviation industry. In this industry, there is a great demand for technologies ensuring structural joints with high strength, which could be used for the construction of thin-walled stiffened structures.

Despite the undisputed advantages of the RFSSW technology over riveting, this technology, being relatively new, is not yet fully understood. Controlling the parameters of the welding process means that there are many combinations of parameters which translate into different conditions and, consequently, different quality levels of the joint in terms of strength and structure. As part of the research carried out by the authors of this work, parameters of the welding process were selected to ensure a high load-bearing capacity and the required quality of the joint structure in the variant under consideration, as presented in the works [10, 11].

Loads of static forces and cyclically repeating variable loads causing fatigue are the basic, but incomplete

spectrum of operational loads of stiffened thin-walled structures, used, among others, in aircraft construction. An important issue that should be considered in the tests of this type of structure is damage due to random events causing dynamic loads.

Aviation structures can be exposed to many dynamic impact events. Basically, in civil aviation, such events can be divided into two groups. The first is the collision of an aircraft with a foreign object during the flight [17]. These are mainly the impacts of ice blocks during hail [8, 9], as well as collisions with birds [4, 19]. These types of damage to aircraft structures are generally associated with a high impact velocity and a relatively low mass of the object.

However, most damage of aircraft structures as a result of random foreign object strikes in civil aircraft occurs primarily in ground handling [6]. Then, accidental impacts occur during loading or unloading, and this is the most common form of damage to the structural elements of an aircraft [6]. Dynamic impacts of aircraft skins during maintenance are also common. Finally, there are cases of collisions with objects, e.g. during taxiing [3].

Ground damage cases caused by dynamic impacts are characterized by a relatively low impact speed, as well as a significant mass of the objects defined as foreign bodies. The authors of the studies [5, 14, 16] defined the speed range for collisions classified as low speed in the range of 1-10 m/s. In practice, however, the impact speed are usually around 2 m/s [4]. Therefore, when carrying out experimental research or modelling phenomena occurring in the considered events, they are considered as quasi-static phenomena [3, 4]. With low-speed impacts, the contact between the object and the structure is so long that the entire structure carries a dynamic load, similar to a static load [1, 15].

Charpy and Izod tests as well as drop weight tests are commonly used for impact testing with low impact velocities [16]. In the case of impact strength tests of aircraft structures, the last of the mentioned methods most precisely reflects the conditions of real random events related to dynamic loading of the structure [2, 13].

This paper presents the results of tests of RFSSW joints subjected to static shear tests. The failure mechanism was analysed based on metallographic investigations. Modelling of the welding process using the FEM method was also performed in order to theoretically determine the mechanical phenomena occurring during joining the sheets. In the next step, comparative tests of single-row RFSSW lap joints and riveted joints subjected to the impact bending test were carried out. Since the considered joint is being analysed in terms of the possibility of using it as an alternative form of joining of thin-walled structures, where rivets are commonly used, therefore, comparative tests were carried out. The comparative tests were carried out for single-row lap joints typically found in thin-walled aircraft structures. The drop weight impact test was carried out. The justification for conducting such tests is the exposure of thin-walled structures to various types of random events that may be associated with a dynamic impact on the structure.

Materials and method

The tests were carried out for overlap joints of sheets with different thicknesses, corresponding to the stringer and the skin, based on the example of a thin-walled aircraft structure. It was assumed that both elements would be made of EN AW-7075-T6 aluminium alloy. This alloy is characterized by a high static and fatigue strength [11]. It is difficult to deform the material plastically as the yield point is close to the tensile strength [11]. Moreover, the material is difficult to weld and has a relatively low corrosion resistance [11]. The basic feature, which is a high strength while maintaining a low weight, makes this material widely used in the construction of aircraft structures. Due to the relatively high susceptibility to intercrystalline corrosion, the sheets used in the construction of thin-walled aircraft structures are usually clad, i.e. covered with a thin (about 5% of the thickness of the parent material) layer of technical aluminium, i.e. almost pure aluminium, in the hot rolling process. Fig. 1 shows a microscopic view of a 1.6 mm thick sheet with the visible clad layer.

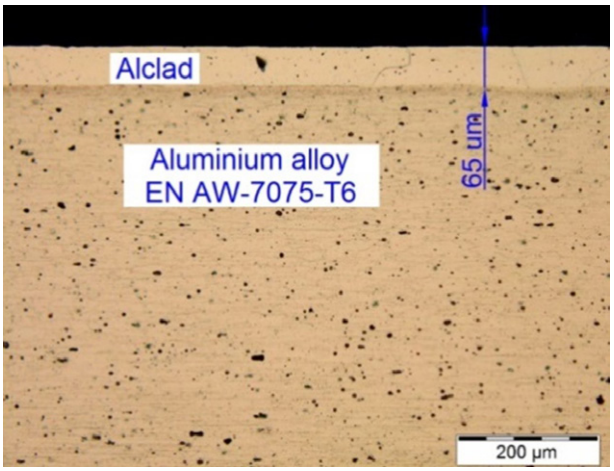

Fig. 1. Microscopic view of the sheet used in the tests with a visible layer of the alclad

For the sheets used, the mechanical properties were determined in static tensile tests according to EN ISO 6892-1: 2016 [7]. The tests were made for three different directions in relation to the rolling direction of the sheet, i.e. 0 °, 45 ° and 90 °. Five repetitions were performed for each of the directions. Table 1 summarizes the values of the basic parameters determining the mechanical properties of the material used.

Single-point lap joints with the dimensions shown in Fig. 2 were subjected to static tests. The welded joints were made with the use of a special machine for RFSSW spot welding, i.e. RPS100 VA11 by Harms & Wende GmbH & Co KG (Hamburg, Germany). The samples

Table 1. Basic mechanical properties of 7075-T6 aluminium alloy sheets

Parameter	Young's modulus E MPa	Yield stress Rp0.2, MPa	Ultimate tensile strength Rm, MPa
Value	70316	463	530

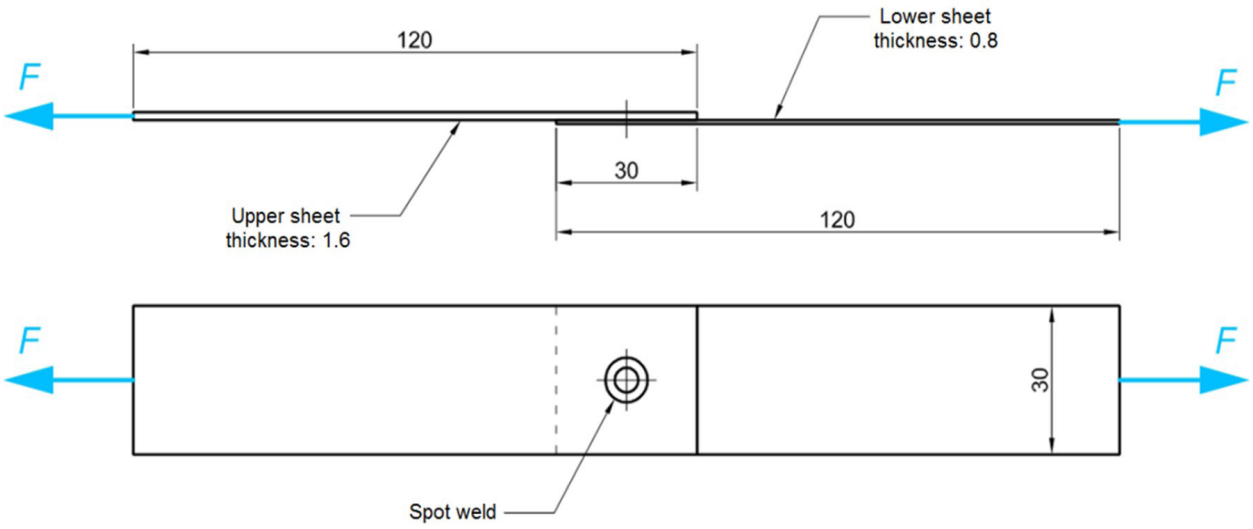

Fig. 2. Shape and dimensions (in mm) of the welding specimens

used in the tests were made using the following welding parameters: tool rotational speed n = 2400 rpm, sleeve plunge depth g = 1.55 mm and welding time t = 3.5 s.

The tests of static strength were carried out at room temperature on a Zwick / Roell Z100 testing machine, the jaw feed rate was 5 mm/min.

Microstructure and fracture morphologies of selected specimens were analysed using a Phenom ProX (Phenom-World B.V., Eindhoven, Netherlands) variable pressure scanning electron microscope (SEM).

The numerical simulation model of the RFSSW process has been conducted using the Simufact Forming software (Simufact Engineering Gmbh, Hamburg, Germany). Due to the symmetrical nature of the process, a 2D axisymmetric simulation was performed.

In FE-based simulations of the welding process, a number of simplifications of the numerical model have been adopted in relation to the real conditions. Individual elements of the tool, i.e. pin, sleeve and clamping ring in the FE model were adopted as cylindrical bodies with smooth surfaces. So, characteristic grooves made on the outer surfaces of the pin and sleeve were omitted. Due to the relatively small plunge depths of pin and sleeve, these grooves do not significantly affect the welding process conditions in the case of joining thin sheets. The sleeve, pin and clamping ring were all considered as rigid bodies. It is well known that the Alclad layers have a significant effect on the heat distribution during the welding process due to the significantly higher thermal conductivity of the Alclad material in relation to the material of base plate. Therefore, the model consists in an intermediate layer between sheets to reflect the properties of the Alclad. The thickness of the Alclad layer in the numerical model was equal sum of the Alclad layers on both upper and lower sheets.

The sheets and Alclad were modelled with 2D elements, destined for analysis of 2D axisymmetric problems, called Quad (10) in Simufact Forming terminology [18]. Rigid tools were modelled with quad elements called Quad (40) [18]. The initial mesh (Fig. 3) has been generated using Advanced Front Quad mesher. During

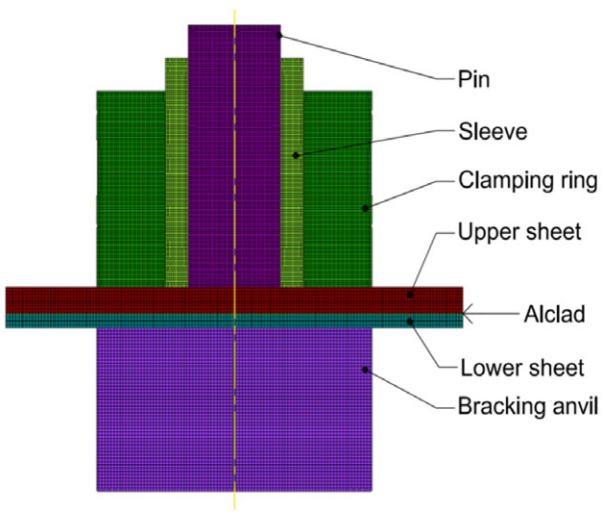

Fig. 3. Finite element mesh of 2D model

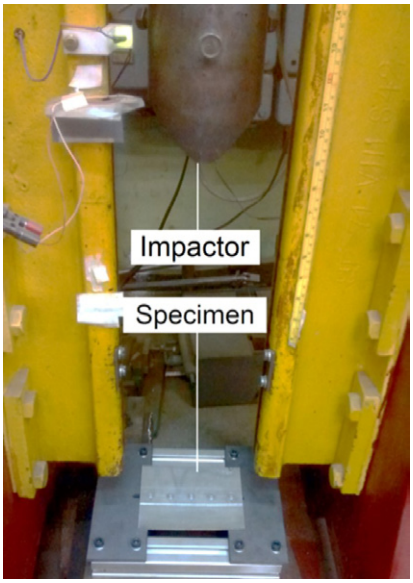

Fig. 4. Drop weight test stand

the simulation of the RFSSW process, the initial mesh gets distorted due to the large displacement and does not fit the required mesh quality anymore. Excessive mesh distortion of the FE-based model leads to divergence problems. To avoid too much distortion of the mesh elements, an automatic remeshing that automatically regenerates the mesh was used and the simulation is continued using the new mesh. The sheets and Alclad models were composed of 3474 elements Rigid bodies consists of 4549 elements.

Impact tests were carried out using a drop weight testing machine. The complete test stand with the test sample is shown in Fig. 4. The element causing the dynamic load by gravity is composed of a drop weight with a mass of 27 kg and an impactor with a mass of 8.81 kg, which gives a total mass of 35.81 kg.

Tests of single-row lap joints were carried out for RFSSW welded joints with different spacing of welds, as well as for riveted joints. The riveted specimens were made with anodized, roll-formed aviation rivets with a mushroom head 3 mm in diameter, made of PA24 aluminium alloy.

Fig. 5 shows the geometry and dimensions as well as the method of supporting the samples of single row joints used in dynamic tests.

In the dynamic load test, the measurements of geometric quantities characterizing the degree of sample deformation were made. The presented configuration of the load is a classic three-point bending, therefore the values of the deflection of the sample were measured. The plastic deflection was determined after the test, while the elastic deflection had to be recorded at the moment the hammer hit the sample. Thus, the registration of the elastic deflection was made by placing plastic masses directly under the sample, which fixed the value of this deflection.

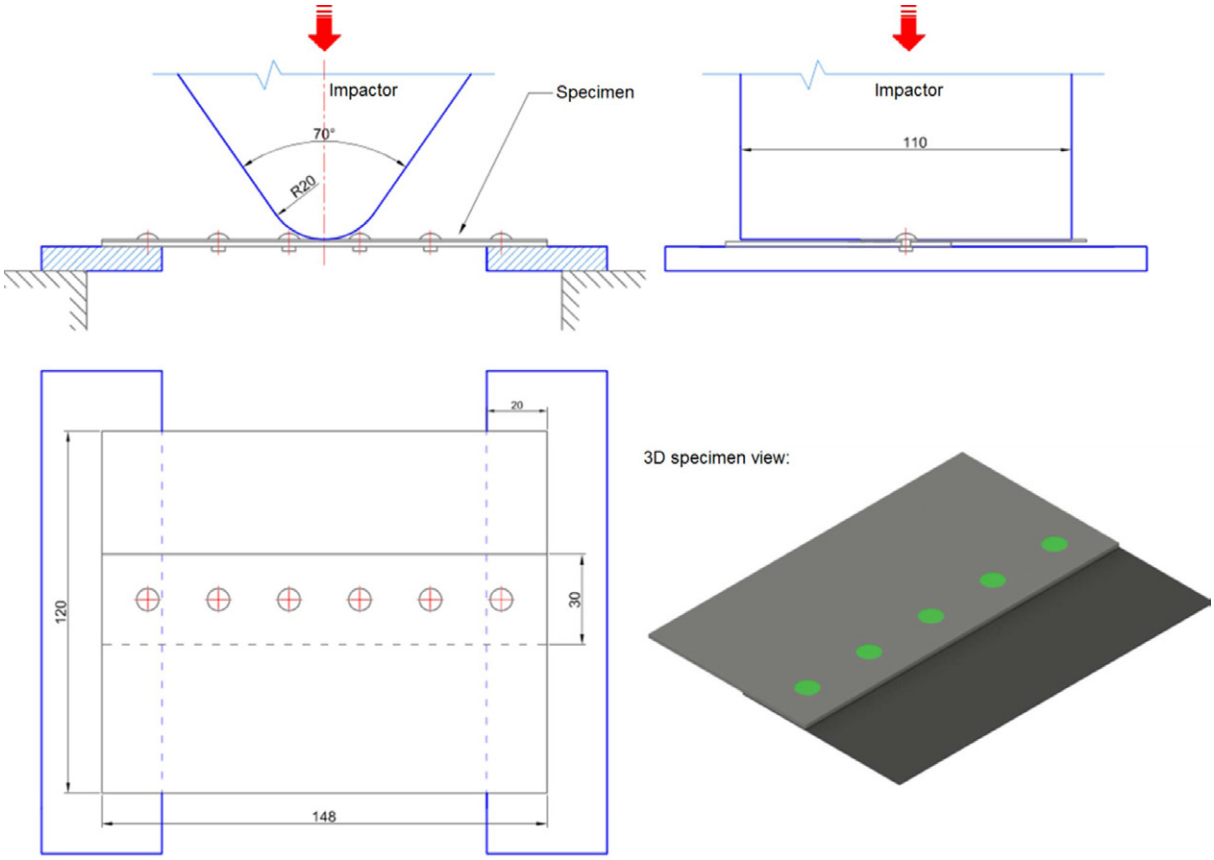

Fig. 5. Dimensions and configuration of the support and loading of the specimen during the impact test

A rivet spacing of 23.5 mm was used, as this value is used in typical thin-walled aircraft structures. In the case of welded joints, two different spacings were used. In the first case, the principle of spacing between the edges of the joints was followed, while maintaining the same dimensions between the edges for welded joints as in the case of riveted joints, which are schematically shown in Fig. 6. Thus, a spacing of 29.5 mm was used. Due to the larger surface area of the welded joint compared to the rivet, the welded samples with a spacing of 50% greater, i.e. 44.25 mm, were additionally tested.

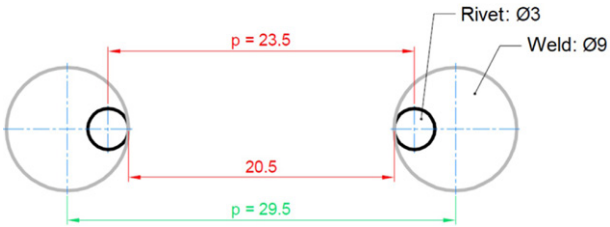

Fig. 6. The diagram illustrating the selection of the basic spacing of welds based on the spacing of rivets

Results

Fig. 7 shows a representative curve obtained in a static shear test for the joined samples considered. It was shown that in case of the welding process parameters used, the failure of the joint was achieved by tension of the lower sheet, while the crack was initiated at the perimeter of the weld in the heat-affected zone (HAZ) (Fig. 8).

The mean value of the load capacity for the five repetitions carried out is 5.78 kN (SD: 47.20 N). The demonstrated method of sample destruction proves the high strength of the joint itself, which was not sheared. The crack in the sheet in tension is not the result of the load reaching the Rm value of the material used. Directly at the weld, due to thermo-mechanical phenomena, the sheet was locally weakened, assuming lower strength parameters than the parent material in the T6 state.

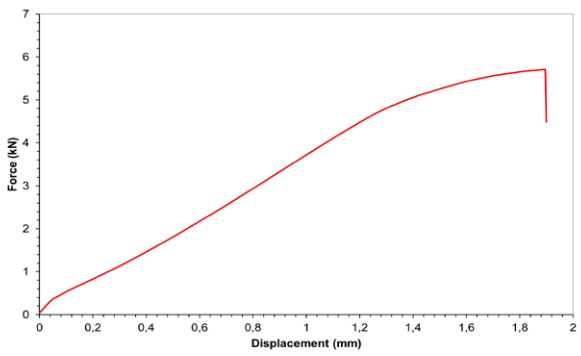

Fig. 7. Representative curve Force-Displacement obtained in a static shear test for single-lap joints

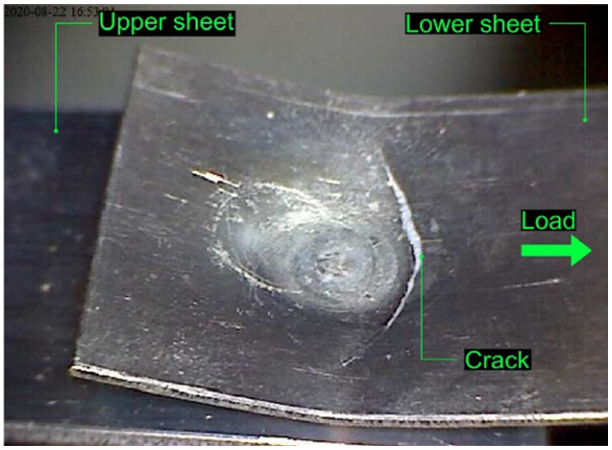

Fig. 8. View of the lower sheet with a visible crack due to tensile stress at the perimeter of the weld

It was observed that the lower sheet was deflected before it cracked due to the bending moment. The failure mechanism of the joint in question is strictly dependent on the configuration of the sheets to be joined. As the sheets have different thicknesses, hence a significant difference in their stiffness leads to an asymmetric state of stresses when loading the lap with an axial force. Fig. 9 shows the stresses that arise in the joint during its loading with uniaxial force.

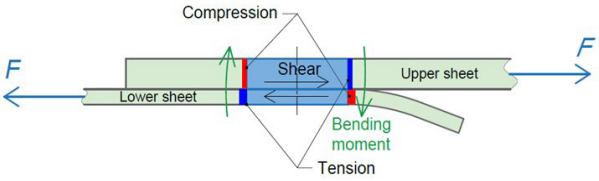

Fig. 9. Stresses in the lap joint caused by uniaxial tensile force

When the critical stress value is exceeded, the bottom plate cracks at the perimeter of the weld. Based on the metallographic analysis, it was shown that in the joint forming process, plastic deformation of the lower sheet occurs caused by the material pressed through the sleeve at the end of the process (Fig. 10). This phenomenon was confirmed on the basis of the FEM numerical model. Figs. 11a, b show the final stage of the simulation of the joint creation, indicating the phenomena taking place in the material on the basis of the accumulated plastic strain (Fig. 11a) and also the displacement vector (Fig. 11b). This deformation along the periphery of the weld leads to a reduction in the cross-sectional area of the lower plate, which in turn results in cracking at that location. Additionally, in the place where the cracking of the sheet was found, the material was weakened by the influence of the heat-affected zone. Regarding the fracture, a typical separation ductile fracture was observed, which is due both to the direction of the fracture (fracture at an angle of about 45°) and the nature of the fracture surface shown in the SEM image - Fig. 12.

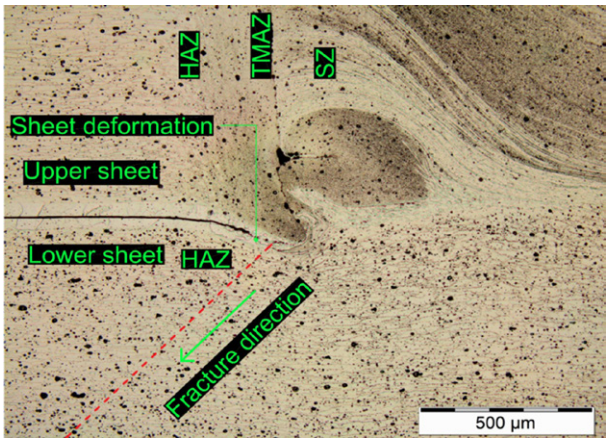

Fig. 10. Macroscopic image of the weld corner with visible deformation of the lower sheet and with the direction of cracking marked

In the tests, the assumed impact energy was 26.3 J, which corresponds to the hammer height of 75 mm. As a result, an impact velocity of 1.33 m/s was obtained. After the impact, the plastic and elastic deflections at the moment of impact were measured. Table 2 summarizes the average values of the measured values for individual variants.

Each of the joint points was also verified, assessing whether they were damaged or not. Fig. 13 shows samples for each variant. In the case of samples welded in both considered spacings, the welds were coherent (Figs. 13b, c). In the case of the riveted joint (Fig. 13a), the two extreme rivets were sheared. The microscopic images (Fig. 14) clearly show that there was a relative shift of the sheets due to the bending of the overlap, and thus the rivets were sheared in the plane of the sheet connection.

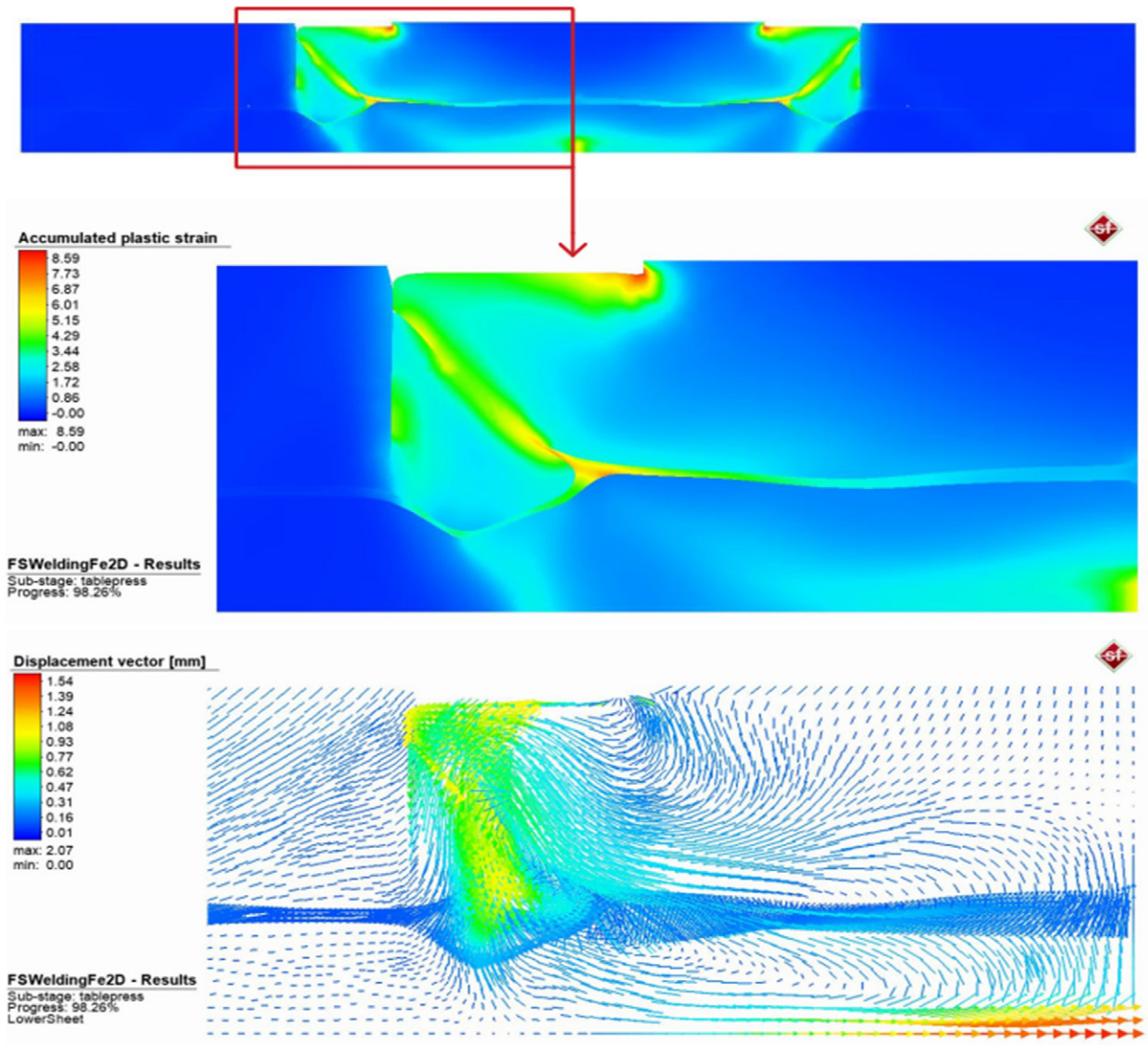

Fig. 11. View of the deformation in the weld zone at 98.26% of the RFSSW cycle: a) accumulated plastic strain, b) displacement vector (mm)

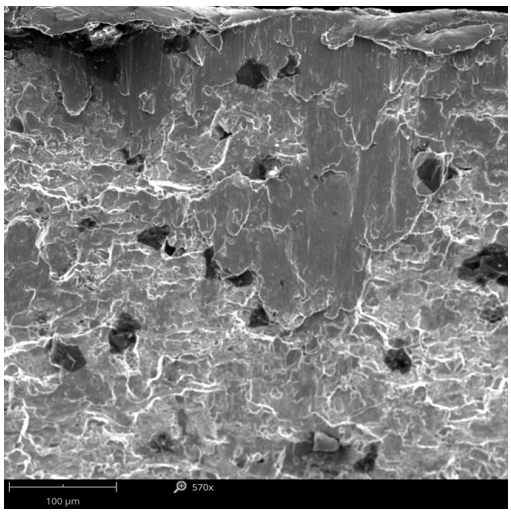

Fig.12. SEM micrograph showing the fracture surface morphology of lower sheet

Based on the test results, it has been shown that the RFSSW joint is more rigid than the rivet joint. This is influenced by various factors. The lower stiffness of the riveted joint is due to the holes in the sheets, in addition, the total area of the joint is greater in the case of welded variants (rivet diameter is 3 mm, weld diameter - 9 mm). It should also be noted that in the presented tests, the extreme rivets sheared, which also had an impact on the reduction of joint stiffness. It has also been shown that the stiffness of the welded joint is higher for a smaller spacing of the welds.

Fig. 15 shows SEM images of the chamfer surface of rivet 1 (Fig. 15a). In a small fracture area at the edge of the rivet, a brittle fracture can be observed, as shown by the SEM images shown in Figs. 15b, c. The area where brittle fracture occurs is at the edge at which the fracture initiated under dynamic loading. However, the dominant form of failure in the dynamic bending test was plastic

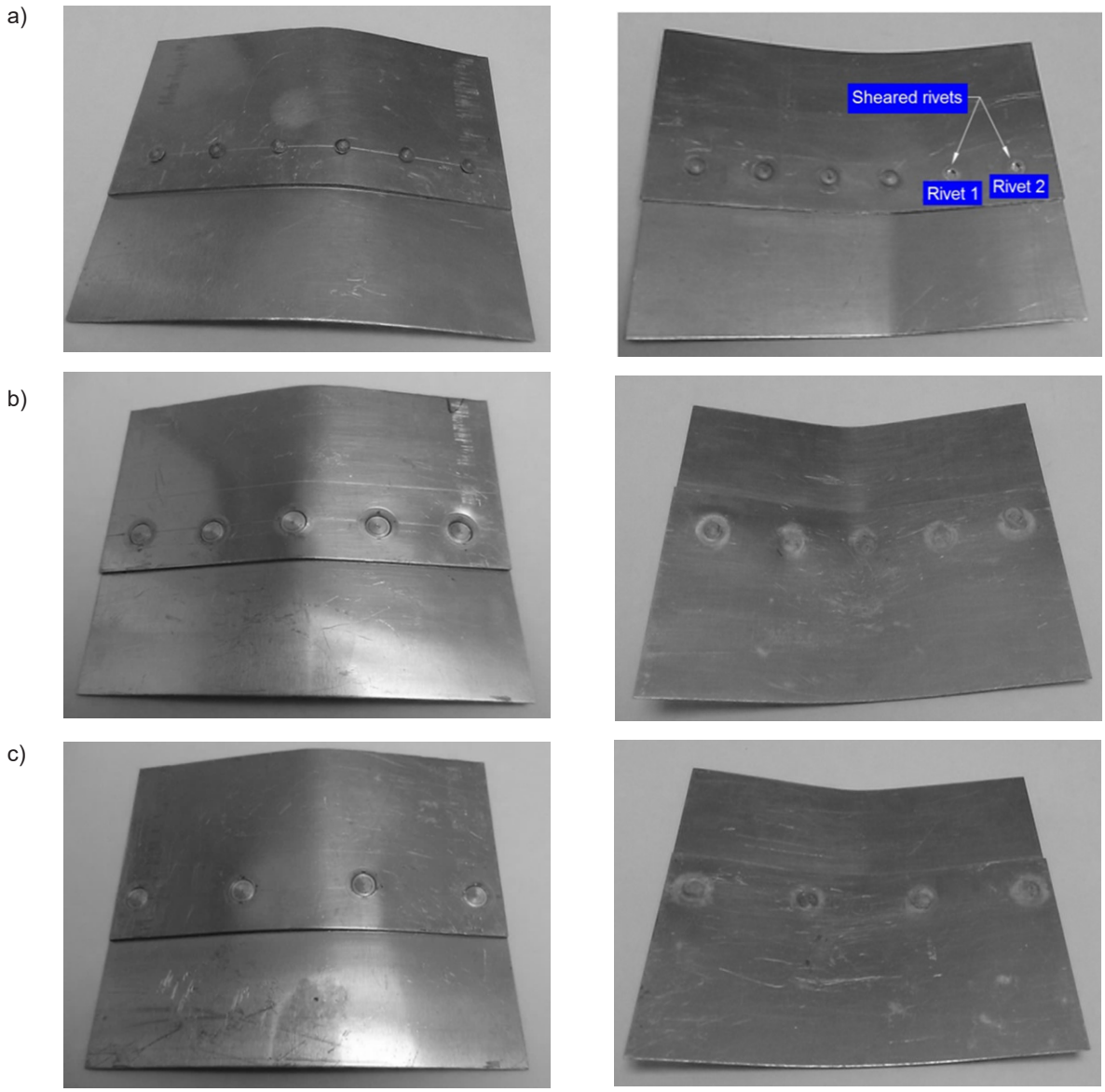

Fig.13. Lap joints of flat sheets after impact tests: a) riveted joint with a spacing of 23.5 mm, b) joint made with the RFSSW technology with a weld spacing of 29.5 mm, c) joint made with the RFSSW technology with a spacing of 44.25 mm

Table 2. Results of measurements of deflection under the influence of dynamic impact of lap samples

Lp.	Specimen variant	Impact energy J	Impact velocity m/s	Plastic deflection [mm]	Plastic+elastic deflection [mm]
1	Riveted joint with a spacing of 23.5 mm	26.3	1.33	12.9	13.6
2	Welded joint with a spacing of 29.5 mm	26.3	1.33	9.4	10.9
3	Riveted joint with a spacing of 44.25 mm	26.3	1.33	9.7	11.3

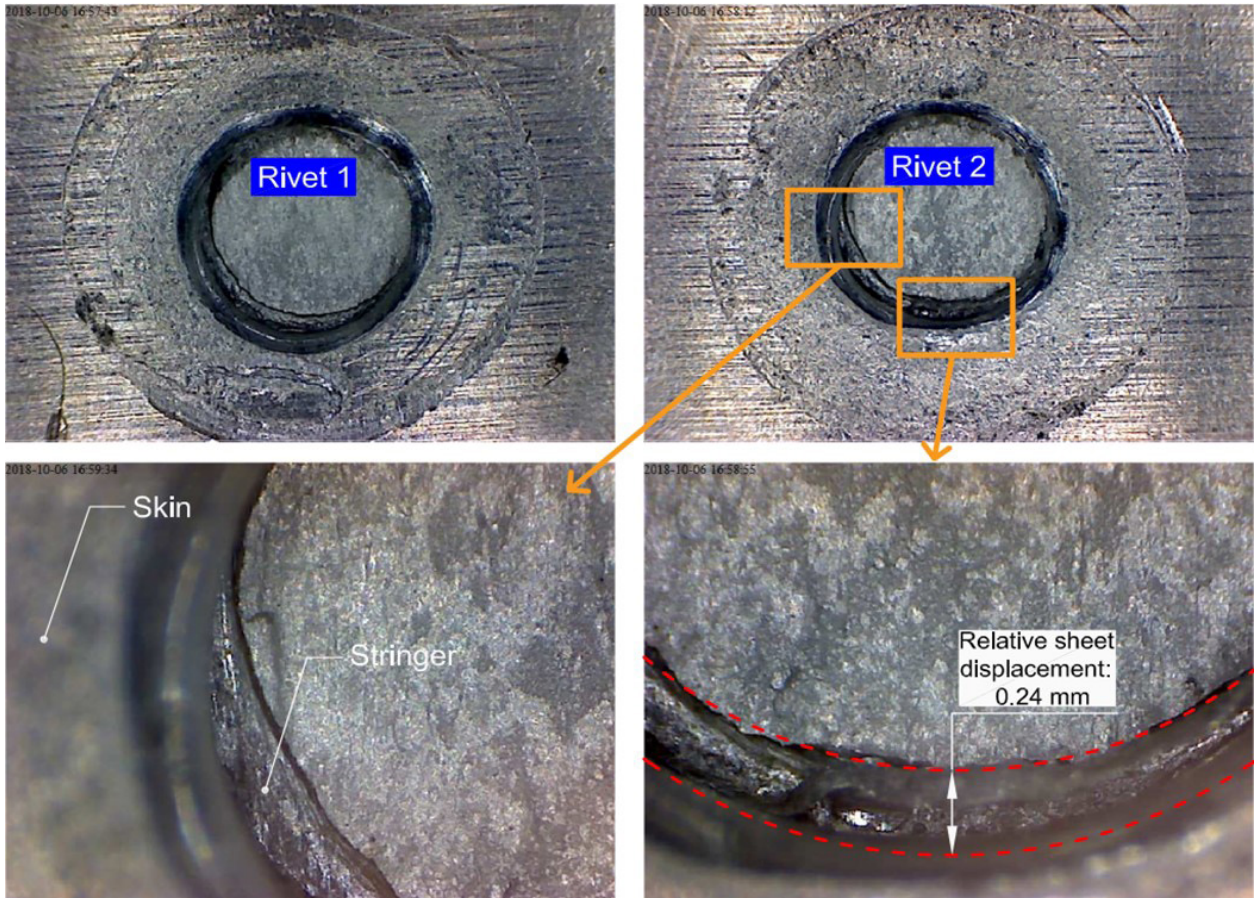

Fig. 14. Macroscopic images of the sheared surfaces of the rivets showing the relative displacement of the joined sheets

cracking that occurs on the remainder of the surface. In the central region of the fracture of the rivet, dimples of different sizes were shown, which are typical for ductile fracture (Figs. 15d, e). From the views of the fracture, typical ductile cracking can be observed, characterized by the formation of pits, i.e. pits and craters. It is the effect of material flow, the phenomenon of cracking took place here by nucleation and growth of voids. In the area marked by points f and g in Fig. 15a, a plastic breakthrough is primarily shown (Figs. 15f, g).

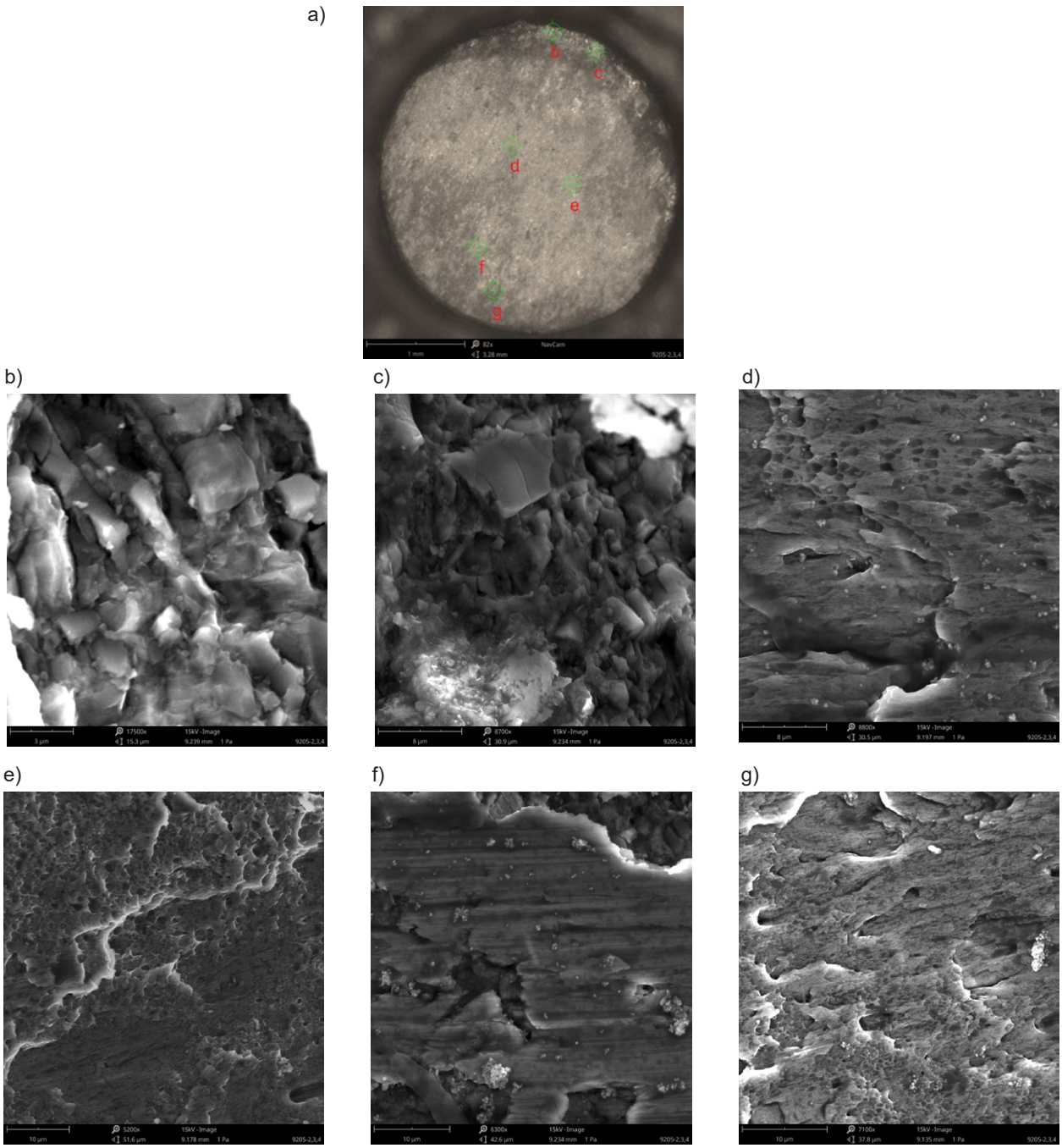

Fig. 15. Fracture surface of sheared rivet: a) macrograph of whole surface; b) - g) SEM micrographs showing the fracture surface morphology of characteristic areas

Conclusions

One of the objectives of the research presented in the paper was to experimentally determine the mechanism of failure of lap joints made by the RFSSW method in the static shear test. It has been shown that a correctly created joint of sheets made of the EN AW-7075-T6 Alclad alloy with thicknesses corresponding to the stringer (thickness 1.6 mm) and the skin sheet (0.8 mm) is fractured in the static shear test as a result of tensile stress of the thinner sheet. This is due to the weakening of the material in the HAZ, but also the deformation occurring during welding, which leads to a reduction in the cross-section of the sheet, which was demonstrated on the basis of the joint macrostructure and the FEM numerical model. Before failure, the lower sheet undergoes plastic deflection due to the bending moment resulting from the joint geometry used.

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THE EFFECT OF THE SURFACE PREPARATION METHOD ON THE ULTIMATE STRENGTH OF A SINGLE LAP ADHESIVE JOINTS OF SELECTED CONSTRUCTION MATERIALS

Wpływ sposobu przygotowania powierzchni na wytrzymałość doraźną zakładkowych połączeń klejowych wybranych materiałów konstrukcyjnych

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Abstract: The aim of the article was to present issues related to the determination of the influence of the surface preparation method on the strength of adhesive joints made of three types of construction materials: structural steel C45, aluminium alloy EN AW-1050A and stainless steel 1.4401. The surfaces of the analysed materials were prepared by machining with three different abrasive tools of different gradations: P120, P220, P400. Adhesive joints were prepared using the E53/Z-1/100:10 epoxy adhesive composition. After the process of adhesive joint curing, destructive tests were carried out on the Zwick/Roell Z150 strength machine, in accordance with PN-EN 1465 standard, which determined the shear strength of the analyzed joints. During the tests it was observed that the most advantageous method of surface preparation is treatment using P220 grit abrasive.
Keywords: structural steel C45, aluminium alloy EN AW-1050A, stainless steel 1.4401, shear strength, adhesive joints

Streszczenie: Celem artykułu było zaprezentowanie zagadnień związanych z określeniem wpływu sposobu przygotowania powierzchni na wytrzymałość połączeń klejowych wykonanych z trzech rodzajów materiałów konstrukcyjnych: stali konstrukcyjnej C45, stopu aluminium EN AW-1050A oraz stali nierdzewnej 1.4401. Powierzchnie analizowanych materiałów zostały przygotowane poprzez obróbkę trzema różnymi narzędziami ściernymi różnej gradacji: P120, P220, P400. Połączenia klejowe przygotowano z użyciem kompozycji klejowej epoksydowej E53/Z-1/100:10. Po procesie utwardzania spoiny klejowej przeprowadzono badania niszczące na maszynie wytrzymałościowej Zwick/Roell Z150, zgodnie z normą PN-EN 1465, dzięki którym wyznaczono wytrzymałość na ścinanie analizowanych połączeń. W trakcie badań zaobserwowano, że najkorzystniejszym sposobem przygotowania powierzchni jest obróbka wykorzystująca ścierniwo ziarnistości P220.
Słowa kluczowe: stal konstrukcyjna C45, stop aluminium EN AW-1050A, stal nierdzewna 1.4401, wytrzymałość na ścinanie, połączenia klejowe

Introduction

The design of structural adhesive joints sometimes poses difficulties due to the fact that the short-term strength of such bonds depends on many factors: material, construction, technological and operational [8, 13, 24]. Among these factors, one of the most important is how to prepare the surfaces of the materials to be joined. The proper preparation of the surface in the process of bonding determines the correct execution of the adhesive joint and obtaining the appropriate strength of the joint, and, consequently, determines the correct operation of the joint in specific conditions, as well as increases the resistance of the joint to various operating factors [1, 2, 32, 39, 39]. This stage determines the correct operation of the joint to a large extent. It should ensure the strongest possible adhesive bonds in the adhesive joint. For this purpose, it is necessary to [7, 14]:

- remove all impurities from the surfaces of the elements to be bonded (such as: grease, dust, grease, microorganisms, gas bubbles, loosely bonded corrosive layers), which can significantly reduce the adhesive bond strength,
- get the appropriate surface "roll-out",
- achieve good activation of the surfaces of the elements being joined.

The choice of surface preparation method depends on many factors, including the type, properties and stereometric structure of the surface of the materials being joined [4, 33]. Depending on the properties of the materials, technical and technological conditions, workshop possibilities and others, the surface preparation process can consist of different operations:

- cleaning and degreasing the surface,
- special processing,
- actions immediately prior to establishing the joint.

Degreasing is designed to remove contaminants from the surface which include: oil, grease, moisture and other undesirable substances that make it difficult for further processes to activate the surface. Surface degreasing can be performed manually in case of unit production or in case of complicated shape of the degreased element. This type of degreasing is relatively imperfect and time- and labour-intensive, therefore degreasing is most often carried out in baths of solvents or their vapours. Various solvents (e.g. acetone, gasoline) can be used for degreasing. When using water for degreasing, it is necessary to check whether the material being treated absorbs water - whether it is hydrophilic. If so, the pre-treatment must be carried out by removing the water, e.g. by drying, which can be done in the ambient air, in an air stream (can be heated to 40-50°C), in an inert gas atmosphere (e.g. nitrogen, argon) or in a chamber dryer.

The purpose of special surface treatment is to develop the surface properly and increase its physical and chemical activity. Special surface treatments can include mechanical, chemical, laser, plasma, electrochemical and other methods [11, 12, 16, 35, 36].

Mechanical methods include: abrasive machining, abrasive blasting (e.g. sandblasting, shot blasting), peening, scraping, brushing, grinding [27]. These methods enable the surface's geometric structure to be constituted, but do not guarantee good surface activation [31].

Chemical methods allow for appropriate development of the surface and surface layer with a chemical composition that ensures high surface physicochemical activity in relation to the adhesive used. Chemical treatment usually consists in pickling the surface of elements to be glued in baths of appropriate composition and temperature. The etching time is also important.

The application of special primers is recommended for some materials in the final stage of surface preparation. These agents contain chemically active functional groups that react both with the adhesive and with the surfaces to be bonded. This operation has a positive effect on increasing the adhesive strength of the adhesive joint [31].

A properly prepared surface for the bonding process should be characterized:

- no impurities reducing adhesion,
- good wettability of the adhesive,
- the ability to produce interphase bonds,
- stability for the assumed conditions and the life of the connection,
- the repeatability of the obtained properties,
- the presence of activators/properdisposition agents (if required).

The change of factors influencing the quality of the bonding process may affect the properties of certain joints in different ways. The issues of influence of these factors on the strength of adhesive joints are described in many works [5, 37]. However, due to the specification of the joints under consideration, it is necessary to conduct research related to the analysis of the influence of these factors in relation to specific cases and applications. The change of these factors for a particular joint may affect the properties of the joint, e.g. another material, including its strength properties, in a slightly different way.

The choice of the method of preparing the surface for the bonding process depends on many factors, but one of the most important is the type of material analysed. With regard to low-alloy steel, there are recommendations for the application of surface preparation method presented in some works [25, 28]. Due to the properties of C45 steel for ease of machining, it is recommended to grinding, abrasive machining, sandblasting, shot blasting, superfinishing and polishing.

In terms of surface preparation of aluminium alloys, chemical and electrochemical treatments are recommended [3, 10, 15, 23]. Often used treatment is anodizing, chromating and phosphating. The first operation in the process of surface preparation of aluminium and aluminium alloys is degreasing, which can be carried out using various techniques and degreasing agents [26, 30].

Equally often the recommended treatment for aluminium alloys is mechanical. This is carried out using abrasive bulk tools. It results in a geometrical development of the surface, which significantly increases mechanical adhesion, which is related to the increase in the active contact surface of the adhesive with the bonded material. When using mechanical processing, the key aspect is the appropriate selection of the abrasive grain size. Too small a grain may cause the impurities to wash away on the surface, while coarse a grain creates too deep scratches, which may cause changes in the properties of the surface layer.

A significant impact of mechanical processing on the strength of adhesive bonds can be observed in the results of research published in the previous studies [6, 29, 33]. On the basis of the results presented in the paper [29], it can be seen that in the case of aluminium alloy, better results in relation to the strength of joints were obtained using electrochemical treatment. However, when choosing the surface treatment, the dimensions and shape of the structure must be taken into account in addition to the properties of the material from which the joint is made. This is due to factors such as costs and complexity of the preparation process. Mechanical treatment will be relatively cheaper and less invasive and less harmful as a method of surface preparation than electrochemical treatment. It should be stressed that e.g. inappropriate composition of the pickling bath as well as too long pickling time contribute to the high porosity of the conversion layer, which may result in a deterioration of the corrosion resistance.

With regard to stainless steel, the surface can be subjected to both chemical and mechanical treatment [18]. One of the chemical methods is etching, whose technological parameters can be adjusted to the properties of the alloys.

The aim of the research was to compare the ultimate strength of single-lap adhesive joints, made using three

types of construction materials: structural steel C45, aluminium alloy EN AW-1050A and stainless steel 1.4401, whose surfaces for the bonding process have been prepared by mechanical treatment with abrasive grit tools of different gradations.

Methodology of experimental testing

Adhesive joints being the subject of the tests were made of metal sheets with dimensions: 100x25x2 mm. Single-lap joints were made. The thickness of the adhesive layer was 0.1 ± 0.02 mm. The scheme and geometry of the joints are shown in Figure 1.

To make the connections, sheets of three types of construction materials were used, which are often used in machine building [9, 34]. Structural steel sheet C45, aluminium alloy EN AW-1050A and stainless steel 1.4401 were used. The mechanical and physical properties of the materials used are presented in Table 1.

The surface of the samples to be bonded has been prepared with the use of mechanical abrasive treatment with gritting and degreasing tools. This treatment consisted in roughening the surface with graded abrasive paper: P120, P220 and P400. 30 rotary movements with the abrasive papers of the aforementioned grit sizes were performer on the surface of each samples. After mechanical working the samples were degreased by rubbing-through two times with use of a extraction gasoline. The drying time after degreasing was 2 minutes.

For the adhesive joints, the Epidian 53 epoxy resin adhesive composition and Z-1 curing agent in the amounts of 100 grams of resin and 10 grams of hardener were used (composition designation E53/Z-1/100:10).

Epidian 53 (producer: CIECH S.A.) is a mixture of the epoxide resin made of bisphenol A and epichlorohydrin (Epidian 5) and styrene. It is characterized by low adhesiveness (at 25 °C: 900–1500 mPa·s) and lower density than Epidian 5 (at 20°C: 1.11–1.15 g/cm^3). Epidian 53 is characterized by high strength at a temperature of about 110°C [17]. Its modifications are used in joining glass laminates. Due to great electro-insulation and resistance properties, it can be used in radio engineering, aviation, and optics.

Curing agent Z-1 (producer: CIECH S.A.) is an aliphatic amine. It has a viscosity of 20-30 mPa·s (at 25 °C) and a density of 0.978-0.983 g/cm^3 (at 20 °C). It is mainly used in compositions with low-molecular-weight epoxy resins and preparations based on them. It is used in industrial, specialized and consumer applications.

Weighing of components of adhesive compositions was performed with the use of KERN CKE 3600-2 electronic laboratory balance with measurement accuracy of 0.01 g. The composition was mixed mechanically using a paddle mixer, with the speed of 460 rpm in 2 minutes. The adhesive was prepared directly before the joining process. The adhesive was applied manually in a thin layer on two joined surfaces using a polymer spatula.

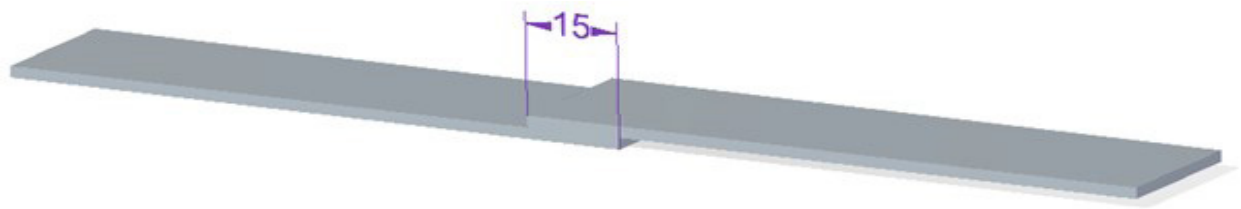

Fig. 1. Single-lap adhesive joint to be tested

Table 1. Mechanical and physical properties of steels used in tests [28, 18, 20, 21, 22]

The properties	Structural steel C45	Aluminium alloy EN AW-1050A	Stainless steel 1.4401
Tensile strength Rm	560-850 MPa	65-95 MPa	500-700 MPa
Yield strength, Re	275-490 MPa	20 MPa	≥195 MPa
Elongation, A	14-17 %	26 %	>40 %
Shear moduls, E	198-207 GPa	69 GPa	200 GPa
Thermal capacity, cp	482 J·kg^{-1}·K^{-1}	899 J·kg^{-1}·K^{-1}	500 J·kg^{-1}·K^{-1}
Thermal conductivity, λ	49.4 W·m^{-1}·K^{-1}	229 W·m^{-1}·K^{-1}	15 W·m^{-1}·K^{-1}
Hardness	≤219 HB	20 HB	<230 HB

The joining process was performed at a temperature of 25±2°C with a humidity of 27±2%. Under the same conditions, a one-stage curing process of the adhesive joint was carried out, using a pressure of 0.20 MPa. There were 10 adhesive joints prepared for each type of material and for each method of surface preparation. In total, 90 adhesive bonds were prepared for strength testing.

After a curing time of 7 days, the adhesive joints were subjected to strength tests on the Zwick/Roell Z150 strength machine in accordance with PN-EN 1465:2009 [19] at a test speed of 5 mm/min. Shear strength results of the tested adhesive joints were obtained during the tests.

Results and analysis of the obtained research results

The average value and standard deviation were calculated for each batch of samples. During the analysis of the experimental results, the extreme values for a specific batch of samples were rejected. Extreme results (too high and too low in relation to other values) were rejected when the differences between the results were large. Differing results could have resulted, among other things, from defects in the weld structure that could have occurred during its execution.

The average results of shear strength of adhesive joints of C45 structural steel sheets, EN AW-1050A aluminium alloy and 1.4401 stainless steel, the surfaces of which were machined with three gradations of P120, P220 and P400, are shown in Figure 2.

Analyzing the obtained results of the shear strength test of single-lap adhesive joints of C45, EN AW-1050A and 1.4401 stainless steel, the surfaces of which were prepared using P120 grade sandpaper, it can be seen that the highest strength was obtained in the case of joints made of C45 structural steel (4.06 MPa). Lower by about 38% strength was obtained in the case of the other two materials - the strength of adhesive joints of aluminum alloy EN AW-1050A was 2.50 MPa, and stainless steel 1.4401 - 2.53 MPa.

In the case of adhesive joints of the analyzed materials, the surface of which was prepared with the use of P220 gradation sandpaper, the highest strength was characterized by joints made of C45 (5.10 MPa) structural steel sheets. The lowest shear strength was obtained in the case of joints made of 1.4401 (2.73 MPa) stainless steel sheets. In the case of adhesive joints made with aluminum alloy sheets

EN AW-1050A, shear strength of 3.05 MPa was obtained.

Comparing the obtained results of shear strength of adhesive joints made of materials whose surfaces were prepared with the use of P400 graded abrasive paper, it can be seen that the highest strength was obtained in the case of C45 - 4.14 MPa stainless steel joints. Stainless steel connections 1.4401 - 1.66 MPa had the lowest strength.

The highest repeatability of results was obtained in the case of joints, which were also characterized by the highest strength among the analysed materials, i.e. made of C45 structural steel sheets.

However, in order to be able to accurately assess the differences between the shear strength results obtained in individual groups, it was necessary to carry out a more

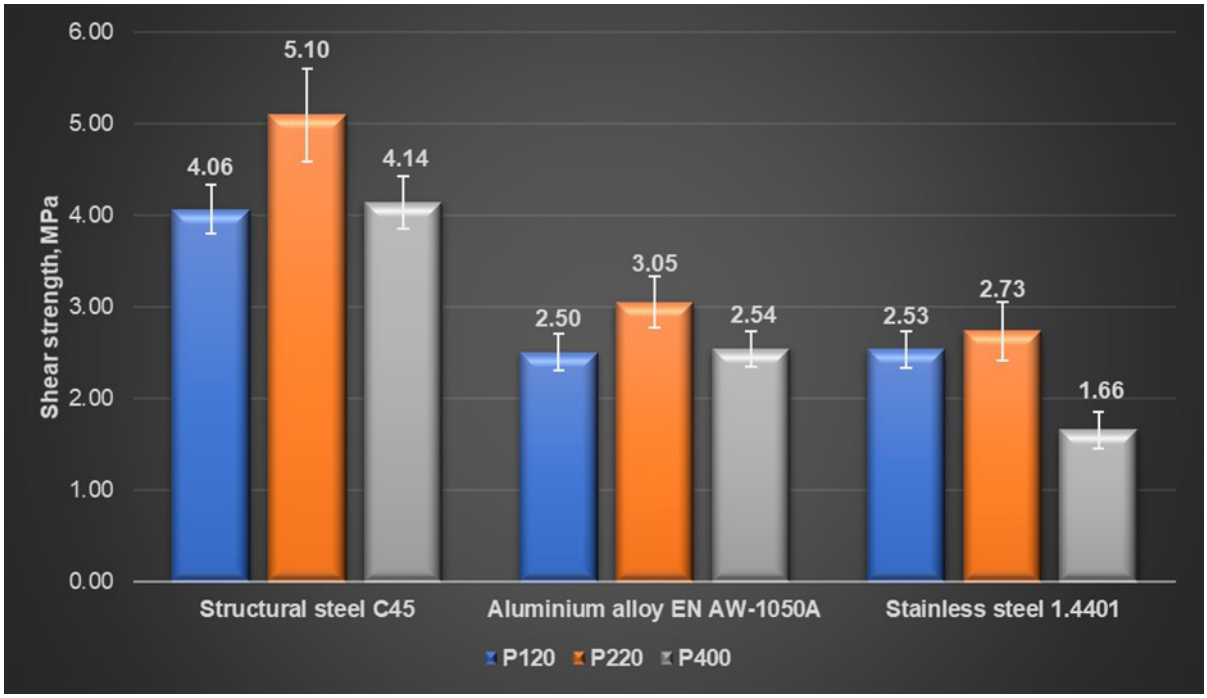

Fig. 2. Comparison of the shear strength results of adhesive joints made with E53/Z-1/100:10 due to the surface preparation method

Table 2. Results of the K-S distribution normality test

Type of material	Type of sanding paper	Level p for K-S test	Normality of distribution
Structural steel C45	P120	p > .20	YES
Structural steel C45	P220	p > .20	YES
Structural steel C45	P400	p > .20	YES
Aluminium alloy EN AW-1050A	P120	p > .20	YES
Aluminium alloy EN AW-1050A	P220	p > .20	YES
Aluminium alloy EN AW-1050A	P400	p > .20	YES
Stainless steel 1.4401	P120	p > .20	YES
Stainless steel 1.4401	P220	p > .20	YES
Stainless steel 1.4401	P400	p > .20	YES

Table 3. Levene's test results

	MS Effect	MS Error	The statistical value F	p level for the Levene test
Shear strength	0.024385	0.016731	1.457432	0.210450

Table 4. Results of Tukey's homogeneous post-hoc group test (HSD)

Type of material	Type of sanding paper	Shear strength	Homogenous group			
			1	2	3	4
Structural steel C45	P120	4.06		****		
Structural steel C45	P220	5.10				****
Structural steel C45	P400	4.14		****		
Aluminium alloy EN AW-1050A	P120	2.50	****			
Aluminium alloy EN AW-1050A	P220	3.05	****			
Aluminium alloy EN AW-1050A	P400	2.54	****			
Stainless steel 1.4401	P120	2.53	****			
Stainless steel 1.4401	P220	2.73	****			
Stainless steel 1.4401	P400	1.66			****	

accurate statistical analysis of the results obtained. Therefore, the normal distribution of the obtained results was checked at the beginning. For this purpose the Kolmogorov-Smirnov test (K-S) was used. The results of this test are presented in Table 2.

The results presented in Table 2 indicate that the distribution of the analyzed results is consistent with the normal distribution. Therefore, in the next step the assumption of equal variance was checked using Levene's test. The results of this test are presented in Table 3.

Level p for the Levene test is 0.211, which is higher than the assumed significance level of 0.05, which means that the assumption of the uniformity of variance is fulfilled. Thus, ANOVA was analyzed using the post-hoc test. The results of the homogeneous Tukey's test (HSD) are presented in Table 4.

The aim of the test was to determine which average values differ significantly and to separate groups of adhesive joints whose average shear strength values are at a similar level. Tukey's test formed 4 homogeneous groups. Analyzing the test results, it can be seen that the joints with the highest strength (made of sheets of C45 structural steel, the surfaces of which have been roughened with P220 abrasive paper are in a separate homogeneous group. Similarly, the joints which showed the lowest shear strength, i.e. the joints of stainless steel sheets 1.4401. This means that none of the other groups

of joints had a similar strength result at the assumed level of materiality. In the case of adhesive joints of C45 structural steel sheets, the surfaces of which were prepared using P120 and P400 sandpaper, the average values are in one homogeneous group, i.e. with the assumed level of materiality α = 0.05 they do not differ significantly. The remaining groups of samples, which were analyzed during the work, i.e. adhesive joints made of aluminum alloy sheets EN AW-1050A, whose surfaces were prepared with abrasive papers of gradations P120, P220 and P400, as well as joints of stainless steel 1.4401, whose surfaces were prepared with abrasive papers P120 and P220, are in one homogeneous group, i.e. there are no significant differences between them at the assumed level of materiality.

Conclusions

On the basis of the presented results of the experimental research, it can be concluded that the selection of an appropriate method of surface preparation and appropriate tools for their implementation has a significant impact on the strength of the adhesive joints. In the case of mechanical processing with a coated abrasive tool, the proper selection of the abrasive tool gradation is of particular importance. The analysis of the conducted tests shows that in case of adhesive joining of selected structural materials the most advantageous results were obtained in case of joining sheets of C45 structural steel. This may be due to the properties of the material itself, as this steel has better workability compared to the aluminium alloy EN AW-1050A and stainless steel 1.4401. The best method of treatment for all materials used in the tests turned out to be surface treatment with abrasive grit P220. Adhesive joints made of metal sheets subjected to such treatment were characterized by the highest shear strength.

The lowest strength of all joints was found in the joints of 1.4401 stainless steel sheets, the surface of which was prepared using P400 graded abrasive paper. Such an effect may be due to the fact that this sheet is characterized by the highest hardness among the materials analyzed in the study (Table 1), and the use of fine grain abrasive did not give a sufficient surface development.

In summary, it should be stated that mechanical surface treatment of the materials to be joined has a significant impact on the strength of the adhesive joints. The use of abrasive paper with too large a grain size may result in too deep cavities where the adhesive may not reach, while in the case of the use of fine papers there is a risk of insufficient surface development. However, this is also strictly related to the properties of the material, especially its hardness, as well as the properties of the adhesive used, especially its viscosity. The application of an appropriate gradation of the abrasive allows to properly prepare the surface of the elements to be joined and, as a result, to obtain a strong adhesive bond, which is the result of a strong adhesion of the adhesive to the material surface.

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PROCESS OF PERFORMING THE ACCELERATING STRUCTURE FOR LINEAR ELECTRON ACCELERATORS

Proces wykonania struktury przyspieszającej do akceleratorów liniowych elektronów

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Abstract: The article describes technological processes implemented during the production of accelerating structures for linear electron accelerators. In the production of accelerating structures, in order to obtain the expected final parameters of the electron beam, it is necessary to maintain very high accuracy of successive technological operations. Some dimensions of the resonance cavities constituting the basis of the structure should be in accordance with the design documentation, prepared on the basis of previously performed calculations and simulations with the use of programs solving partial differential equations, made with an accuracy of one hundredth of a millimetre. Additionally, due to the need to create a very high vacuum inside the structure the manufacturing of the structure, it is necessary during the production process to follow the cleanliness conditions of the works, specified by the technologist, for some technological operations. Time consuming production stages, expensive materials, complicated technologies using specialized machines and tools cause high costs and thus require the use of continuous inter-operational control. The article presents a new technological solution consisting in making cavities with higher tolerance of dimensions crucial for the electron acceleration process and connecting the cavities by brazing them together with other components of the accelerating structure in a way that guarantees the vacuum in the space where the electrons are accelerated. Until now, diffusion-connected resonators were inserted into a pipe made of stainless steel, which served as a vacuum jacket. The final part of the article describes the method of liquidation of vacuum leaks formed in the soldering process, which, when found, especially in the final stages of production, cause significant losses. It is, therefore, important to ensure that such damage can be repaired such a way that guarantees a vacuum during the entire life of the accelerator.

Keywords: linear electron accelerator, accelerating structure, vacuum

Streszczenie: W artykule opisano procesy technologiczne realizowane podczas produkcji struktur przyspieszających liniowych akceleratorów elektronów. Przy wytwarzaniu struktur przyspieszających, dla uzyskania oczekiwanych parametrów końcowych wiązki przyspieszanych elektronów, konieczne jest zachowanie bardzo wysokiej dokładności kolejno wykonywanych operacji technologicznych. Niektóre wymiary wnęk rezonansowych stanowiących podstawę struktury winny być, zgodnie z dokumentacją konstrukcyjną, opracowaną na podstawie wykonanych wcześniej obliczeń i symulacji z wykorzystaniem narzędzi informatycznych rozwiązujących równania różniczkowe cząstkowe, wykonane z dokładnością jednej setnej części milimetra. Dodatkowo, z powodu konieczności wytworzenia we wnętrzu struktury bardzo wysokiej próżni, należy podczas procesu produkcji przestrzegać, określonych przez technologa, dla niektórych operacji technologicznych wręcz sterylnych, warunków czystości prowadzenia prac. Czasochłonność etapów produkcji, drogie materiały, skomplikowane technologie z wykorzystaniem wyspecjalizowanych maszyn i narzędzi, to powody wysokich kosztów produkcji i tym samym konieczne jest stosowanie ciągłej kontroli międzyoperacyjnej. Celem artykułu jest przedstawienie nowego rozwiązania technologicznego polegającego na wykonaniu wnęk z większą tolerancją kluczowych dla procesu przyspieszania elektronów wymiarów oraz połączeniu rezonatorów poprzez ich zlutowanie, łącznie z pozostałymi podzespołami struktury akceleracyjnej, w sposób gwarantujący zachowanie próżni w przestrzeni, w której przyspieszane są elektrony. Dotychczasowo rezonatory połączone dyfuzyjnie wsuwane były do rury wykonanej ze stali kwasoodpornej, która stanowiła płaszcz próżniowy. W końcowej części artykułu opisano sposób likwidacji powstałych w procesie lutowania nieszczelności próżniowych, które stwierdzone, zwłaszcza w końcowych etapach produkcji, powodują duże straty materialne, dlatego też istotne jest zapewnienie możliwości naprawy takich uszkodzeń i to w sposób gwarantujący utrzymanie próżni podczas całego okresu użytkowania akceleratora.

Słowa kluczowe: akcelerator liniowy elektronów, struktura przyspieszająca, próżnia

Introduction

The main element of linear accelerator, serving for generation of ionizing radiation is the accelerating structure (Fig. 1). Electrons, as being accelerated by electric component of electromagnetic field, are moving along the axis of the structure under a high vacuum (for the structures produced in NCJB, reaching energies of 2 – 15 MeV). The electromagnetic field of high frequency is shaped by the respective internal shape of resonance cavities. Although the process of shaping a field inside the structure is a problem, described by Maxwell equations [9], so it belongs to the domain of physics and electronics, the performance of resonance cavities – the shape of which is calculated by a complicated software – must be implemented by machining process, by the development of machining technology and, successively, by development of the technology of connecting the

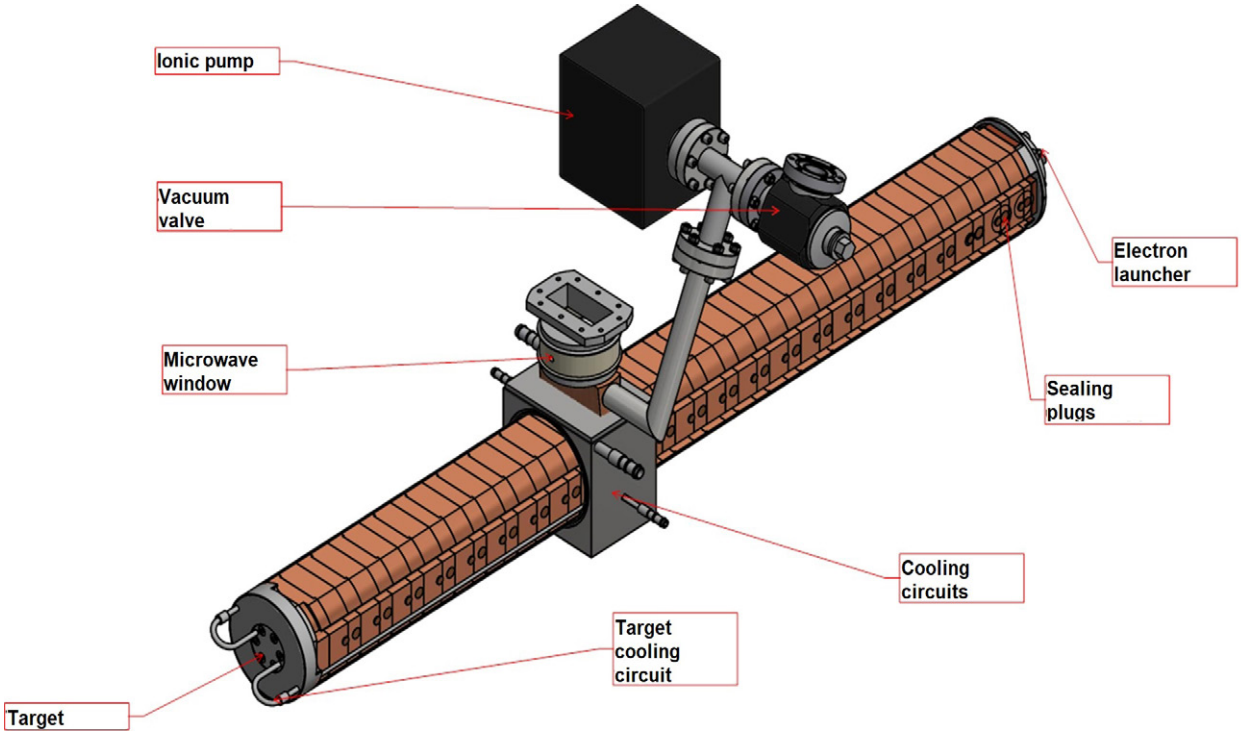

Fig. 1. Accelerating structure

resonance cavities. The beam of the accelerated electrons is introduced outside the structure. If photons are utilized in the anticipated application of accelerator, the beam of electrons falls on the conversion shield which may be built into the vacuum area or be found outside it. In this site, the conversion of electrons and obtaining of a stream of photons takes place.

The total process of electron accelerating occurs in a high vacuum. The temperature is a factor, which has a greatest effect on deterioration of vacuum; it causes liberation of gases from the internal surfaces of the structure. A high capacity of vacuum area, i.e. relatively high internal space, participating in gas desorption does not allow stating that vacuum in the structure has a static nature. Therefore, ionic pumps with the velocity dependent on their size are assembled to each structure.

To have the effective process of keeping the appropriate vacuum level during the structure's work and the employed vacuum pump be efficient, the structure must be vacuum-proof and deprived of contaminations, especially in the upper layers of its inside. Even a small leak may cause damage of electron launcher and, in effect, damage of the structure. To ensure vacuum inside the structure, its mutually connected resonators have been (at NCBJ) for many years slipped to acid-resistant pipe which constituted a vacuum jacket.

This work presents a new solution in two areas. The first one includes a development of the copper machining technology; the mentioned element is a basic material from which the resonators are produced (Fig. 2). The need of developing the discussed technology resulted from the conducted simulation by NCBJ, with the utilization of the newest calculating instruments [10, 11, 12]. As a result of it, the new data concerning the shape of resonance cavities were obtained. From the conducted calculations it is followed that the rise of the precision of certain dimensions of the mentioned cavities would allow obtaining better effectiveness of the acceleration of electrons at lower outlays on their performance. The precision of conducting the measurements of resonators has a direct impact on their own resonance frequency which must be consistent with the frequency of electromagnetic wave, feeding the structure. The frequency of the source of microwave power may be tuned from 2993 MHz to 3002 MHz and this raw range of retuning is used for automatic compensation of the changes in dimensions of resonators, resulting from the changes in their temperature during the work with a beam of electrons.

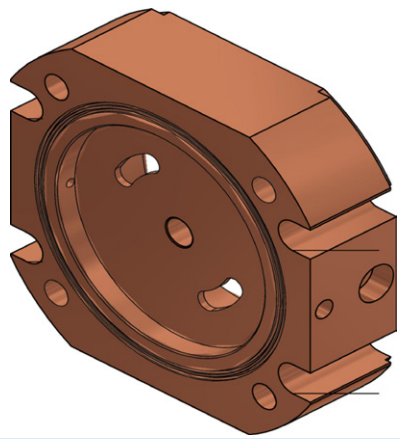

Fig. 2. Cavity

Thus, for example, on the grounds of the conducted simulations, the precision of performing the internal diameter of cavity should amount to +/- 0.02 mm; the depth of accelerating cavity should be equal to +/- 0.01 mm and the length of "nose", constituting the limitation of the acceleration area should be also +/- 0.01 mm. Until now, the submitted above tolerances of dimensions were even twice exceeded. The introduction of selection of the performed cavities was the solution of the discussed problem. As a result of the selection process, about 10% of the produced cavities had to be scrapped.

Additionally, the new programmable machining equipment, as being furnished with the newest tools, guarantee not only the possibility of rising the tolerance of performing the dimensions but also the possibility of decreasing the roughness of the surface, which is significant from the viewpoint of the properties of microwave resonance cavities. The roughness of the surface affects the quality factor of resonance cavities which may be directly translated into the obtained energy of the accelerated electrons per unit of length of the structure.

The second area, presented in this study, is the technology of combining the resonators and the remaining constructional elements of the structure by brazing. The brazing process must ensure the permanent mechanical joining of all elements of the structure with preservation of vacuum in the acceleration area, high electric conductivity of joints, deciding on the quality factor of the structure and preservation of vacuum during the work of the structure with the beam of electron. During the work, the heating of the structure's inside takes place, what causes a considerable difference of temperatures between its inside and outside layers, which are additionally cooled with water flow or by other cooling liquids [6]. The mentioned difference of temperatures cannot cause leakages, infringing the level of vacuum. The brazing (soldering) process of the structure must ensure so reliable joining of its elements as to guarantee the tightness of the vacuum area at the changes of temperature.

Materials, methods and the results of the tests

To obtain the appropriate parameters of the structure and its reliable work, it is necessary to select properly the materials and technological processes, implemented during the whole cycle of production. The materials used in production of accelerating elements, forming and converting the beam of electrons, should have a small expansion coefficient and not deteriorate the level of vacuum. To enable the correct work in the places where high quantities of heat are generated, the materials should also facilitate its quick removal outside so as to limit the changes on the dimensions of resonators. For these ends, the structure is also cooled by a liquid with constant temperature of ca. 40°C.

According to the mentioned above requirements, the oxygen-free copper is the main material from which the resonators, the basic elements of the structure, are constructed (Fig. 2). The contaminations in copper do not exceed 40 ppm; it ensures good conducting parameters and good parameters of heat dissipation; it is so technologically prepared that it does not contain big quantities of residual gases inside. Non-magnetic, acid-resistant steel is a technological material serving for fixing the cavities and other elements of the structure (Fig. 1): microwave window, ionic pump, vacuum valve, launcher of electrons, cooling system and system of leading the beam of electrons to the target. For mechanical joining of the particular elements, Ag-Cu binder is employed; it ensures a reliable combination and does not introduce any organic contaminations to the inside of the structure. Moreover, the melting temperatures of the used solders are so selected as to implement the processes of binding the elements of the structure in few stages. All technological processes must ensure mechanical and electric parameters of the resonators, as being assumed in the construction documentation

• Machining

The process of the structure production is commenced from the production of resonators (Fig. 2), the elements forming and accelerating the beam of electrons. Resonance cavities are performed by machining. The mentioned process was previously carried out in the simple, traditional lathes and milling machines and the parameters of treatment were so fixed that they allowed performing the cavities but it was necessary to carry out their segregation (roughly by measurement of their key dimensions) and then, to measure their own resonance frequency. It was caused by the dispersion of the dimensions of the produced resonators outside the requirements of documentation. The inspection process allowed classifying the groups of the resonators, being produced sufficiently identically as to make the whole structure from them. The passage from simple machining machines to the precise treatment centres (CNC, Computerized Numerical Control) required determination of the sequence of performing the operations as well as correction of the parameters of each operation, that is, a choice of the machining tool and velocity of machining, machine feed and depth of machining. Copper, which is subjected to machining, is very soft (hardness 50 HB). The treatment of such soft material is highly difficult. Adoption of too low value of machining depth may cause that the material would be not cut but squeezed. It is therefore, necessary to employ thicker chip what makes the machining process more difficult. At the same time, the experiments with the knife radius were carried out in aspect of the obtained roughness of the surface. The effects of machining were evaluated by the measurement of some experimentally treated cavities. The preliminary

measurement consisted in the inspection of the measurements, and then, own resonance frequency and quality factor of the cavities were assessed. The first reached results allowed obtaining the appropriate dimensions of the cavities, with the expected tolerance – i.e. 0.01 mm (depth of the cavity, length of "nose") and 0.02 mm (diameter of resonator) respectively, at the roughness of the surface Ra of order 0.3 μm, in result of which the quality factor was equal to 5000. After optimization of the treatment parameters, the required precision of dimensions was obtained at roughness Ra 0.11−0.12 μm; after the procedure of cleaning and electro-polishing, the roughness was de creased to Ra 0.07−0.09 μm what allowed exceeding the expected quality factor 9000−10000. As a result of the conducted trials, the targeted technology of machining of the resonators was developed. The mentioned technology contains the control measuring points where checking of the dimensions and/or measurement of the surface roughness is carried out. In the successive stage, the control of microwave parameters of individual resonators is conducted. A positive result of this inspection enables for assembling the cavities into sets. The discussed technological operation is also carried out by the measurement of microwave parameters. As obtaining of the appropriate frequency in the successive accelerating and coupling cavities and of the appropriate distribution of electromagnetic field, requires almost always tuning of each cavity, each resonator has a place left for the elements used in such operation. They have the possibility of changing the expected value. After completion of the whole set of resonators and inlet of high frequency power, checking of the microwave parameters of the set is carried out. At this stage, the resonance frequency, quality factor, electric field distribution and coefficient of coupling the structure with wave line, feeding it with high frequency energy, are preliminarily determined.

Purification before brazing process

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

Brazing process

Brazing (soldering) is carried out in the horizontal oven where the temperature distribution is controlled by a series of thermocouples. During the brazing, the vacuum in the oven is better than 10^{-5} mbar. The resonators of the structure are completed respectively to the earlier terminated process of microwave tuning. The solder of 1 mm diameter is introduced into the brazing channels. The channels are so shapes as to eliminate the outflow of solder to the inside of the cavity. The parameters of brazing i.e. shape of channels, diameter of solder, composition of the solder and the pressure of the joined resonators have been experimentally selected during the brazing trials. The mentioned trials were performed by soldering of a few resonators. The implementation of the trials was based upon own experience and literature [7, 8]. After brazing, the tightness of the soldered sample was examined by helium detector of leakages and later on, it was cut off for visual inspection of the joints. On the grounds of literature data [2, 3] and with the assumed sizes of vacuum area and the anticipated ionic pumps, it was established that the leak as measured by helium detector cannot exceed value of 10^{-11}mbar x l/s. as a result, the following parameters of the process were adopted:

- Pressure of the joined resonators by momentum 3Nm,
- Application of solder with the composition 0.72 Ag−0.28 Cu,
- Heating of the batch in the oven at velocity of ca. 5°C/min up to the temperature of 768°C and then, slowing down the rate of temperature change and heating up to temperature approximate to 800°C and then, after reaching this temperature, switching off the heating and cooling the batch to its complete cooling down, still at ensured vacuum.

For brazing, the resonators of the structure are twisted with four pins with the utilization of dynamometric key and they are put into the bed of the oven, based upon the ceramic washers, placed in the oven. After reaching the required vacuum in the chamber of the oven, the process of brazing is commenced. After the first soldering, the checking of the quality of brazing and of the tightness of joints is performed using helium detector. Next, the structure is finally tuned and the appropriate sealing plugs are installed; they close the places where the tuning elements were placed.

After their soldering, the sealing plugs (Fig. 3) should ensure the appropriate level of vacuum tightness. The last stage of performing the structure includes their brazing. The mentioned process takes place also in the vacuum oven in such a way as to obtain a certain binding in the sites of the sealing plugs and not cause the disconnection of the earlier combined elements. After the conducted tests until the mentioned stage, the solder with the following parameters was selected: 0.61 Ag – 0.24 Cu – 0.15 In. Its melting temperature is 705°C and

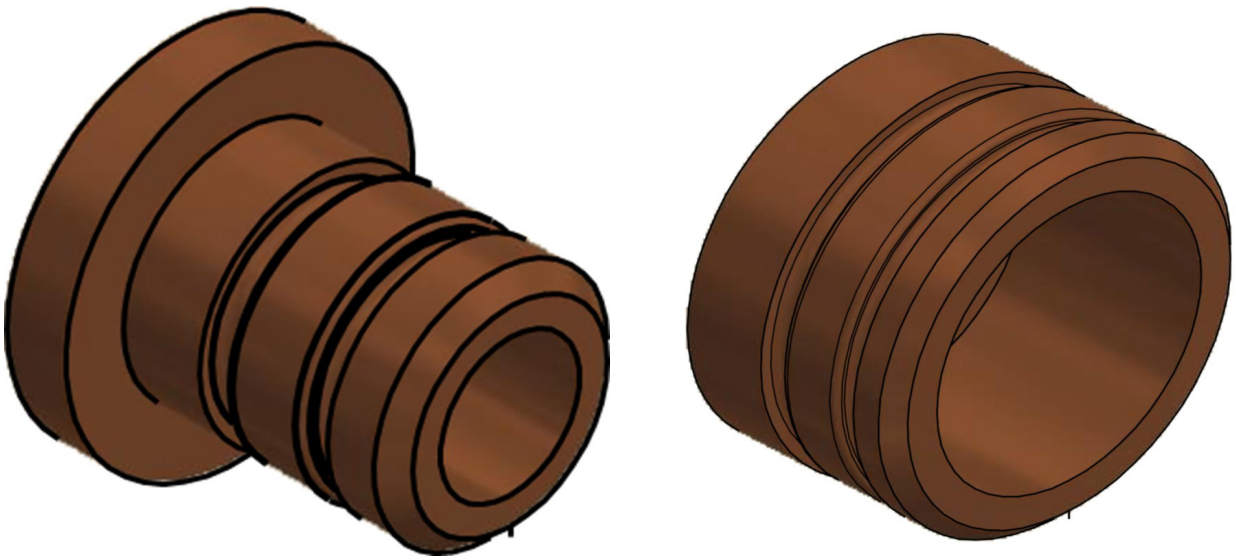

Fig. 3. Sealing plugs

the process of heating and cooling down the structure runs similarly as the previously, with the switching off the heating at temperature of 720°C. After the discussed stage, a final checking of vacuum tightness is performed and in the case of positive result, joining of the launcher of electrons is carried out. During the implementation of the brazing process, it is necessary to observe strictly the temperature and time requirements, described in the technology of brazing. so prepared structure is subjected to thermal treatment [4, 5] and then, microwave treatment in order to degasify it finally. At the end of the described process, the structure is placed in a special stand for testing of the structures [1] where the tests of all its parameters, in particular energy and current of the beam of accelerated electrons are carried out.

• The errors of brazing

Vacuum leak may be practically detected at each stage of the described above process of performing the structure. It is especially expensive in the case of the last stages of brazing or already during the thermal or microwave treatment. Therefore, it has become significant to develop a method for removal of leaks, found during the final stages of performing and treatment of the structure. The reasons for occurrence of leaks may be different. The main reasons are as follows:

- Use of improper material;
- Failure to meet the technologically specified requirements concerning the purity of the surface;
- Failure to keep the parameters, specified in the technology;
- Failures of the equipment during the conducted technological treatments.

It is therefore, important to employ the appropriate materials with certificates and to buy them from certified (proven) suppliers, guaranteeing the parameters, specified in the certificates. The acquired experience, as described in production technology, ensures the appropriate selection of the parameters connected with the preparation of the surface and conducting each stage of the process of the structure production. In the case of the multi-stage diversified and complicated process, making the mistakes is unavoidable and the situations resulting in leak occurrence may happen. On the one hand, automation of the brazing process in vacuum ovens causes a high precision and repeatability but, on the other hand, a complicated construction and automation of the oven may expose the implemented process to the disturbances. Failures of the oven may cause interruption of the brazing process at any moment. It is especially dangerous in the situation when the whole batch has a high temperature and ionic pumps or the systems of their cooling become damaged. Then the loss of vacuum oxidation of the batch may occur. If the temperature is sufficiently high as cause the oxidation process, we are encountered with the leak, caused by generation of oxides on the surfaces of the solder's melting. Such case causes practically a lack of tightness in each resonator. The leaks at the individual sealing plugs occur more rarely; they are caused by defects of material or by human error. The discussed leakages are discovered very often during the thermal or microwave treatment. The costs of production of the structure born up to this stage justify the application of repairing work what, in turned, forced a development of repair methods and technologies.

After having stated leaks, it is necessary to develop, each time, the method for its liquidation, with the consideration of the place of the leakage, size of the leak and technical possibilities of its removal. It is relatively easy to remove the leaks found during the first stages of joining the resonators (after the first stage of brazing). Then, during the second stage, i.e. soldering of the plugs, we place the sealing material in the leakage points; their task is to eliminate the leaks. The problem is more complicated when the leaks are found in the sealing plugs

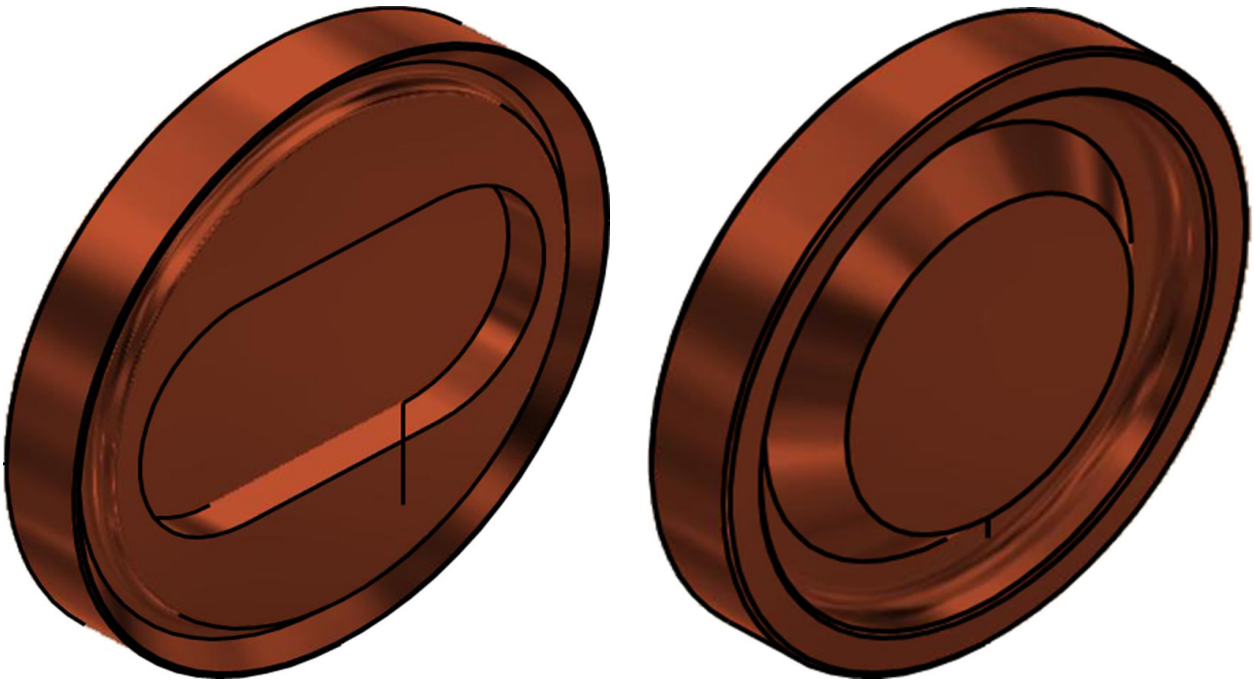

Fig. 4. Additional plugs

sated in the final stages of treatment. In such case, we have to analyse, each time, the site of their occurrence and develop the appropriate shapes of additional plugs and perform their additional brazing. Fig. 4. shows the examples of additional sealing plugs.

During soldering, we have to remember that the conducted process will be the additional process. We have, therefore, to select the technology of its performing, choose not only the shape of the sealing elements but also the composition of the solder and the parameters of brazing and, eventually, correct the successive processes as rto lead to the positive termination of the structure's production.

Conclusions

When utilizing the possessed and acquired experience, owing to the analysis, the conducted tests and the studies and the constant inspection, gradual introduction of automation, we have developed the constructional and technological documentation, allowing the repeatable, effective production of the accelerating structures of linear electron accelerations via the precise production of cavities in numerically controlled machines and vacuum brazing of the structure's elements. The both aims, being presented at the beginning of this paper, have been reached. Thus, as a result of machining operation, the specified, key dimensions (significant for the utility of resonators) are performed with the accuracy of 0.01 mm and 0.02 mm, respectively. The adopted parameters of machining process (the resulting roughness of the surface R 0.11-0.12) together with the later stage of chemical treatment of the resonators guarantee obtaining the microwave quality factor by the cavities, exceeding 10000. The specified conditions of the brazing process in two stages are as follows:

Stage 1 – set of resonators:

- Pressure of the joined resonators with the moment 3Nm,
- Application of the solder with the composition 0.72 Ag – 0.28 Cu,
- Heating of the batch in the oven with velocity of 5°C/min up to the temperature of 768°C , then slowing down the rate of change in the temperature and heating up to the temperature approximate 800°C when the switching heating off and cooling down the batch takes place.

Stage 2 – sealing plugs:

- Solder with the composition 0.61 Ag – 0.24 Cu – 0.15 In,
- Heating and cooling down of the structure as above, with the switching off the heating at temperature of 720°C.

This ensures effective and repeatable mechanical joining of resonators and vacuum leak lower than 10^{-11} mbar x l/s. We should, however, mention that it is necessary to observe strictly the requirements, recorded in the developed technologies, concerning the parameters of the implemented technological processes, what, in effect, allows minimizing the occurrence of defects. In the light of expensive and labour-consuming process of the structure production, the elimination of the losses, caused by the defects of materials, human errors or failures of machines, is very important element of technological process. The additionally developed technology of liquidation of vacuum leaks allowed, several times, to lead to their effective repair. As a result it

allowed performing the fully valuable structures which did not require assembling of additional plugs. Relatively low costs of such repair in relation to the losses, resulting form he eventual scrapping of the structure, justify fully such technological process. It is significant that the employed recovering process does not have any negative impact on the expected parameters and vitality of the structure.

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POLYURETHANE COATINGS IN MEANS OF TRANSPORT

Powłoki poliuretanowe w środkach transportu

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Abstract: Polyurethane coatings are becoming increasingly popular, particularly due to their numerous beneficial properties. They are resistant to environmental weather conditions and other impacts associated with operation and time, including mechanical loads. The article is an introduction to investigations on the use of such paints in aircraft constructions to protect aircraft coatings. It presents the subject of polyurethane paints and their main types. It also describes what actions should be taken before starting the coating process, mainly the polyurethane one, also including many other types of coatings. Apart from the characteristics of surface cleaning methods, the authors list the types of impurities and the main types of surfaces on which coatings are applied. The selected areas of industry, in which polyurethane coatings are used, have also been presented. A very important feature of coatings is their adhesion to applied surfaces. This feature has also been analysed, describing the main methods of checking adhesion. The basic mechanical and thermo-physical properties of the coating as a cast material are determined in the experimental studies. A polyurethane coating, commercially known as Rangers 2K, has been used for the research.
Keywords: polyurethane coating, mechanical strength, tribological properties

Streszczenie: Powłoki poliuretanowe stają się coraz bardziej popularne, głównie za sprawą wielu korzystnych właściwości. Są odporne na środowiskowe warunki atmosferyczne oraz inne oddziaływania związane z użytkowaniem oraz upływem czasu, między innymi na obciążenia mechaniczne. Artykuł stanowi wstęp do badań nad zastosowaniem tego typu farb w konstrukcjach lotniczych do zabezpieczenia pokryć statków powietrznych. Zaprezentowano czym są farby poliuretanowe oraz jakie są ich główne rodzaje. Opisano również jakie czynności powinno podjąć się przed rozpoczęciem procesu nakładania powłoki, gównie poliuretanowej, lecz także wielu innych rodzajów. Oprócz charakterystyki metod oczyszczania powierzchni, wyszczególniono także rodzaje zanieczyszczeń oraz główne typy powierzchni, na które nakłada się powłoki. Przedstawiono także wybrane obszary przemysłu, w których powłoki poliuretanowe znajdują zastosowanie. Bardzo ważną cechą powłok jest ich przyczepność do nakładanych powierzchni i tą właściwość również poddano analizie, opisując także główne metody sprawdzenia adhezji. W badaniach eksperymentalnych określono podstawowe właściwości mechaniczne i termofizyczne powłoki w postaci materiału odlewanego. Do badań wykorzystano powłokę poliuretanową o handlowej nazwie Rangers 2K.
Słowa kluczowe: powłoka poliuretanowa, właściwości mechaniczne, parametry trybologiczne

Introduction

Polyurethane paints were invented in 1937. At present, they are gaining popularity [4] mainly in shipbuilding, construction and mechanical industry. This is because these paints have very good properties. First of all, they are characterized by a high abrasion resistance [2, 6, 12, 21] and very good adhesion [6, 13, 18]. Moreover, they are flexible [13, 18, 19] and have good chemical resistance [9, 13, 19]. Additionally, polyurethane paint is resistant to corrosion [12], many external factors, i.e. mainly weather conditions [6, 9, 13] water and UV radiation. It is also worth mentioning that coatings of this type of paint can be applied at low temperatures [19] (with a minimum temperature of -5°C), so taking into account Poland's current climate, it is possible to use the paint practically throughout the whole year, which definitely distinguishes polyurethane paints from other types of coatings. They are made of a mixture of resins or only one polyester, polyether, acrylic, and also special hardeners, depending on their type. Owing to the latter component, this type of paint is resistant to external factors as well as colour change [5].

Painting with a polyurethane paint is not difficult, although the surface which is to be painted needs to be properly prepared beforehand [20]. Additionally, one should be aware that a special care must be taken when preparing the surface for painting and applying coatings since the paint may produce toxic chemical compounds [2, 9], which are usually caused by hardeners used for curing a polymer coating. The cured polyurethane paint coating no longer releases any harmful substances. Therefore, the paints can be used in many industries, including the food industry, although they cannot come into a direct contact with food [1].

Types of polyurethane paints

It is possible to distinguish two types of polyurethane paints [3, 11]:

- one-component;
- two-component.

One of the types of a polyurethane paint is a one-component polyurethane paint which is only made up of resin. It is easier to use than two-component paint. It is cured most often under the influence of moisture in the environment.

It is relatively easy to use and has usually excellent adhesion and hardness. It can be used as protection against rain, variable temperatures and frost. Due to its good adhesion, this type of a polyurethane paint is also suitable for more demanding surfaces. One-component paint is ready for use immediately after opening the container in which it is stored, as opposed to a two-component type, which must be mixed prior to its use [15].

The second type is a two-component polyurethane paint, which consists of two parts: resin and hardener. It is more difficult to use than its one-component counterpart because before the use, both components must be thoroughly mixed in proper proportions and used as soon as possible [15]. This type of paint is characterised by a high flexibility of the coating and equally high resistance to various factors as in the case of one-component paint. The two-component paint is often used as a protective coating for cars, aircraft, mechanisms and high-quality furniture [7]. This type of polyurethane paint is applied by means of a special roller, brush or spraying equipment [19]. The process of application is usually repeated two or three times with an interval.

It should also be remembered that both types can produce toxic chemicals. For this reason, before applying the paint, it is necessary to wear appropriate protective clothing and be particularly careful when painting.

Surface preparation for the application of coatings

Before applying the coating to any surface, in the first place it is necessary to properly prepare the surface. Firstly, it is essential to select an appropriate painting kit. The selection should take into account experimental research as well as a technical and economic analysis, which should include the following factors:

- an environmental corrosive impact on the paint coat,
- dimensions, shape of the surface to be painted and its type,
- expectations and ensured durability of the paint coat,
- characteristics of paint coatings (physico-chemical properties),
- technology of surface preparation for painting,
- methodology of paint application (layer thickness, drying/hardening time, method of application, required equipment, etc.),
- a period required for making coatings, taking into account environmental conditions (humidity, temperature, precipitation),
- dependence of durability and strength of coatings as a function of expenditures and an assumed service life,
- environmental and fire protection requirements.

After selecting the right painting kit, the surface to be coated should be inspected so as to determine all impurities and classify them properly. Depending on the impurity type, a proper method of its removal should be chosen. In the case of steel products, one of the most common types of impurities is rust, i.e. a product of steel oxidation, in the form of the released iron oxides forming layers of variable thickness and in various morphological forms, poorly adhered to the ground [17]. Another common dust is the one which is produced by all industry branches. However, it cannot gather on the surface due to different weather conditions. Due to dusts, moisture remains on a given surface. Mill scale (metal elements) can also be found on a great deal of surfaces. It results from gaseous corrosion, which is formed by a layer of metal oxides on the surface of heated metal objects as a result of their contact with air. Leaving the scorch mill may cause e.g.: detachment of metal sheets and consequently of a paint coating, emergence of a corrosive cell [8]. If the surface to be coated (metals and non-metals) is at the point where fats, greases and oils are present, greasy spots may appear, being the reason for a lack of adhesion. As it was already mentioned, dusts cause moisture to persist, which is also one of the contaminants depositing on surfaces. It usually occurs due to fog or other precipitation and can form undercoat corrosion. Two types of impurities can also be distinguished as ionic pollution. These are salts - invisible to the naked eye, water-soluble salts such as chlorides, sulphates and nitrates, which, similarly to dust, retain moisture and additionally increase corrosion.

However, the type of impurity is not the only criterion of choosing the surface preparation. It depends on several other factors, such as:

- type of material from which the element is made,
- dimensions and shape of the object surface,
- type of surface,
- surface condition and impurity area,
- aggressiveness of the corrosive environment.

Surface cleaning usually consists of two main stages. The first one is a preliminary removal of loose and ionic impurities. Next, it is necessary to proceed to proper cleaning, during which corrosion, and an old coating is removed and appropriate roughness is given. Greasy and dusty surfaces should be sprayed with water under high pressure. The areas in which ionic contamination may occur should be rinsed with a corrosion inhibitor dissolved in clean water.

In general, there are several methods of surface preparation for the application of coatings. A common method is a mechanical method. This includes brushing,

grinding, hammering, scraping, stream-abrasive treatment and fire treatment. Another popular method of surface cleaning is a manual-mechanical method, i.e. grinding, hammering and brushing, however with both manual and mechanical tools. These methods prove effective e.g. in removing rust or scale. However, the most optimal method of preparing the surface for coating is stream-abrasive treatment, which involves applying an abrasive onto a coating by means of compressed air. There are several types of such cleaning:

- with open or closed circulation of the abrasive medium,
- dry or wet,
- depending on air pressure.

Preparation of the coating by stream-abrasive treatment is characterised by the number of factors that need to be determined:

- size, type and structure of the abrasive medium,
- angle of incidence of an abrasive stream and the distance of the nozzle from the work surface,
- compressed air pressure,
- type and shape of the nozzle dosing an abrasive.

Another main method of surface preparation is physico-chemical cleaning, which is carried out by means of alkaline, acid and steam-water washing and solvent degreasing. This method of cleaning can remove dust and sand, ion and rust impurities, as well as residues from mechanical treatment.

The last of the most important cleaning methods is spraying with aqueous solutions. It does not cause undercoat corrosion, yet afterwards it is recommended to wash the surface again with clean water.

An important issue prior to applying a coating onto a surface is a classification of the type of surface to be painted, as there may be other methods of surface preparation depending on it.

The most frequently covered type of surface is steel. The impurities of this kind are as follows: rust, oils, greases, iron dust and filings. A proper way to remove such substances is to wash the surface with water under high pressure. Washing and degreasing the surface prior to cleaning may be conducted manually or mechanically using steam, water with a detergent, organic solvents, emulsions and alkaline and acidic agents. The method of spraying aqueous solutions with biodegradable detergents is particularly recommended, for economic and ecological reasons [16].

Another frequently painted material is galvanised sheet metal. Due to poor adhesion of the paint coating, it may be difficult to apply the coating to galvanised sheet metal. However, there are several cleaning methods that will work well with this type of surface. This includes washing the surface with an ammonia solution, brushing with suitable brushes and using e.g. a solution of Emulsion RN - 1.

Non-ferrous metals, similarly to galvanised sheet metal, are not a favourable surface for coatings. It can be cleaned, among others, with a conversion coating produced by chemical or electrochemical methods. In this way, it is possible to enhance greater resistance to corrosion as well as improving surface adhesion.

Another very popular type of surface, i.e. a plastic surface, is also worth mentioning. This type has relatively low adhesion; therefore, coating usually proves to be quite a difficult task. Such a surface should be previously matted and degreased. Plastics exercise excellent resistance to chemicals, thus damage to such surfaces will not take place. As this type of a surface has a low adhesion, measures can be taken to improve this property. A correct way may be to roughen the plastic with P240, P360 or P600 abrasive paper. Obviously, the surface prepared in this way must be cleaned with an antistatic cloth. Another possibility is to treat the surface with petroleum ether.

Use of polyurethane coatings

Polyurethane coatings are used in a lot of types of industry, mainly in construction and mechanical engineering. However, there are some more specific areas where such coatings are extremely useful, for example floors. There are many types of flooring that can be covered with polyurethane. Industrial floors and those found in commercial centres are the most common ones. Polyurethane floors are used in bowling alleys to make them look shiny and well-polished. Due to its durability, polyurethane is also found on the floors of hangars and garages.

Another type of industry in which polyurethane coatings are used is the aircraft manufacturing industry. Such special polyurethane coatings are frequently designed for aviation applications. They are also used by many companies manufacturing aircraft and helicopters. Polyurethane coatings, apart from protecting aircraft components, also help to save fuel by reducing air resistance. It should also be noted that polyurethane paints is not the most popular polyurethane used in aircraft - these are foams, used in various applications including sandwich structures.

Polyurethane coatings can help protect valuable industrial equipment from various types of external damage that can often occur in this working environment. In addition, polyurethanes also improve performance of a machine; therefore it can operate for an extended period of time.

Apart from the air industry, another transport industry which exploits polyurethanes is the maritime industry. Polyurethane coatings are used to protect sea hulls from corrosion and adverse weather conditions. They are used in all categories of boats and vessels, with different sizes and applications. Additionally, they are used to secure and seal diving equipment.

Transmission infrastructure is another area where polyurethane coatings are used. This permanent coating is used to protect gas and oil pipelines. Many of them run underwater. Due to the fact that polyurethanes can

withstand high pressure and harsh conditions, they are an ideal choice. They can also be used in other pipeline categories.

One of the most frequently coated polyurethane materials is steel. Therefore, roofs made of this material are ideal for the application of polyurethane coating. Polyurethane can give a roof a longer life rather than the acrylic base product. Extending the life of an industrial roof is a big saving on costly repairs. For this reason, it is the right choice for any project manager who cares about the economic, long-term features of the structure.

Another application of polyurethane coatings, worth mentioning, is the production of wind turbines. Coatings are used on blades and turbine bases. Polyurethane is a commonly used coating in this category as it can increase the energy efficiency of a turbine. Besides, it provides the right protection.

Adhesion of coatings

Each coating is characterized by adhesion depending on numerous factors. Two phenomena must occur - adhesion and cohesion if this property is to remain on a proper level. Adhesion is the joining together of surface layers of physical bodies or phases [10], while cohesion denotes resistance of physical bodies, which undergo separation. Its measure is the work needed to separate a specific body into parts, divided by the surface area resulting from this separation [14]. An adhesion test is performed to check that the coating has got the required adhesion and that it will adhere properly to the surface. There are several types of tests to measure the adhesion of paints and coatings to the surface, such as the cross-cut test, the scraping test, the pull-off test, etc.

In the scraping test, the adhesion of organic coatings is measured after their application to smooth, flat surfaces of surfaces. This is helpful in giving relative ratings for many coated panels, showing significant differences in adhesion. The tested materials are applied in uniform thickness on flat panels, mainly on metal sheets. Once the materials have dried, adhesion is determined by pressing the panels under a rounded stylus, which is loaded with increasing masses until the coating is removed from the ground surface.

The adhesion of a coating or of several coated samples of any paint product is measured by evaluating the minimum tensile stress needed to tear off or remove the coating perpendicular to the ground. Unlike other methods, the pull-off method maximises tensile stress, thus the findings may not be comparable with other results. The test consists of securing the loads (trolleys) perpendicularly to the surface of the coating with an adhesive. The test apparatus is then attached to the load handling device. Next it is levelled off so as to apply the voltage perpendicularly to the test surface. The applied force gradually increases and is monitored until the coating has been removed or a predetermined value has been reached.

The cross-cut test is a method of determining the resistance of paints and coatings to being separated from the ground, using a tool to cut out a coating pattern at the right angle, penetrating to the ground itself. Using this method, it is possible to perform a quick positive/ negative test. When testing a multilayer system, one can determine resistance to separation of individual layers against one another. There are two methods described in the ASTM norm.

The A ASTM D 3359 test method

The cut X is made through the coating to the ground, with a cemented carbide tool. A self-adhesive tape is applied to the incision. The tape is smoothed in place with an elastic band in the incision area. The tape is removed by quickly pulling it back as close as possible to 180°. The adhesion is assessed on a scale from 0 to 5.

The test method B ASTM D 3359

The cross pattern is made through a coating to the ground. The torn off coating parts are removed by soft brushing. The pressure-sensitive tape is applied to the grid cut. Next, everything is performed in the same way as in the previous method. The adhesion is also assessed on a 0-5 scale.

Research methodology

A set of samples made by casting from the examined material was prepared in order to conduct experimental testing of basic properties of polyurethane paints.

The properties were estimated on the basis of the following:

- stretching test,
- compression test
- tribological tests,
- investigations of softening temperature.

In the first stage, moulds made of MM922 silicone were cast for samples to be tested:

- bone-shaped samples for tensile strength tests with the dimensions shown in the figure (Fig. 1),
- cylindrical test pieces for compression testing, at a diameter of 12.2 mm and a height of approximately 17 mm,
- samples for determining the softening temperature, sized 15x15 mm and 4 mm in thickness,
- tribological test specimens sized 80x10 mm and 4 mm in thickness.

The components were then put together in proportions recommended by the manufacturer (3:1 in volume), thoroughly mixed and placed in a vacuum chamber for degassing. The prepared mixture was cast into moulds and left to harden for 24 hours. Later it was removed from the moulds. The mixture excess was removed and the surfaces were sanded to make them even. Consequently the authors prepared: 5 samples for tensile and compression testing, 10 samples for tribological testing, 6 samples for Vicat softening temperature testing.

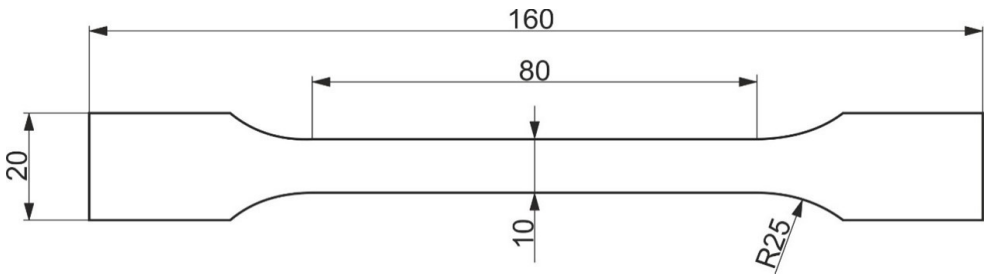

Fig.1. Dimensions of sample for tensile strength tests

Research results

The tensile and compressive strength tests were carried out using a Zwick/Roell 5kW testing machine. The tests of tensile strength were conducted in accordance with the conditions of PN-EN ISO 527 standard. The speed of the traverse movement equalled 2 mm/min. The findings of the tests are presented in Fig. 2. The average tensile strength of the test material is 1.97 ± 0.53 MPa, whereas the value of Young's modulus is 14.8 ± 1.28 MPa. The observation of failure makes it possible to conclude that the destruction of the examined samples occurred in the non-defective areas, so the results can be considered reliable.

The average strain of the samples during their destruction equals approximately 17.5 %.

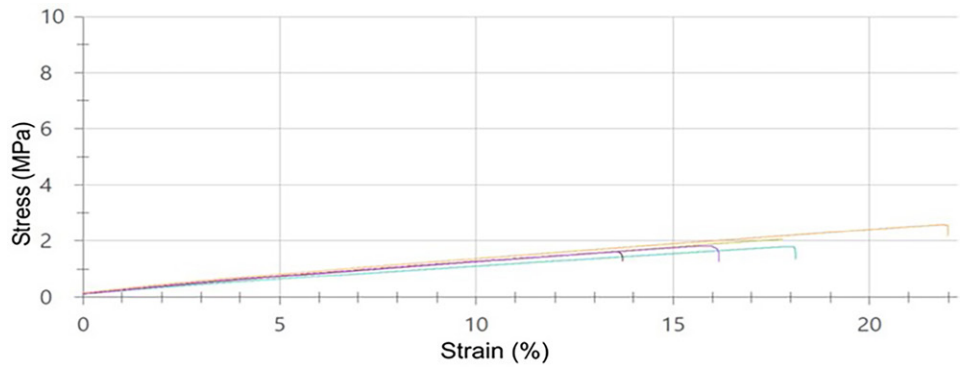

Fig. 2. Chart of material tensile strength

The compressive strength tests were conducted in accordance with the standard of PN-EN ISO 604:2006. The speed of the traverse movement equalled 2 mm/min.

The results of the testing for compressive strength have been presented in Fig. 3. The value of compressive strength is 46.5 MPa, whereas the value of Young's modulus is 10.1 ± 0.45 MPa. The sample destruction during its compression occurred along the height with deformations above 65%.

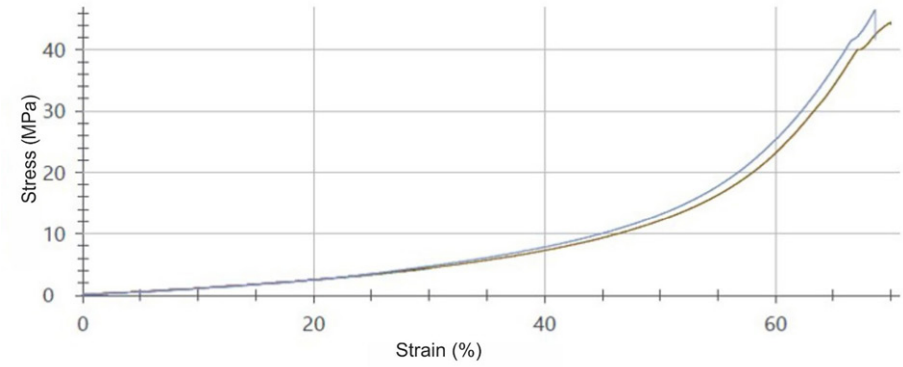

Fig.3. Chart of compressive strength test

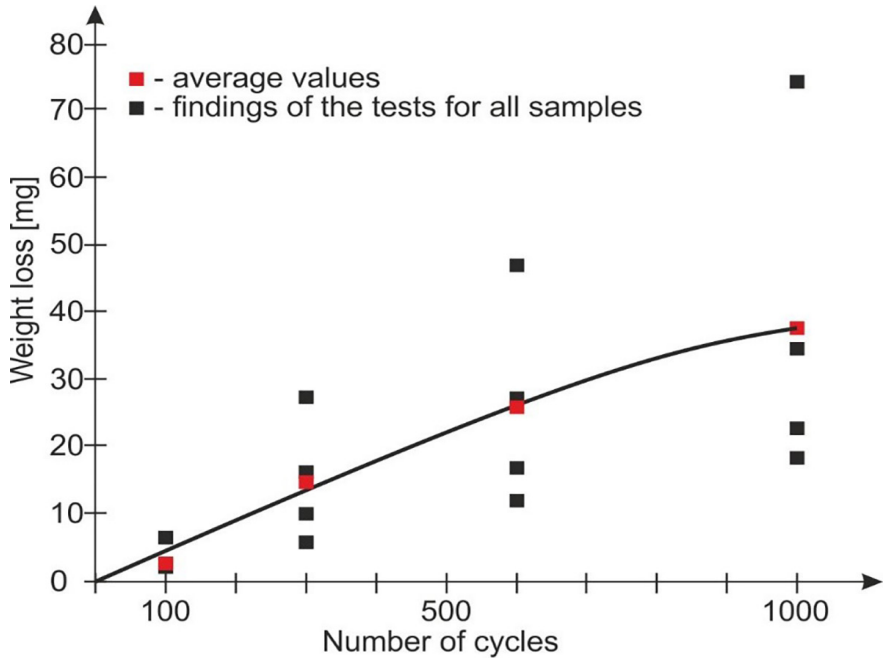

Fig. 4. Loss of sample mass during the abrasion test

The tribological examination was conducted using the Taber Linear Abraser tribometer and Mettler Toledo XSE205 laboratory balance. During the examination, the authors recorded a mass loss of the sample, which was subjected to abrasive wear with the head load of 1,850 grams. The mass loss was recorded after 100, 300, 600 and 1,000 cycles. The findings of the tests are presented in Fig. 4.

An analysis of the results in Fig. 4 shows an almost linear loss of mass as a function of the number of abrasion cycles. A significant scattering of results is characteristic for the test.

Determining the softening temperature of the polyurethane paint was carried out on a laboratory stand HDT and Vicat - Instron HV6X, on which 6 test samples were placed simultaneously. The samples were thermostated in oil at 25°C for 5 minutes and then heated at 120K/hour in (VST) in accordance with EN ISO 306 standard. The penetration measurement of the indenter loaded with a force of 10 N was conducted until a 1 mm material penetration was obtained (Fig. 5). When analysing the results of the softening temperature determination tests, it was noted that in the temperature range 52 - 55°C, most of the samples started to react to the acting force of the indenter (only two samples started to react under different temperature conditions - one at a much lower temperature around 35°C and the other at a much higher temperature around 70°C), however only approximately 0.7-0.9 mm of the penetration was obtained. This might have been caused by the surface and viscosity forces of the paint material. Thus, in subsequent experiments, much larger and thicker samples will be prepared for experimental testing.

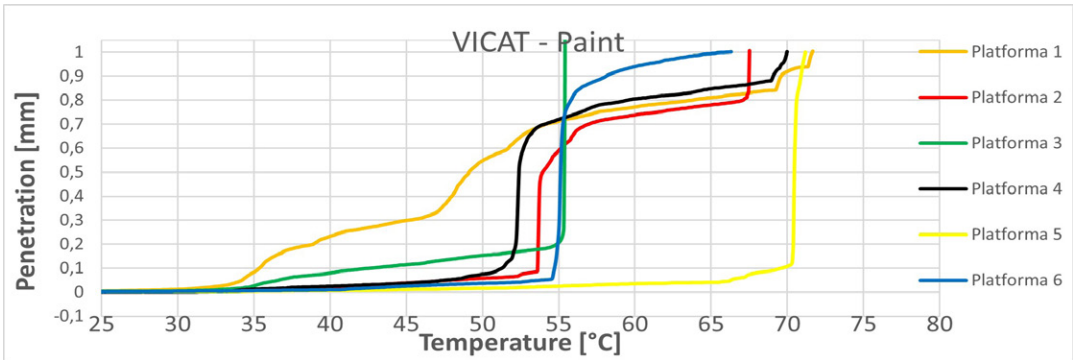

Fig. 5. Penetration of the indenter into the tested material during heating - determination of paint softening temperature

Conclusions

1. During the sample preparation, it is essential to use methods which will enable removing air bubbles from the mixture.
2. The values of the coefficient of longitudinal elasticity determined in the compression and tensile test have different values, despite the same traverse movement speed in both tests.
3. The nature of the tensile and compressive curves indicates a high similarity of the internal structure of the specimens obtained by degassing the mixture of components.
4. The obtained results of mass loss tests after the process of surface abrasion of the material show a linear change of this parameter as a function of the number of abrasion cycles. Yet, at the same time, they are burdened with a large scatter of the obtained experimental results.
5. The softening temperature of the material appears to be around 52 - 55°C.

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REPRAP P3STEEL SPATIAL PRINTER CONSTRUCTION DESIGN

Projekt budowy drukarki przestrzennej REPRAP P3STEEL

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Abstract: The introduction describes the purpose of the article, i.e. designing a REPRAP printer. The article includes an overview of additive manufacturing techniques. The next section discusses the definition of a self-replicating REPRAP printer. Then, the example of the method for extruding thermoplastic materials with the use of the FDM / FFF technique served to present the list of parts and the design of the REPRAP P3STEEL spatial printer. Tests were also carried out and the prints were compared with the Zoltrax M200 serial production printer.
Keywords: assembly, 3D printers

Streszczenie: We wstępie został przedstawiony cel pracy, czyli projekt drukarki REPRAP. Praca zawiera przegląd technik przyrostowych. W kolejnej części omówiono definicję samoreplikującej się drukarki RERAP. Następnie na przykładzie metody wytłaczania tworzyw termoplastycznych techniką FDM/FFF przedstawiono wykaz części i projekt drukarki przestrzennej REPRAP P3STEEL. Przeprowadzono również testy i porównano wydruki z seryjną drukarką Zoltrax M200.
Słowa kluczowe: montaż, drukarki 3D

Introduction

Although 3D printers are not a novelty on the market, they are becoming more and more popular. They are used not only for exclusively engineering purposes, but also as a hobby or in commercial applications, e.g. while printing promotional materials for companies.

The scope of 3D printing is not limited to standard plastics such as ABS or PLA. It also includes printing from non-standard materials such as chocolate or concrete.

The price of three-dimension printing machines can still be high, especially when used in professional systems, but after analysing the costs, it can be concluded that their construction can be cheaper and simpler. This article presents a method for constructing an inexpensive open source RepRap P3Steel printer.

Additive Manufacturing Techniques

Extremely fast development of spatial modelling techniques, including solid and surface modelling, allowed making equally dynamic advances in rapid prototyping methods. Taking advantage of the geometry designed in the engineering process makes it possible to form such geometry into a real object. The object is formed by dividing its geometry into individual layers, on the basis of which a machine code controlling the prototyping machine is generated. The machine engaged in the printing process constructs the model in a layer-by-layer manner by combining successive layers [2, 9, 10]. When the term “rapid prototyping” is used in the context of 3D printing it definitely means creating a real object with the use of a digital model [10].

3D printing is, therefore, a visualization of the possibilities of computer-aided engineering. Currently, the use of 3D printing in rapid prototyping is becoming a very popular method helping to check printed models. 3D printing has also appeared in medical applications, where, for example, on the basis of the printed model of an organ or the structure obtained from a tomographic scan, precise consultations and attempts at predicting a course of surgery [3, 4, 5].

3D printing has also found its application at homes as it has allowed ordinary people to visualize their creative mental ideas. Thanks to a huge community interested in it, 3D printing is also a source of infinite ideas, new devices facilitating household chores or gadgets [9].

Stages of three-dimensional printing

The process of developing an idea into a physical object has several stages. The design must be prepared in a virtual three-dimensional space, actually its mesh geometry allowing to map the model, and then it must be exported to CAM software which is responsible for dividing the model into layers and generating motion paths for applying the binding agent, a molten material, or motion paths for the laser beam, in the form of a code understood by a numerically controlled machine tool (CNC). After completing this process, the object is ready for possible finishing, such as smoothing surfaces or removing unnecessary filling. Sometimes it is also necessary to remove unnecessary additional supports [10].

The above description is presented in the form of a diagram in Figure 1.

3D CAD	3D CAM	3D Print	Physical object
The stage involves preparing virtual spatial geometry in the 3D modelling system and its converting into mesh geometry	The stage consists in dividing virtual geometry into layers and programming the movements of how to apply material, a binding agent or a laser beam	The stage involves producing a real object with the use of an additive manufacturing technique in a numerically controlled machine (NC/CNC)	The stage consists in removing the real object from the machine and its possible finishing treatment

Fig. 1. The main stages of the 3D printing process [10]

Printing methods

Additive manufacturing techniques are divided according to the printing method used. They include the following:

- Stereolithography – SLA,
- Laminated Object Manufacturing – LOM,
- Fused Deposition Modelling/Fused Filament Fabrication – FDM/FFF,
- Jetting Modelling – JM,
- Powder-Based 3D Printing 3DP,
- SLS/SLM/LENS.

The method for extruding thermoplastic materials with the use of the FDM/FFF technique was applied in the printer presented below.

Extruding thermoplastic materials – FDM/FFF Fused Deposition Modelling or Fused Filament Fabrication – is an additive manufacturing technology consisting in extruding material through a nozzle along paths. The semi-fluid material bides with adjacent paths, forming a solid model in a layer-by-layer manner [9, 10].

This technique mainly uses thermoplastic materials such as ABS, PLA or nylon. The process involves introducing the material in the form of a fishing line from the spool into the pushing mechanism which presses it into the print head, where in the temperature range suitable for melting a given material (190ºC – 280ºC), it is transformed to a semi-liquid state and extruded through a nozzle of the appropriate size, along the path in the horizontal X-Y axes. After extrusion, the material solidifies, biding with adjacent paths, creating a ready model in a layer-by-layer manner [9, 10].

The general model of the printer construction in the FDM technique consists of two feeders controlling the amount of material pumped into the heated nozzles. The material in them is heated to the melting temperature and pressed directly onto the working platform or the previous layer of the model. The working platform usually consists of a heating table (due to the considerable shrinking of the material when it is cooled and the detaching of the model or its part from the working platform). The nozzles move in the X-Y axes, while the Z axis is responsible for the movement of the platform [10], which is shown in Fig. 2.

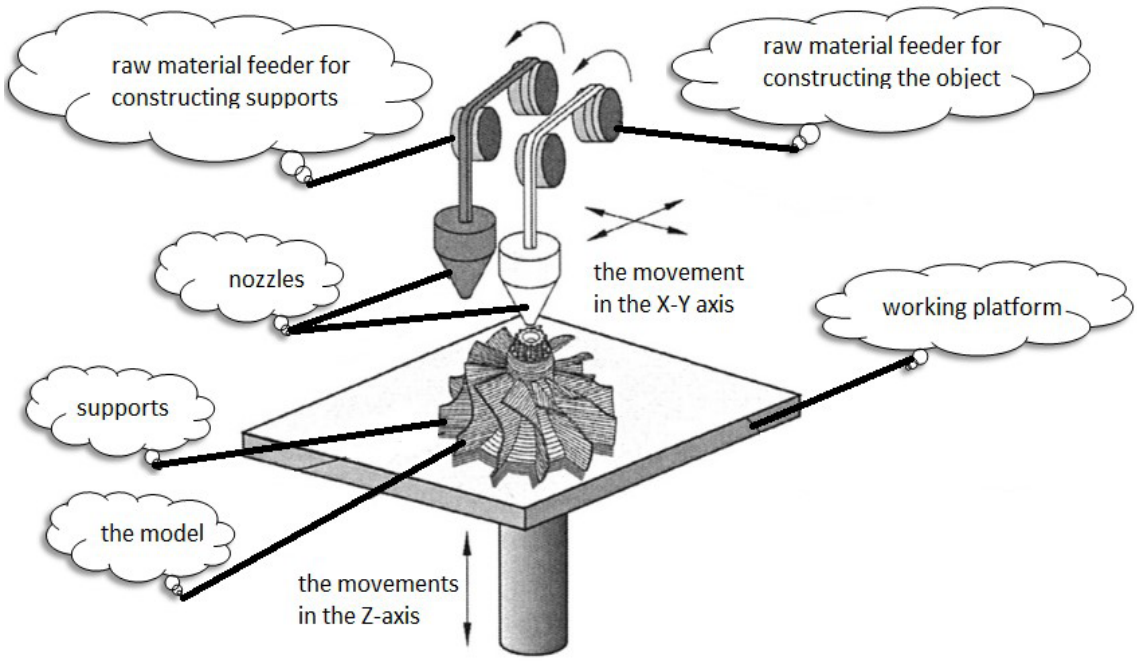


Fig. 2. Model construction diagram according to the FDM technique [10]

Selfreplicating RepRap machine

RepRap is an open, i.e. having sources available for everyone, design of a utility spatial printer. The machines in this design mainly consist of plastic parts printed with the use of one of the additive manufacturing techniques. After a new printer is completely assembled, it is able to produce further parts, enabling self-replication [1, 7, 8].

RepRap printer design

The growing popularity of 3D printing, particularly the FDM technique, has contributed to the appearance of many printer designs and new concepts for how to construct them. Designs of and modifications to 3D printers which are developed by individual users, who improve structures, and which are made available to the public under a free license are gaining more and more popularity and becoming another well-developed standard for improvement.

The table below shows the parts suggested for the construction of the printer (Tab. 1).

This printer consists of only a few printed parts, because all the fragments of the support frame made in this way have been eliminated. Connecting standard steel parts and additively manufactured ones is carried out without any problems. The assembly of the printer according to the concept presented in the article is shown in figures 3-9.

Table 1. List of parts used for constructing a 3D printer

	Type of parts	Selection
1.	Print method	FDM
2.	Frame	“P3Stell” model
3.	Drive	42BYGHM809 engine by “Wantmotor” was selected Their specifications are: • resolution: 400 steps per turn (0.9 °) • rated voltage: 3V • current consumption per coil: 1.7 A • coil resistance 1.8 Ω • winding inductance: 2,88 mH • moment holding 4.89 kg*cm (0.48 Nm) • outputs: bipolar (four wires) • shaft diameter: 5 mm • weight: 360 g • dimensions: 42 x 42 x 48 mm (without a shaft) - NEMA 17
4.	Extruder	“MK8” by “Geeetech” Specification: • heater: 6 mm, 12 V, 35 W • built-in stepper motor KS42STH48-1684A • motor current: 0.83A • engine speed: up to 40 mm/s • filament diameter: 1.75 mm • nozzle diameter: 0.40 mm • thermistor: 100K NTC • normal operating temperature: 190230°C¬ • supported material: PLA and ABS and other • built-in fan: 40x40 mm • metal construction • net weight: 450 g
5.	Electronic parts	Arduino Mega 2560 microcontroller board paired with RAMPS version 1.4 driver, and drivers for DRV8825 stepper motors, “Full Graphic Smart LCD Controller" display by Reprapdiscount.
6.	Table	aluminium heating table, RepRap Alu-Heatbed MK3
7.	Inductive sensor	model: LJ12A3-4-Z/BX. Its specifications: • output configuration: NPN / NO • range: 0-4.0 mm • supply voltage: 6-36 V DC • operating current max: 200 mA • sensor housing: M12 • number of pins: 3 • cable length: 1.0 m • dimensions: 63 x 12 mm
8.	Power supply	Zalman ZM400-LX
9.	Printed elements	printing of all parts took about 80 hours and was performed on a Zortrax M200 3D printer
10.	Firmware	Firmware used in RepRap machines is a comprehensive program controlling the operation of engines, heaters and sensors. It is controlled by means of common numerically controlled machine codes, the G-code command language. The program works in real time by sampling signals from thermistors. It allows printing from a mass storage device connected to the controller or via computer connection (this solution may cause delays and consequent print quality problems

Source: http://wantmotor.com/product/42byghm.html, http://geeetech.com/wiki/index.php/MK8_Extruder, http://reprap.org/wiki/Arduino_Mega_Pololu_Shield, Kaziunas France A., Świat druku 3D, Wydawnictwo Helion, 2014

Fig. 3. The assembly method with the use of M3 self-locking screws and nuts, P3Steel printer frame [own elaboration]

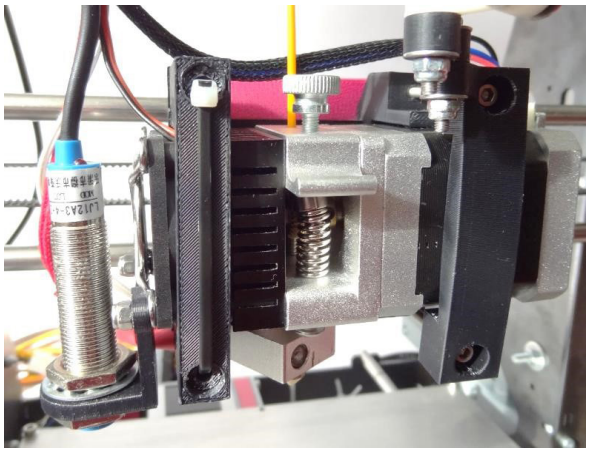


Fig. 6. The complete MK8 extruder mounted with the use of printed parts [own elaboration]

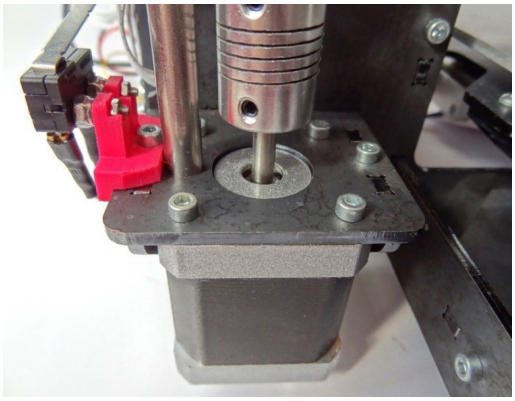


Fig. 4. The complete lower end of the Z-axis [own elaboration]

Fig. 7. The mounted holders for the spool of printer raw material [own elaboration]

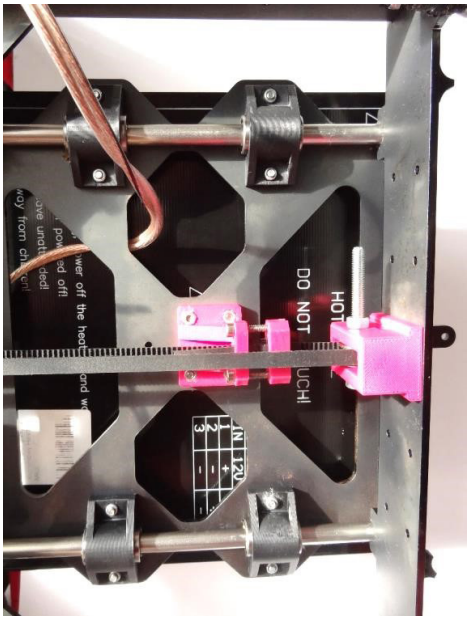


Fig. 5. The assembled Y-axis, bearings mounting, tensioner mounting, toothed belt mounting, and the installed heating plate [own elaboration]

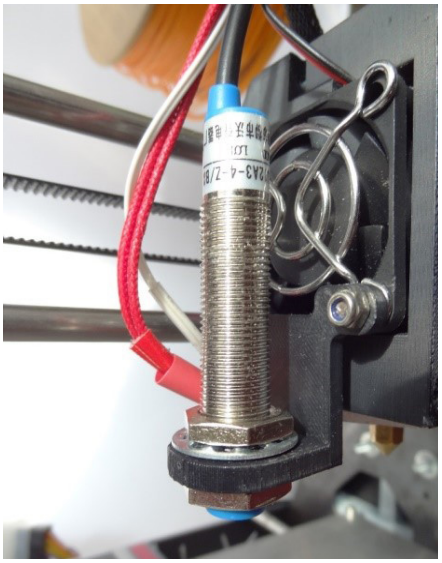
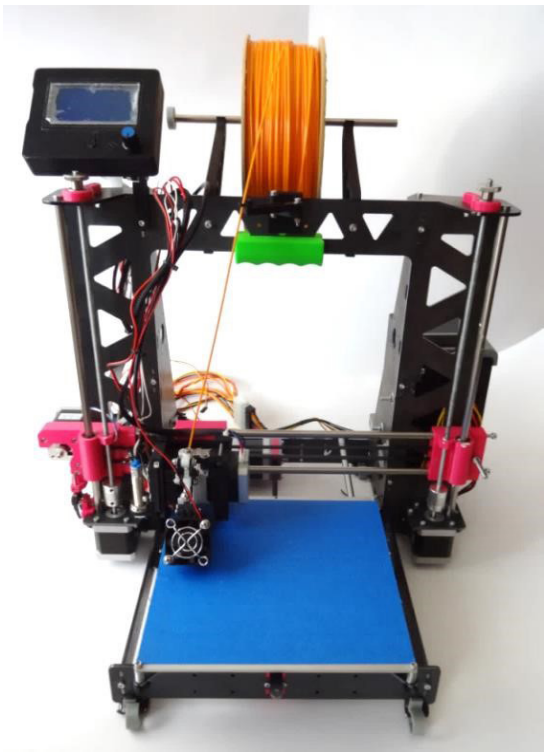


Fig. 8. The holder, the mounting and location of the inductive sensor relative to the extruder nozzle [own elaboration]



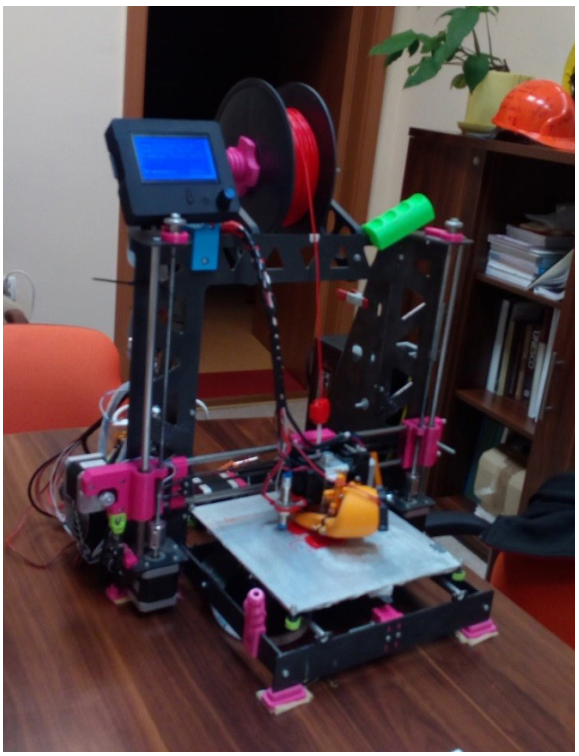
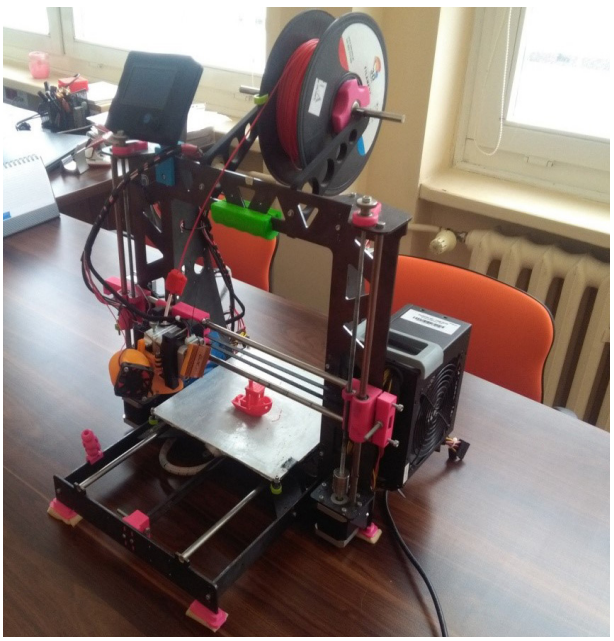


Fig. 9. The complete RepRap P3Steel device – on the left-hand side, The 3D printer during the test – on the right-hand side [own elaboration]

Comparison of printout quality

In order to verify the printouts generated by the RepRap printer presented in the article, the quality of its printouts was compared with those generated by the Zortrax M200 printer, as shown in Figures 10 and 11. There were no significant differences in the quality of printouts from both printers in terms of resolution and the surface itself.



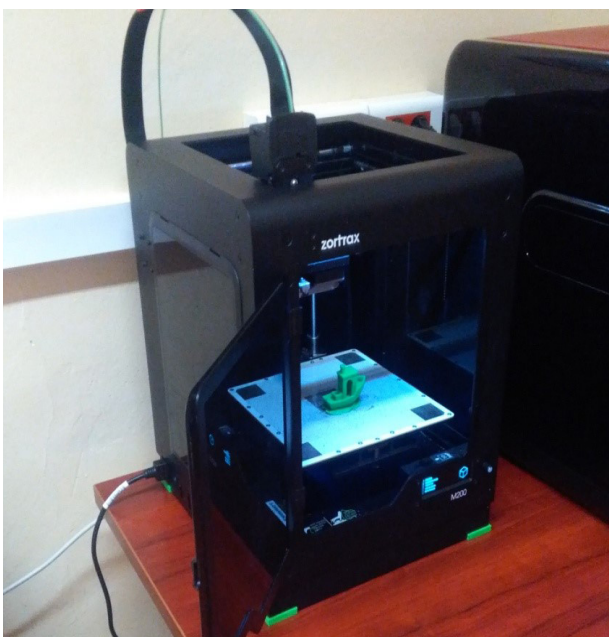


Fig. 10. The printout of the model generated by RepRap P3Steel and Zortrax M200 [own elaboration]

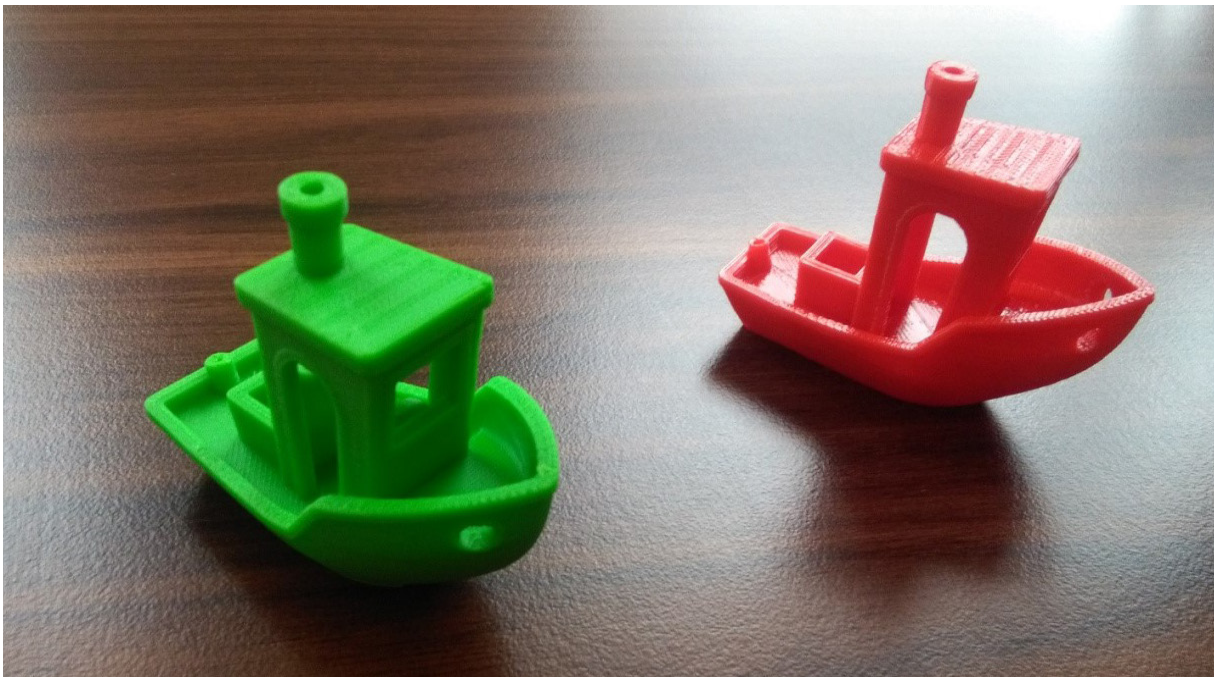


Fig.11. The prints from RepRap P3Steel and Zortrax M200 [own elaboration]

Conclusions

The increase in the popularity of 3D printing, in particular the FDM technique, has contributed to the emergence of many printer designs and new concepts. Projects and modifications developed by individual users, who are constantly improving their own designs as well as constructions available to the public under a free license, are gaining popularity and are becoming another well-developed standard for community improvement.

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PASSIVE SAFETY OF EARTHMOVING MACHINE OPERATORS

Bezpieczeństwo bierne operatorów maszyn do robót ziemnych

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Abstract: Falling objects and roll over earthmoving machines are a huge hazard and a major cause of accidents. Safety structures called FOPS (Falling Object Protective Structures) and ROPS (Roll Over Protective Structures) have been used to protect the operators. A FOPS and ROPS cabin should withstand the loads and consume energy during accidents. FOPS and ROPS standards require full scale destructive testing to validate its conformity with the requirements, at present. This is caused due to a lack of fundamental research information on the nonlinear inelastic response of the cabs structures. However, a non-linear, static or dynamic, finite element analysis (FEA) has been used to simulate the FOPS/ROPS testing. The FEA results have been compared with those of experimental testing and the FEA methodology has been improved to get a good correlation. The FEA approach will be used to finalize the FOPS/ROPS design prior to full scale testing to minimize the number of prototype and thereby, to reduce the development cost and time. This paper presents the FEM as sufficiently verified method for both tests, FOPS and ROPS, at the first step of the design process. The accuracy of the mapping of the object with the model adopted for the simulation has a primary impact on the convergence of calculations with test results. This applies both to its geometry, the accepted loads and to the mechanical properties of the materials used.
Keywords: FEA simulation, operator's safety, FOPS/ROPS testing

Streszczenie: Spadające przedmioty i przewrócenie się są ogromnym zagrożeniem i główną przyczyną wypadków maszyn do robót ziemnych. Do ochrony operatorów wykorzystano konstrukcje zabezpieczające o nazwie FOPS (Falling Object Protective Structures) i ROPS (Roll Over Protective Structures). Kabina FOPS i ROPS powinna wytrzymać obciążenia i pochłaniać energię podczas wypadku. Normy FOPS i ROPS wymagają obecnie przeprowadzenia testów niszczących obiektu rzeczywistego w celu sprawdzenia jego zgodności z wymaganiami. Jest to spowodowane brakiem podstawowych informacji badawczych na temat odkształcania konstrukcji kabin. Jednak do symulacji testów FOPS/ROPS wykorzystano nieliniową, statyczną i dynamiczną metodę elementów skończonych (FEA/FEM). Wyniki symulacji zostały porównane z wynikami badań eksperymentalnych, a metodologia FEA została ulepszona, aby uzyskać dobrą korelację. Podejście to zostanie wykorzystane do sfinalizowania projektu konstrukcji FOPS/ROPS przed pełnym testowaniem obiektu rzeczywistego, aby zminimalizować liczbę prototypów, a tym samym zmniejszyć koszty i czas prac b+r. W niniejszej pracy przedstawiono FEM jako wystarczająco zweryfikowaną metodę zarówno dla testów, FOPS, jak i ROPS, na pierwszym etapie procesu projektowania. Dokładność mapowania obiektu z modelem przyjętym do symulacji ma podstawowy wpływ na zbieżność obliczeń z wynikami badań. Dotyczy to zarówno jego geometrii, przyjętych obciążeń, jak i właściwości mechanicznych użytych materiałów.
Słowa kluczowe: analiza MES, bezpieczeństwo operatora, badania FOPS/ROPS

Introduction

Falling objects and roll over earthmoving machines are a huge hazard and a major cause of accidents. Safety structures called FOPS (Falling Object Protective Structures) and ROPS (Roll Over Protective Structures) have been used to protect the operators. A FOPS and ROPS cabin should withstand the loads and consume energy during accidents. FOPS and ROPS standards require full scale destructive testing to validate its conformity with requirements, at present. This is caused due to lack of fundamental research information on the nonlinear inelastic response of the cabs structures. However, a non-linear, static or dynamic, finite element analysis (FEA) has been used to simulate the FOPS/ROPS testing. The FEA results have been compared with that of experimental testing and the FEA methodology has been improved to get a good correlation. The FEA approach will be used to finalize the FOPS/ROPS design prior to full scale testing to minimize the number of prototype and thereby reduces the development cost and time.

Cabs should be designed such that energy absorption occurs without reducing stiffness and strength [1]. When the cab structure element cracks, the energy is not absorbed by the permanent plastic deformation of the FOPS/ROPS components [7]. Absorbing impact or rollover energy structure is usually made as an assembly of bars, tubular frame and sheets. This is the main operator's space protection. Cabs can be equipped with suspension components to reduce vibration hazards. They have got a big influence to course of accident. At the same time, they are the most difficult element for modeling, both in the static and dynamic range.

Improving energy absorption by partially modifying FOPS/ROPS element shapes and mechanical properties is a potential best method. Andrews et al. [2] has reported that cylinder crushes in an axis symmetric mode absorb more energy than in a non-axis symmetric mode. They showed that the crush mode was dependent on the cylinder dimensions (diameter, thickness, length). Partial modeling of cab frame elements geometry was conducted by Elmarakbi et al. [4] using finite element simulations of the thin S-shaped longitudinal members with variable cross-sections made of different materials. They used the optimized members to determine the desired variables for the design of energy absorbing system to enhance vehicle safety. Kotełko [11] described the destruction and energy absorption of the compressed and bent thin plates and thin-walled 13 girders and columns on analytical and FEA way. Full geometry modeling of cab frame leaded by Haruyama [6], obtained that cab structures elements according to their thickness combination were influenced by wrinkle which can reduce energy absorption. Some modification was subjected to increased energy and avoided wrinkle. [12] and [8] modeling cab frame for roll over test according to certain model developed by specific companies and conducted FEA analysis to perform result for later loading condition.

The main aim of this work was to evaluate FEA as sufficiently verified method for both tests, FOPS and ROPS, at the first step of the design process in SBŁ-IMBiGS practice. The accuracy of the object mapping with the model adopted for the simulation has a primary impact on the convergence of calculations with the test results. This applies both to its geometry, accepted loads and to the mechanical properties of the materials used.

In the area of earthmoving machinery, the minimum requirements in this regard are laid down in the following standards:

- EN ISO 3449:2009 Earth-moving machinery - Falling-object protective structures - Laboratory tests and performance requirements
- EN ISO 3471:2009 Earth-moving machinery - Roll-over protective structures - Laboratory tests and performance requirements

These standards are harmonized with 2006/42/EC Directive - Machinery.

Simulations and tests have been done as a part of **POIR.01.01.01-00-0236/15** grant, sponsored by The National Centre for Research and Development (NCBiR).

RD 165 FHAD (Full Hydraulic Advanced Drive) grader prototype: the first in the graders family was the aim for manufacturer. It was achieved with the cooperation with SBŁ-IMBiGS by carry out grader components such as the main and rear frame, equipment, and integrated control system, hydraulic systems, FHAD and TIER IV Final engine cooling system.

This paper shows simulation and test validation of the graders FOPS/ROPS structure in meeting mentioned above standards requirements.

Fig. 1. RD 165 grader

FOPS test procedure

FOPS test is executed in the dynamic mode. It is made by hitting with a freefalling probe into a protection structure. The probe energy value at the impact moment

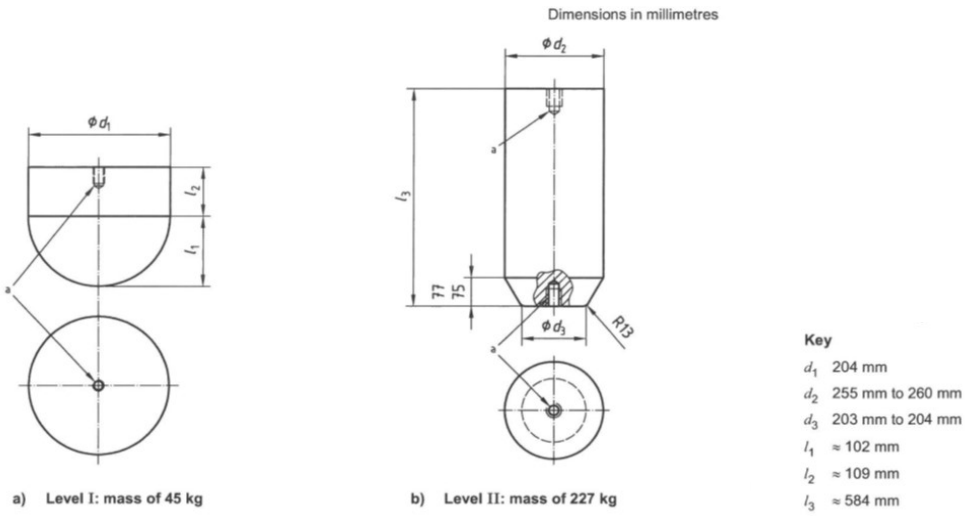


Fig. 2. Shape and dimensions of the test probes. Given values are indicative [13]

must correspond to the selected level of protection. The shape of the probe is also dependent on the energy value. PN EN ISO 3449 defines two levels of protection:

1. protection **Level** I for falling small objects such as bricks, small concrete blocks, hand tools. The energy value in this case is equal to 1 365 J.
2. protection **Level II** occurs in the case of large falling objects' hazards, such as trees, boulders, large stones, etc. The energy value is equal to 11,6 kJ.

The impact point should be closest to the center of the protection area and in the Outline DLV (Deflection Limiting Volume Fig. 4).

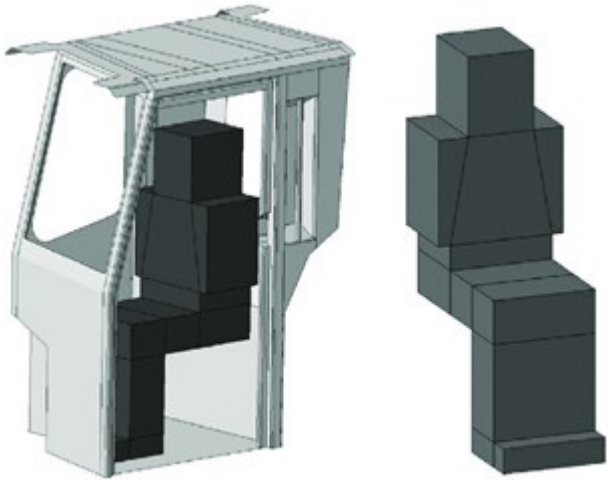


Fig. 3. DLV shape and placement in the cab [5]

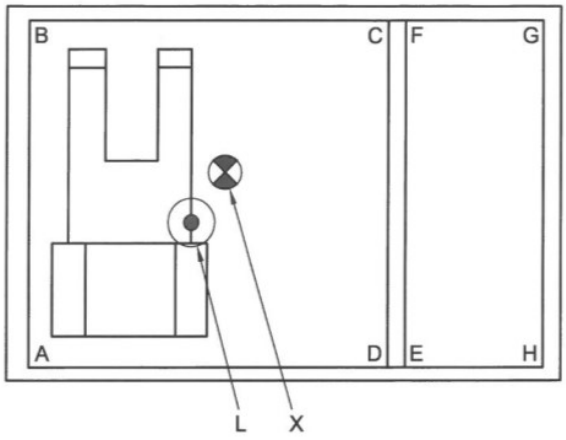


Fig. 4. The impact point placement "L" vs roof center "X" [13]

ROPS test procedure

The ROPS test involves further loading the protection structure from the side, top and along the longitudinal plane of its symmetry. During the lateral load, the deformation energy is calculated. This is the second criterion necessary to be achieved during the test, in addition to the force value.

Load values depend on the type of machine (excavator, loader, dozer, etc.) chassis (wheeled, tracked), frame (rigid, articulated). In addition, PN-EN ISO 3471 makes the value of the structure load forces and its deformation energy to be achieved dependent on the machine total weight.

The force and energy values for a grader with operating mass M [kg] shall be calculated on the basis of the following formulas shown in Tab. 3 [14].

Fig. 5. FOPS test stand example [15]

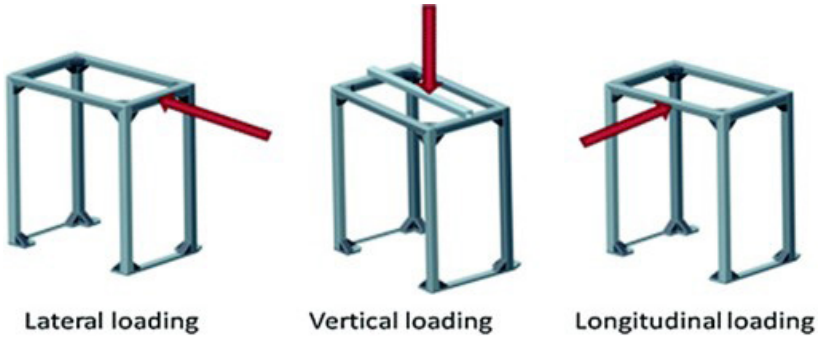


Fig. 6. ROPS tests procedure according to PN-EN ISO 3471:2009 [5]

The RD 165 Grader FOPS/ROPS Structure Testing

Input data

The basic parameters of the protection structure and the position of the seat index point (SIP) are shown in Fig. 7:

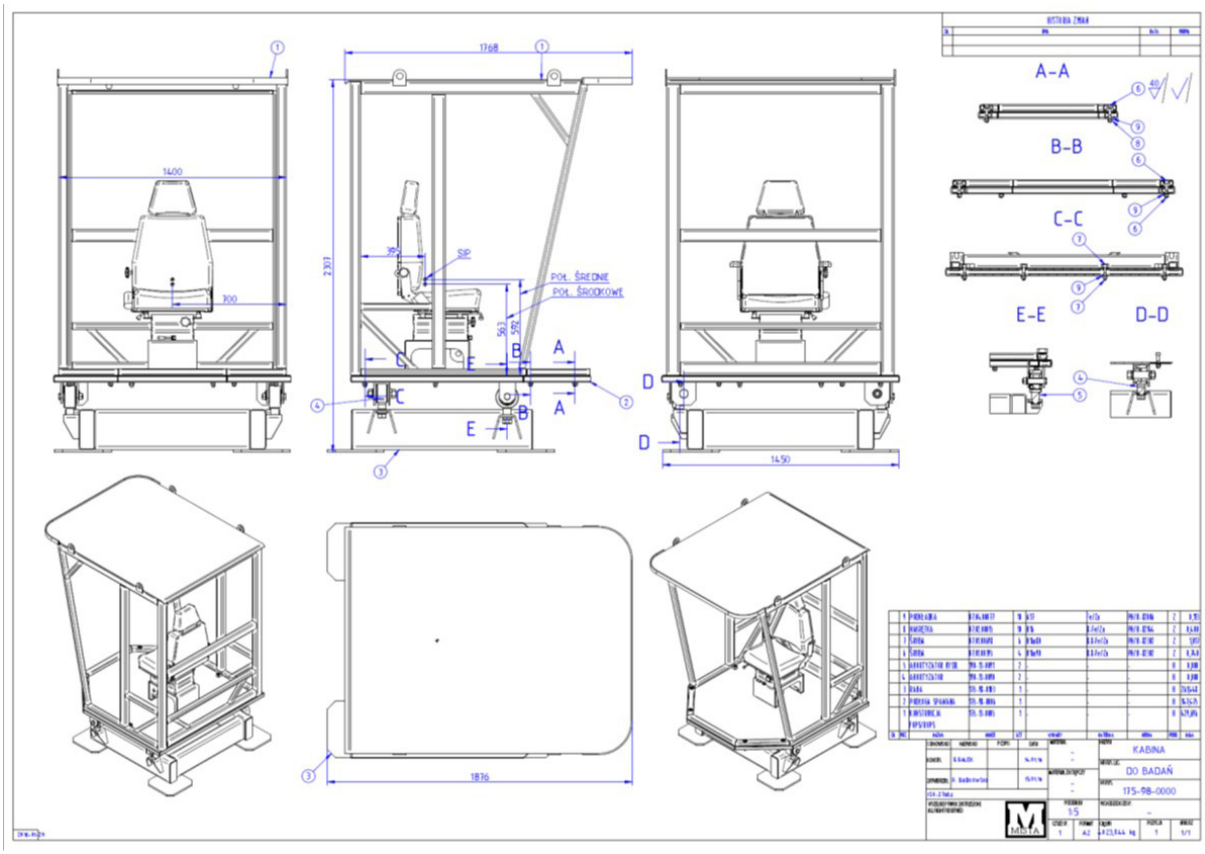


Fig. 7. FOPS/ROPS structure for RD 165 grader

Geometric model

The geometric model of the cabin (Fig. 8) is based on the design documentation (as above) provided by the manufacturer. Solid Works 2020 was used for this purpose.

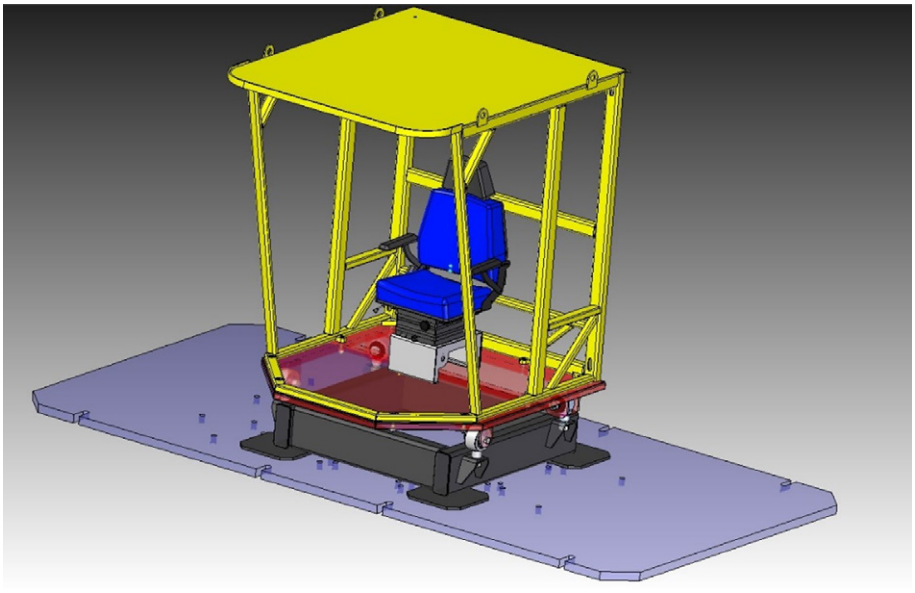


Fig. 8. RD-165 grader's FOPS/ROPS structure geometric model

Material model

The main elements of the protection structure are made of 2 mm thick steel sheet (roof, floor) and rectangular pipes of S355J2+M steel. It is a structural alloy steel, previously known as 18G2A. It is has got high strength and ductility, good workability. The S355J2+M is a steel with guaranteed weldability at an increased yield strength. It is used for the machine structure components manufacturing, mainly load-bearing structures. It is well welded, hot-rolled and cold-formed, with a minimum yield strength ReH = 390 MPa. The mechanical properties of this steel are shown in Tab. 1.

The model shown on Fig. 9 is used for simulation. This is the blinear model. Values from material approvals have been adopted.

Tab. 1. S355J2+M steel mechanical properties

Yield strength () min [MPa]	Tensile strength R_m [MPa]	Percentage elongation after breaking A_{80} Min % Sample thickness t < 3mm	Percentage elongation after break A_5 Min % Sample thicknesst <3mm
390	593	10	12

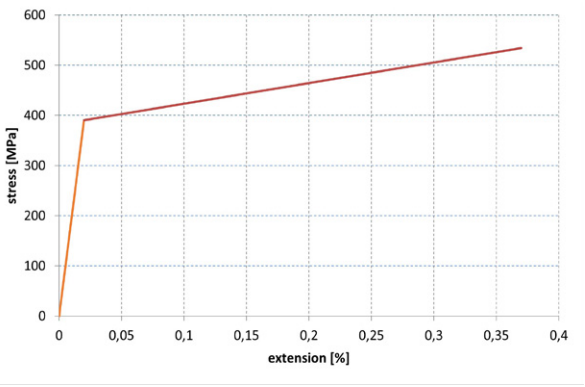


Fig. 9. S355J2+M steel stress-extension curve. Bilinear model adopted to simulation

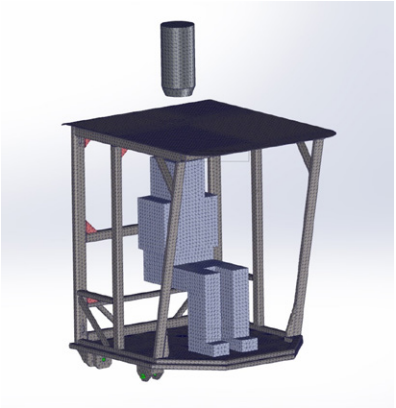
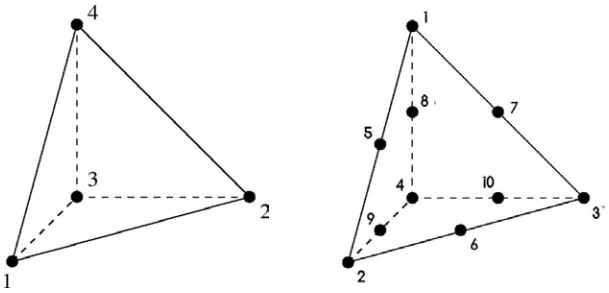


Fig. 11. Structure mesh

Finite element model

A library tetra4 or tetra10 elements was used to model the finite element mesh. Although some of the structure elements such as roof and floor are made of sheet metal, i.e. one dimension is at least one order smaller than the other two, cab was modeled with a tetra4 elements only. It is a spatial element, a tetrahedral, with 4 or 10 nodes, having 6 degrees of freedom each – displacements and rotations relative to the three axes of the local coordinate system (Fig. 10).



a) „tetra4" element b) „tetra10" element

Fig. 10. Library "tetra" elements

Model mesh has got 175 636 elements with 52 229 nodes.

FOPS simulation

Loads

The initial speed of the test probe is due to the impact energy necessary to reach the expected protection level (Fig. 12). Thus, for level II, it is – 10 m/s. The solution time was assumed to be t=0,015 s and its value was based on data in the literature of the subject [9]. Simulation conditions should be so close to real test conditions as possible.

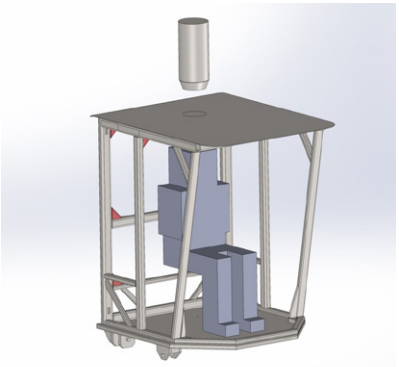


Fig. 12. FOPS simulation loads

Simulation results

The simulation results are presented on Fig. 13 and Fig. 14 in the graphic mode.

The calculations shown above indicate that the cab roof meets the requirements of PN EN ISO 3449:2009 in terms of II level. The DLV was not broken in any simulation time step. The appearance of an element with a stress value that is many times greater than a tensile strength value may be due to mesh imperfection (shape and size of the element). That appears only in the areas where there are mesh elements with small angles of convergence. In other areas, the stress value does not exceed R_m. However, according to this standard, the final confirmation is a positive result of the position test of the real object.

Maximum stress **3 003E6 MPa**

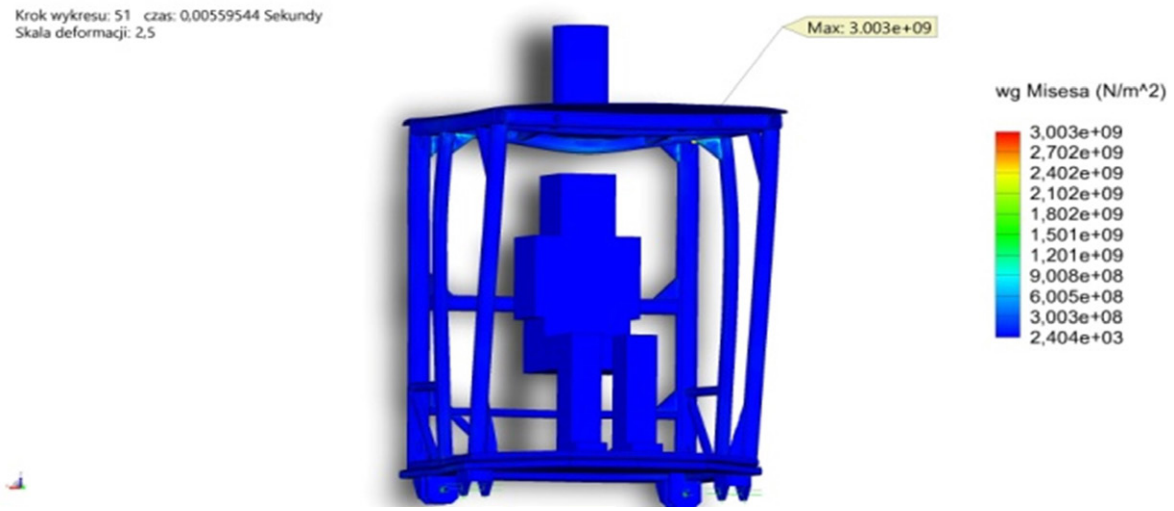


Fig. 13. von Mises stress distribution under the impact load

Maximum translation **49,61 mm**

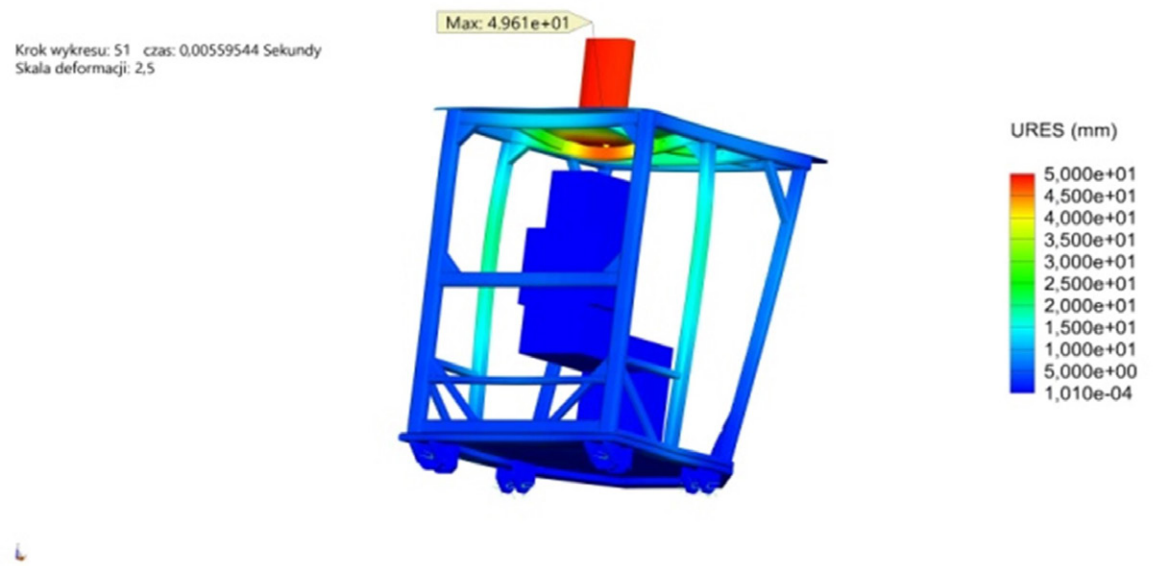


Fig. 14. Translation distribution under the impact load (scale = 2.5:1)

a)

b)

Fig. 15. FOPS structure under test procedure (a) and roof deformation after impact load (b)

Cabs testing

Simulation is verified on the base of real object test results.

A FOP testing of the protection structure for RD 165 grader was conducted in Machine and Construction Laboratory of Lukasiewicz - Institute of Mechanized Construction & Rock Mining. They were made under the conditions specified in EN ISO 3449:2009.

The maximum deformation value is amount 38 mm without braking DLV space.

FOPS conclusions

The simulation displacement values exceed test values on 11 mm i.e. 29%. It is a satisfactory factor for the initial step of the design process. Thus, the key to obtaining acceptable accuracy of the simulation is:

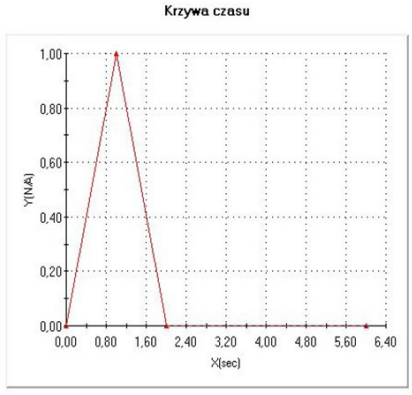
1. Correctly determining of the material mechanical properties, including elasticity and damping coefficients;
2. Impact time value;
3. Probe impact point on the roof structure should be so close to test condition as possible;
4. Mesh density;
5. Correctly defined structure components' contacts.

ROPS Studies

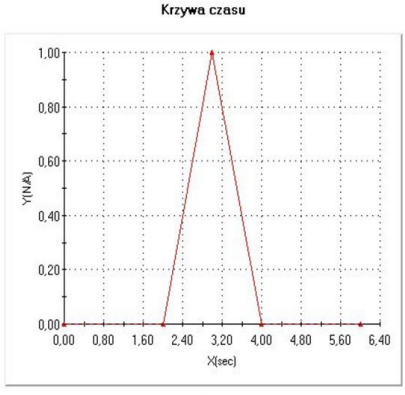
Simulation

Load model

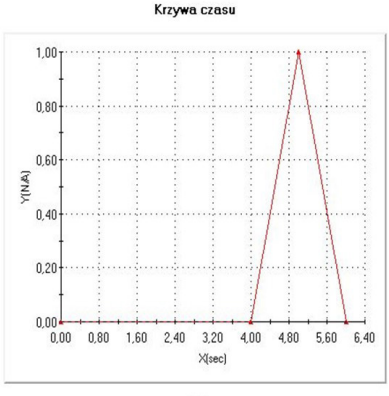
The load model of the protection structure, both in the terms of operating directions and force values, was in accordance with the methodology described in EN ISO PN 3471:2009. This is illustrated in Fig. 16. Loads, structure fixing and material properties were mapped to real conditions as close as possible.



Lateral force 134 000 N



Vertical force 353 000 N



Longitudinal force 107 000 N

Fig. 16. ROPS load force coefficients vs time and force values

Tab. 2. Test properties

Analysis	Nonlinear static analysis
Large displacement expression	On
Solver type	Large Problem Direct Sparse
Solver control	Force
Iteration method	NR (Newtona-Raphson's method)
Integration method	Newmark

Simulation results

Simulation results at after the longitudinal load were shown below in the graphic mode on Fig. 17 and Fig. 18.

Maximum stress value 461,3 MPa

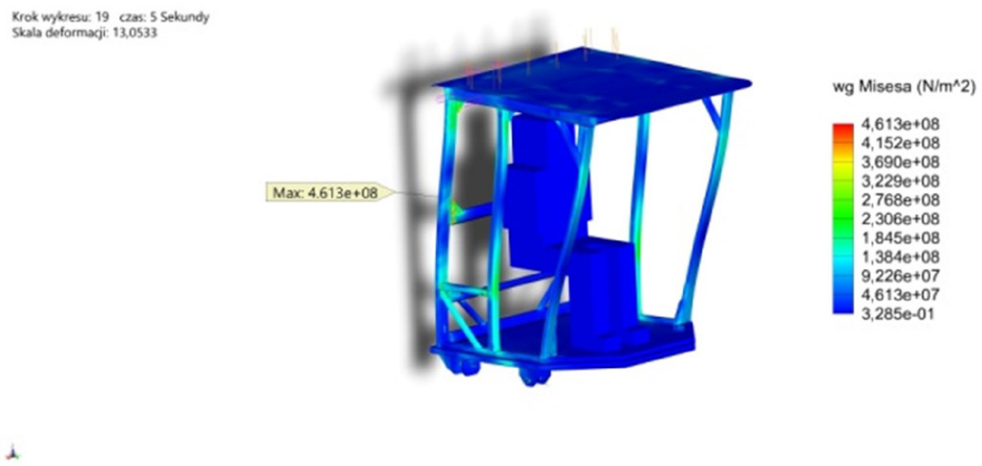


Fig. 17. Stress distribution (von Mises)

Maximum displacement 15,5 mm

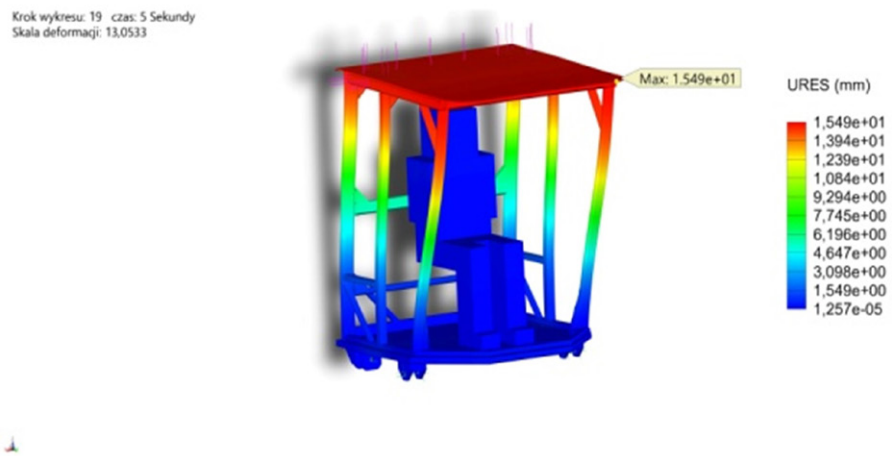


Fig. 18. Displacement distribution

Real object studies

The ROPS was tested in accordance with the procedure described in PN-EN ISO 3471:2009 p. 5 and was mapped in simulation studies.

The studies included the following tests:

- Lateran load;
- Vertical load;
- Longitudinal.

The minimum values requirements for each test are shown in Tab. 3.

Tab. 3. ROPS structure minimum values of test loads

Parameter		Formula	Value
Machine mass	**M [kg]**		**18 000**
Energy with lateral load	**E_p [J]**	$15\,000 \cdot \left(\frac{M}{10\,000}\right)^{1,25}$	**31 274**
Lateral force	**F_p [N]**	$70\,000\left(\frac{M}{10\,000}\right)^{1,1}$	**140 175**
Vertical force	**F_v [N]**	$19.61 \cdot M$	**352 980**
Longitudinal force	**F_w [N]**	$56\,000\left(\frac{M}{10\,000}\right)^{1,1}$	**106 902**

Fig. 19. ROPS structure under the lateral load

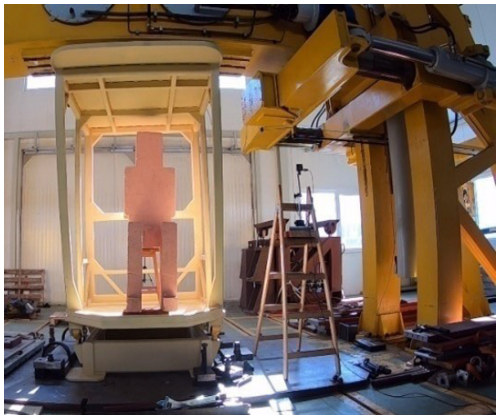


Fig. 20. ROPS structure under the vertical load

Comparison of the simulation and test results

A comparison of the results of FEA and real object studies indicates that the key to acceptable accuracy of simulation are:

1. correct determination of the values of the material mechanical properties;
2. the mapping accuracy of the load model in simulation and studies;
3. Mesh density and type of split mesh and elements contact conditions.

The discrepancy in the resulting displacement values is mainly due to differences into model and real object cab's mounting to the frame. It is actually only possible to obtain the displacement-load characteristics of susceptible components for cab cushioning on the basis of repeated destructive tests. For obvious reasons, this could not have been the case here. The purpose of the simulation was therefore to check whether the protective structure itself would fulfil its role in worse load conditions from the point of view of strength. Since, as the position studies have shown, the largest share of the resulting displacement values is deformation of shock absorbers, the simulation results should be considered valid.

Conclusions

The research of cab structure was described above to provide comprehensive explanation about phenomenon at FOPS/ROPS. Finite element analysis simulation and real object test results pointed the main conclusion of this research as:

1. The design solution adopted for the cab roof covering meets the level II requirements of EN ISO 3449:2009, in this particular case.

2. The key factor is the material properties used during the simulation process. In the studies presented above, this was a relatively simple bilinear model. It already gives an acceptable, especially at an initial stage, accuracy of calculations. For dynamic simulation, it is difficult to determine stiffness and damping coefficients for structure elements. The lack of an access to these data is an additional difficulty.
3. The third factor is the adopted suspension model. Of course, this problem does not occur in the case of a structure rigid fixing to the machine frame, as is the case, for example, in dozers and other crawler machines. It is therefore necessary to obtain strength characteristics for the elements of the sleeper pads, dumpers, etc. Manufacturers of these elements shall provide, rarely, data on dynamic load conditions. As the results of the studies have shown, they do not have a significant impact on the results of FOPS simulation studies (dynamic). Sufficient accuracy, especially at the initial design stage, due to the direction and the duration of the load, is obtained for the elastic-plastic model of the suspension element material. Probably due to longer time response than load time.
4. In assessing the advisability of computer simulations, the so-called economics of calculations are an important aspect. Increasing accuracy, especially by using a fine mesh with more elements, is associated with an increase in calculation time. This is not always advised, especially at the initial stage of designing the structure.

For these reasons, both standards do not allow FEA as a procedure for assessing the conformity of a structure with the requirements. Thus, it is always necessary to conduct the studies of the real object. From the information held by the authors, in technical committee No. 127 ISO, discussions related to the recognition of the Finite Element Method as a conformity assessment procedure have been ongoing for many years. For now, no effects have been obtained.

Simulation results tend to be approximated as compared with the lab test results. Caution will be needed when they are used in designs that pursue optimization of cost reduction and strength assurance to the required limit.

The lead time of the simulation process is proportional to the expected accuracy. 3D shell models developed data for analytic purposes creates a bottleneck. Otherwise, 2D models make worse accuracy.

Future Development

This research studies show that the FEA simulation could be acceptable method for the first step to FOPS/ROPS design. To increase the accuracy of calculations, the following work should be carried out in the future.

The different models of cabs' suspension system should be developed for dynamic mode simulation.

Static simulation (ROPS) needs more fitted stress-extension curves for more steel grades as a library data.

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SUSTAINABLE DEVELOPMENT SUPPORTED BY LEAN TOOLS IN ASSEMBLY PROCESSES – A SYSTEMATIC LITERATURE REVIEW

Zrównoważony rozwój wspierany przez narzędzia lean w procesach montażu – systematyczny przegląd literatury

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Abstract: Sustainable Development (SD) is necessary to implement in production processes in order to improve the economic aspects of enterprises and to protect workers and the environment. This paper demonstrates the needs to continue the research connected with sustainable development. The article deals with research works in the field of assembly and presents a systematic literature review looking for Lean Tools (LT) implementation to improve sustainable development of assembly processes. Topics discussed in the reviewed papers in the context of the research are identified as well as LT implemented were identified. Moreover, the influence on SD aspects presented in the studied papers was identified and the connections with the sustainability goals were indicated. Despite the fact that enterprises have shown interest in the discussed subject the impact of LT on SD aspects, i.e. ecological, economic and social, is not directly indicated in context on assembly. The presented quantitative analysis proves that the problem is not widely discussed in the literature. While the impact of LT on companies was studied in general, the research usually did not focus on the assembly process. On the basis of the conducted literature review, a gap was discovered that can be filled in future research by proposing an LT set that can be used in the organization to improve assembly lines and support SD. In future research, the authors intend to thoroughly analyse the aspects of LT implementation for SD by conducting research at selected assembly sites.
Keywords: Lean Tools, Sustainable Development, assembly process, systematic literature review

Streszczenie: Zrównoważony rozwój (SD) jest konieczny do wdrożenia w procesach produkcyjnych w celu poprawy ekonomicznych aspektów przedsiębiorstw oraz ochrony pracowników i środowiska. W artykule wskazano na potrzebę kontynuowania badań związanych ze zrównoważonym rozwojem. Artykuł dotyczy prac badawczych z zakresu montażu i przedstawia systematyczny przegląd literatury dotyczący wdrażania narzędzi lean w celu poprawy zrównoważonego rozwoju procesów montażu. Ustalano tematy poruszane w analizowanych artykułach w kontekście badań i zidentyfikowano wdrożone narzędzia lean. Ponadto zidentyfikowano wpływ na aspekty zrównoważonego rozwoju przedstawiony w badanych artykułach oraz wskazano związki z celami zrównoważonego rozwoju. Pomimo zainteresowania przedsiębiorstw omawianym tematem, wpływ narzędzi lean na aspekty zrównoważonego rozwoju, tj. ekologiczne, ekonomiczne i społeczne, nie jest bezpośrednio wskazywany w kontekście montażu. Przedstawiona analiza ilościowa dowodzi, że problem ten nie jest szeroko omawiany w literaturze. Chociaż ogólnie badano wpływ narzędzi lean na przedsiębiorstwa, badania zwykle nie koncentrowały się na procesie montażu. Na podstawie przeprowadzonego przeglądu literatury odkryto lukę, którą można wypełnić w przyszłych badaniach proponując zestaw narzędzi lean, który można wykorzystać w organizacji do usprawnienia linii montażowych w celu wsparcia zrównoważonego rozwoju. W przyszłych badaniach autorzy zamierzają dogłębnie przeanalizować aspekty wdrażania narzędzi lean dla zrównoważonego rozwoju prowadząc badania w wybranych procesach montażu.
Słowa kluczowe: narzędzia lean, zrównoważony rozwój, proces montażu, systematyczny przegląd literatury

Introduction

Sustainable Development (SD) is widely discussed in the literature. In Web of Science database 78 165 papers can be found using as a keyword “Sustainable Development”. About 80% of the papers are from the areas such as: environmental sciences and studies, green sustainable science technology, economics, management, engineering environmental, and energy fuels. Moreover, 208 papers present systematic literature review. More than 80% of them are connected with green sustainable science technology and environmental sciences. 4 of the papers presenting systematic literature review are in the group of engineering manufacturing and they discuss sustainability assessment in manufacturing organisations [8], integrated management systems [6], sustainable supply chain management [18] and issues connected with project management [30].

1% of the 78 165 papers are classified in the group of engineering manufacturing what shows how few research, comparing to other fields, were done in area of engineering manufacturing. Moreover, in this group only

18 papers can be retrieved when the word “assembly” is used in the searching process. These papers are connected with remanufacturing [15, 16], disassembly [21], Lean Six Sigma [29], Lean Design for eXcellence [2] and sustainable design [4, 10, 25], strategy for smart automation [31], intelligent systems [27], green productivity [24], products servicing [17] as well as composites, constructions, hole technologies, knowledge management and LCA (Life Cycle Assessment). This short search indicates that sustainability problems are not widely discussed together with assembly processes and Lean Tools.

The authors of this paper aimed to identify Lean Tools which support sustainable development in assembly processes. None of the mentioned papers answered the question how Lean Tools can support sustainable development. It is important to study this topic, since the LTs are simple and easy to be implemented in different environments and do not require high skills from employees who use the LTs. Moreover, if such simple tools can give a positive influence on SD this should be studied and supported. Currently, not all companies are already ready to implement high technologies and sophisticated tools. Still in many cases LTs are the best and maybe the only option. Therefore, the authors decided to develop a methodology and perform a systematic literature review to reach the papers discussing Lean Tools in SD context, in the area of assembly processes.

In the section entitled “Sustainable Development” the authors present what Sustainable Development is. Then, a short review of Lean Tools is presented. In section “Research questions and methodology”, the work methodology and research questions are described. The section “Results analysis and discussion” shows the search results and discussion. The last section summarizes the work presenting conclusions and future work.

Sustainable Development

Sustainable Development (SD) aims in meeting of economic and social needs without jeopardizing natural resources and the quality of environmental which are the basis of human health, safety, security and economic well-being [11]. The United Nations General Assembly adopted a set of 17 goals connected with sustainable development (https://www.un.org/sustainabledevelopment/).

Two of them are directly connected with assembly processes, namely:

- *Goal 9 – Industry, innovation and infrastructure* – innovations in assembly process such as, for example, augmented reality might facilitate the process [5], and
- *Goal 12 – Responsible consumption and production* – implementation of assembly process simulations can decrease a number of errors performed in the process, prevent reassembly and safe resources [22].

Other goals can be indirectly affected by proper organization of assembly processes. Other goals are: Goal 1 – End poverty, Goal 2 – Zero Hunger, Goal 3 – Good Health, Goal 4 – Quality Education, Goal 5 – Gender equality, Goal 6 – Clean Water and Sanitation, Goal 7 – Clean Energy, Goal 8 – Economic Growth, Goal 10 – Reduced Inequality, Goal 11 – Sustainable Cities, Goal 13 – Climate Action, Goal 14 – Protect Oceans, Goal 15 – Protect Biodiversity, Goal 16 – Peace, justice and strong institutions, Goal 17 – Partnerships.

Three SD aspects have been already mentioned: economic, social and environmental aspect. All of them can be analysed in relation to the assembly process. Economic aspects are connected with such work organization that only value added activities and other necessary activities are performed in the process. To improve this aspect a work stand can be also equipped with the tools which can speed up the assembly process so in the same amount of time more products can be assembled. This way there are no wastes in the process or the wastes are minimal and the process is completed in a minimum time. Social aspects are also connected with work organization which should be friendly for workers. Work organization is related to arrangement of work items on a work stand, use of user-friendly tools and proper organization of working time. Environmental aspect in assembly process are related to minimization of resources consumption, especially energy. Assembly methods are also important in the life cycle management because they determine possible future disassembly and reusing of a product components.

Review of Lean Tools to be applied in assembly process

Lean Tools are to identify and eliminate wastes. In industry different lean tools are used to improve work organization [26]. Using the words “Lean Tools” a mental shortcut was applied. By Lean Tools the authors understand lean tools, techniques, methods and systems supporting lean manufacturing. The most popular of them which can be additionally implemented to support an assembly process, are [26, 27]:

- 5S to ensure order at the workplace,
- FIFO to ensure that products are processed in the specified sequence,
- 5Why? to identify source cause in case of problems appearing,
- Work Standardization to ensure process repeatability,
- Poka Yoke to prevent mistakes,
- Team Work to have the benefits of synergy effect,
- Kanbans to implement pull system and assemble only what is needed by customers,
- TPM to ensure that necessary equipment is always ready to be used in a process,
- Visualization enabling quick understanding of what is happening in the workplace,

- Value Stream Mapping to see the whole assembly process which can be realized in different steps and on different workstations,
- Just in Time to minimize inventory levels and in the same time ensure process continuity,
- Takt Time to dictate the pace of production,
- SMED for decreasing a changeover time and prepare fast a workstation for assembly process of other type of products,
- One Piece Flow, to decrease lead time,
- U-shape line to have in the same place input and output of the assembly process and short distance between workstations in case if more than one workstation is operated by one worker.

The question is whether the Lean Tools can support sustainable development and to what extent it is discussed in the literature in context of assembly processes.

Research questions and methodology

In the study the following research questions were identified:

RQ1: How much sustainable development (SD) and lean tools (LT) are discussed in the literature in context of assembly process (AP)?

RQ2: Which are the topics mostly discussed in conjunction with sustainable development (SD) and Lean Tools (LT) in context of assembly process (AP)?

The work methodology contains the following activities: identification of keywords, development of a searching rule, selection of databases and adoption criteria, papers retrieval, analyses and discussion.

In the work tree databases were chosen to be searched: Web of Science, Scopus and Science Direct. The searching process is based on the keywords such as "Lean tools", "Sustainable Development" and "Assembly" as we as the words being the modifications of the mentioned keywords. During the article identification stage, the article title, abstract and author keywords were searched.

The presented searching rule was applied: (*"Lean tools" OR "Lean techniques" OR "Lean methods") AND ("Sustainable Development" OR "Sustainability" OR "Sustained Development" OR "Sustainable-Development" OR "Sustained Growth") AND "Assembly"*.

The search was focused on journal and conference papers as well as book chapters published in English. 16 different papers were retrieved what is a small number. This can mean that the topic is not widely discussed by the researchers. Several of the papers were registered in different databases, therefore it was necessary to eliminate duplicates to have the final number of 16 papers. These papers were the subject of further quantitative and qualitative analysis. The quantitative analysis concerned numbers of publications in years and type of publications. In the frame of qualitative analysis author keywords and available full texts were studied.

Results analysis and discussion

This section presents the performed analysis. Figure 1 shows the interests on the analysed topic in time. The first paper was published in 2006. The analysis does not show a significant increase in interest in the topic.

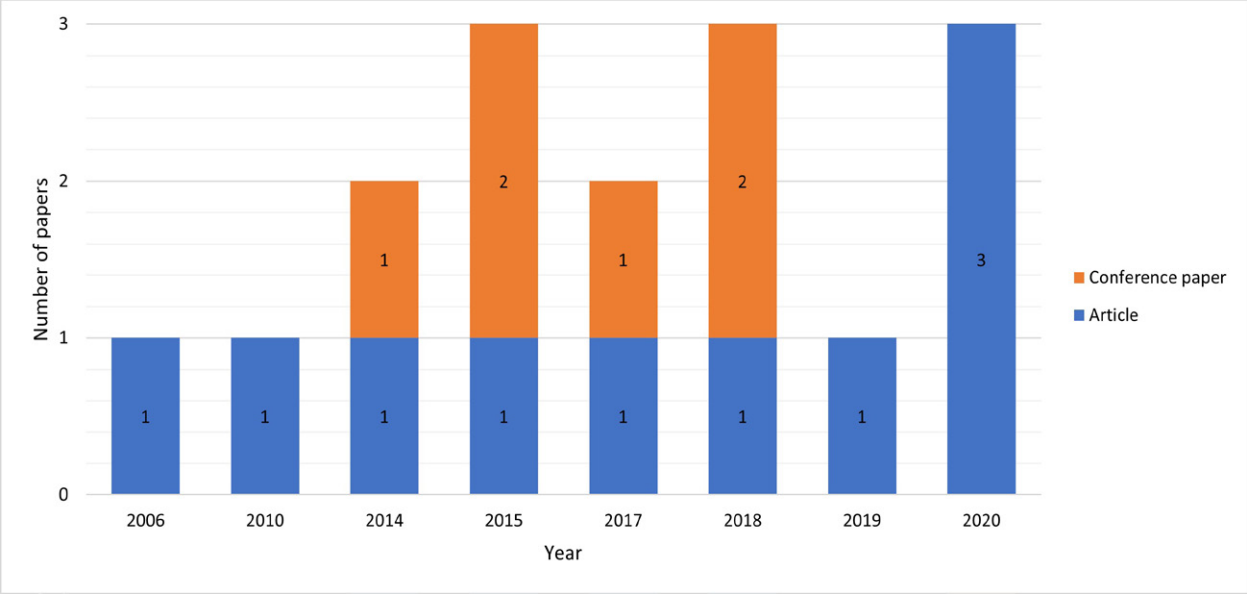

Fig. 1. Number of papers in years by type

In further analyses first, the author keywords coming from the publications were studied. 102 keywords were identified in all analysed papers and grouped to identify the discussed topics (Table 1). Among others, such issues as Lean Tools, Continuous Improvement, System, Sustainability, Economical Aspects, Environmental Aspects, Social Aspects, Optimization, Design, Lean, Construction, Layout and Supply chains were identified.

Table 1. Topics and keywords

Topic	Keywords	Number of keywords
Lean tools	Lean Tools, Lean Tools, 5S, SMED, Value Stream Map (VSM), Value Stream Mapping, VSM, Value Chain, Waste Flow Mapping, TPM, Spaghetti Diagram, Standard Process, String Diagram, Bottleneck Process, Takt Time, Chalk Circle Exercise, DMAIC, Method, Digital Instructions	19
Continuous improvement	Continuous Improvement, Lean Process Improvement, Lead Time Reduction, Lean Transformation, Newly Elaborated Combined Improvement, Improvement Workshop	6
System	Lean Systems, Toyota Production System, Lean Project Delivery System, Last Planner System, Boeing Integrated Defense Systems	5
Sustainability	Sustainability Performance, Sustainable Development, Sustainable Manufacturing System, Sustainable Pallet, Social Sustainability, Enabler For Sustainability, Ingredients of Sustainability	7
Economic aspects	Cost Reduction	1
Environmental aspects	CO2 Emissions, Energy Management, Environmental Impacts, Environmental Management, Environmental Sustainability, Environmental System Analysis, Lean Energy, Material Efficiency, Green Lean, Green Manufacturing	10
Social aspects	Lean Culture, Societies and Institutions, Lean-Educated Workforce	3
Optimization	Multi-Objective Optimization	1
Design	Design Model, Axiomatic Design	2
Lean	Lean Manufacturing, Lean Manufacturing Environment, Lean Production, Lean, Lean Methodology	5
Construction	Lean Construction, Construction Industry	2
Layout	Facility Layout Design, Layout Enhancement, Industrial Plants, Plant Management	4
Supply chains	Supply Chains	1
Other	Apache Helicopters, Manufacturing Industry, COA Label, SLP, DEMATEL, Fishing Industry, GUI Interface, Real Case Study, Engineers, Production Engineering, Rapid Process, Server Manufacturing, Cell Manufacturing, Waste Management Services, Assembly, Small Scale Industry	16

In the next step, the abstracts and the available full texts were analysed. One of the retrieved papers was on application of lean methods to improve surgical clinic experience. Another one, presented a case study from shellfish company. One paper investigated advantages coming from sustainable returnable packaging. Since, they were not connected with assembly processes they were excluded from the papers for further analysis.

Table 2 presents the retrieved papers and connected data such as the information about type of the paper and full text availability as well as the databases in which the papers are registered. Four papers are registered in Scopus, two papers are registered in Web of Science and thirteen papers are registered in Science Direct. Six papers are the conference publications published, among others, in Procedia Manufacturing (4 papers). Three papers are published in Journal of Cleaner Production. For 3 papers full texts were not freely available.

Table 2. Searching results

Paper ID	Authors	Title	Journal / Publication	Paper type	Full text	Database
01	Kovács (2020)	Combination of Lean value-oriented conception and facility layout design for even more significant efficiency improvement and cost reduction	International Journal of Production Research	Article	No	Scopus Science Direct Web of Science
02	Kurdve (2018)	Digital assembly instruction system design with green lean perspective-Case study from building module industry	Procedia CIRP	Conference Paper	Yes	Scopus Web of Science
03	Saha et al. (2014)	Lean transformation for server manufacturing environment	IIE Annual Conference and Expo 2014	Conference Paper	Yes	Scopus
04	James (2006)	It's all in the mind	Manufacturing Engineer	Article	Yes	Scopus
05	Barot et al. (2020)	Implementation of lean practices in water heater manufacturing industry	Materials Today: Proceedings	Article	Yes	Science Direct
06	Verma and Sharma (2017)	Sustainable competitive advantage by implementing lean manufacturing “A Case study for Indian SME”	Materials Today: Proceedings	Article	Yes	Science Direct
07	Oliveira et al. (2017)	Continuous improvement through "Lean Tools": An application in a mechanical company	Procedia Manufacturing	Conference Paper	Yes	Science Direct
09	Francis and Thomas (2020)	Exploring the relationship between lean construction and environmental sustainability: A review of existing literature to decipher broader dimensions	Journal of Cleaner Production	Article	No	Science Direct
10	Chiarini (2014)	Sustainable manufacturing-greening processes using specific Lean Production tools: an empirical observation from European motorcycle component manufacturers	Journal of Cleaner Production	Article	No	Science Direct
12	Fahad et al. (2017)	Energy Management in a Manufacturing Industry through Layout Design	Procedia Manufacturing	Conference Paper	Yes	Science Direct
14	Das (2018)	Integrating lean systems in the design of a sustainable supply chain model	International Journal of Production Economics	Article	Yes	Science Direct
15	Nujoom et al. (2019)	Drafting a cost-effective approach towards a sustainable manufacturing system design	Computers & Industrial Engineering	Article	Yes	Science Direct
16	Kurdve et al. (2015)	Waste flow mapping to improve sustainability of waste management: a case study approach	Journal of Cleaner Production	Article	Yes	Science Direct

Based on the performed keywords analysis it can be seen that SD aspects (economical, ecological and social aspects), were widely discussed. However, only one keyword was assign to economic aspect. The sustainability aspects and connected topics discussed in the papers, identified after full texts reading, are presented in the Table 3. In the table the authors also presented a sustainability goals which can be supported by the actions presented in the papers.

Table 3. Sustainability aspects discussed in the papers

Sustainable Development			Paper ID	Industry/Process	Supported sustainability goals
Ecology	Economy	Social			
-	Work efficiency with the standardized instructions	Standardized instructions to support workers and to ensure "easy jobs", equipment design, training system, ergonomics, safe work environment	02	Construction industry (building modules)	Equality promotion (G1) Reduced Inequality (G10)
Material utilization minimization (paper) by implementing dashboard enabled database system	Production cycle time reduction, minimizing rework activity time	Employee training, employees satisfaction assessment	03	Server manufacturing	Economic Growth (G8) Quality Education (G4)
-	-	Employee training, building awareness among employees, employee support and suggestion program	04	Aviation, car industry	Quality Education (G4) Decent Work (G8)
	Reduction of work in progress, cycle time and lead time	Standardizing work procedure Work conditions improvement	05	A water heater manufacturing	Responsible production (G9)
-	Reduction of the cycle time and cost	-	06	The CNC machining	Responsible production (G9)
Reduction of equipment replacements	Productivity improvement, better quality, less breakdowns, lower costs, reliable deliveries	Employees commitment, motivating working environments, greater safety, improved self-confidence of the employees	07	A mechanical company	Responsible production (G9)
Reduction of material flow, fuel consumption, emissions, carbon footprint, improvements in lighting system	Economic savings from less fuel and energy consumption	-	12	Manufacturing Industry Energy Management	Responsible production (G9) Quality Education (G4) Climate Action (G13)
Alternative materials, reduction of energy, water, waste and all other types of waste of non-renewable materials	improving overall effectiveness, cost reduction, elimination of production-related wastes	Training for employees, empowering employees, eliminating obstacles in material flow, organization of workplaces	14	Supply chain management	Responsible production in a supply chain (G9)
Carbon dioxide (CO_2) emissions, energy consumption,	Cost reduction	-	15	Warehouse area Factory Supplier area	Responsible production in a supply chain (G9)
Optimising of number and type of bins, fractions, optimizing of containers and equipment for separation, sorting and storage	The total operation costs, optimising of maintenance and cost of ownership/rent	-	16	Machine industry (manufacturer of trucks, buses, construction equipment and drive systems for marine)	Climate Action (G13) Responsible production (G9)

The paper 02 (Kurdve, 2018) is focused on work standardization. In the frame of the work digital assembly instructions were developed. The main motivation of the work was to ensure "easy jobs" as many workers being immigrants in Sweden have low education. The problem is to ensure a safety work environment and an efficient work by delivering simple work instructions covering reasonable amount of work and be even done by workers with physical handicaps. Visual work instructions are proposed as solutions of the mentioned problems.

The paper 03 (Saha et al., 2014) is focused on waste elimination in server manufacturing process. The paper presents the process analysis in which lean tools such as fishbone diagram, process map, time study analysis, and employees satisfaction surveys were applied. The wastes existing in the process were identified and adequate countermeasures were proposed. An IT tool was designed to track the process. Then, a training for workers was performed. Next, a survey assessed the workers satisfaction with the new tool.

The paper 04 (James, 2006) addresses issues related to employees' concerns when implementing changes. It shows how companies build awareness among employees through education, communication and employee involvement by empowering them to make decisions and by launching a suggestion system that is to encourage them to actively participate in the continuous improvement process.

This paper 05 (Barot et al., 2020) looks for improvements in water heater manufacturing process. A company has to meet three basic customer requirements: timely delivery, good quality of the product and low price, with a strategy of continuous improvement. Company implemented value stream mapping, String diagram, 5S, TPM, Cellular manufacturing, standard work instructions to reduce non value added activities, cycle time and lead time.

This paper 06 (Verma and Sharma, 2017) work presents a case study of implementation of lean manufacturing in a manufacturing company to identify non value added activities and eliminate wastes. The identified waste are related to equipment failures, bottleneck process, defects, waiting time, inventory and material handling. The above problems are analysed in concern with rejection control, inventory control, setup time and non-value added time. It has been found that the reason for non-value added activities are due to wrong handling material, long distance, defect and improper inventory.

The paper 07 (Oliveira et al., 2017) suggests several lean tools, such as standard work, value stream mapping, 5S, visual management, Kanbans, line balancing, Total Productive Maintenance (TPM), Overall Equipment Effectiveness (OEE), Single-Minute Exchange of Die (SMED), TQM that can be used to indicate the improvements and achieve productivity and profitability. Moreover, it is underlined that lean's purpose is to develop critical skills and competencies in organizations. The paper presents a case study connected with mechanical equipment manufacturing. It is worth to emphasize that the presented LTs can be additionally supported by, for example, digitalization, what can increase the efficiency. An example of LTs digitalization, nowadays quite widely implemented in industry, is connected with electronic Kanban system. In standard Kanban system the paper Kanban cards, as it comes from experience, can be lost, can be taken home by employee what disrupts work of the assembly process. This will never happen in electronic transfer of Kanban cards. An assigned number of the cards will always go around in a loop.

The paper 12 (Fahad et al., 2017) addresses a very important issue regarding energy management, which is a big step towards green production and sustainable development. The main goal of Lean is to increase productivity, i.e. minimize costs and time, as well as analyse waste and use waste that has an impact on the environment. The conducted energy audit allowed for the categorization of the types and costs of energy consumption, the assessment of alternatives that can significantly reduce energy costs and the establishment of an application plan for energy saving projects.

The paper 14 (Das, 2018) presents lean system applications in a supply chain design and planning to improve sustainability performances. The work identifies lean practices that can be applied in supply chain management. It also takes into account lean product development for assembly purpose.

The paper 15 (Nujoom et al., 2019) describes the SMS (Sustainable Manufacturing Systems) system based on the MOO (Multi-objective optimization) model, which was developed in order to search for sustainable development between the economic and environmental aspects. The analysis concerns energy consumption and CO_2 emissions, and the research was conducted in three areas: supplier, warehouse and factory. The MOO model is based on the DEMATEL algorithm. The use of the algorithm makes it easier to make a decision when a compromise is found between minimizing the total cost required to establish the initial development and proper production, energy consumption and CO_2 emissions during operation. However, not in all cases it is possible to have access to data which can be used to create a mathematical model. Moreover, the model needs to be adequate to be applicable for a certain purpose. If it is not a case, simple LTs can be applied to improve a process. Although, the parameters will not be optimal the process will give better results. In many cases it is enough. Especially when continuous improvement is implemented and when in an assembly process there is a large variety and variability of the assembled products.

In the paper 16 (Kurdve et al., 2015) described the analysis intended to find economically competitive environmental improvements on team, site and multi-site level, through best practice examples, and to define suitable performance indicators to secure implementation and continuous improvements. The collected data concerned the volumes and costs of treatment of waste fractions and costs of external services, while environmental and economic data from each site was used to validate and complement the supplier data waste analysis focusing the waste classification and the waste hierarchy. The research was carried out in 16 sites of two companies from the machine industry (trucks, buses, construction equipment, drive systems for marine).

Table 4. Problems discussed in the analysed papers; NP – number of papers

Identified Problems	Paper ID	NP	Identified Problems	Paper ID	NP
Bottleneck process	06, 16	2	Maximum productivity	15	1
Case study	02, 03, 05, 06, 07, 12, 15, 16	8	Risk minimization	15	1
Cellular manufacturing	05	1	Layout	05, 06, 07, 12	4
Continuous improvement	03, 04, 05, 06, 07, 12, 14, 15, 16	9	Overproduction	15	1
CO2 emissions	15	1	Outsourcing	14	1
Costs of production	12	1	Optimization	06	1
Creating partnerships with suppliers	14	1	Unnecessary inventory	15	1
Design of product	14	1	Unnecessary movement of materials	15	1
Depletion of natural resources	15	1	Performance assessment	03, 05, 06, 07, 12, 14, 16	
Economic savings	12	1	Production planning	06	7
Elimination of reworks	14	1	Raw material	14	1
Employees' concerns	04	1	Reduction of stock	14	1
Employee engagement	04, 05, 14	3	Rejection control	06	1
Energy consumption	15	1	Rising energy costs	12	1
Energy Management	12	1	Supply chains	06, 07, 12, 14, 16	1
Excess motion	15	1	Training system	04, 14	5
Green Manufacturing	12	1	Traceability of mistakes	02	2
Industry 4.0	07	1	Quality problems documentation	02	1
Information management	14	1	Waste hierarchy	16	1
Inventory control	06	1	Wastes identification	05, 06, 07, 12, 16	1
Material efficiency	16	1	Waste segregation	16	5
Material handling	16	1	Waste in processing and the waste of rework	14, 15	1
Materials Management	14	1	Work assignment	05, 06	2

The discussed topics are summarized in Table 4.

Table 5 presents Lean Tools discussed in the analysed papers with underlined in the papers positive effect of the environmental (EN), economic (EC), social (SO) aspects.

The presented tools, techniques and methods as well as systems such as TPM or TQM, have been applied in companies which realize assembly processes. Unfortunately, the researches presented in the papers not always are directly related to the assembly process and this process was just one of the processes analysed in the companies. Therefore, it is difficult to conclude that the positive effect of Lean Tools on SD came with

Table 5. Lean tools discussed in the analysed papers with underlined positive effect of the SD aspects: environmental (EN), economic (EC), social (SO); NP – number of papers

Lean and other tools, methods, techniques, systems	Paper ID	NP	SD aspects
5S	05, 07, 14, 16	4	EN, EC, SO
7 wastes	03, 06, 07, 12, 14, 16	5	EN, EC, SO
Fishbone diagram, 5 Why, Root cause analysis, Cause of equipment failure	03, 06, 16	3	EN, EC, SO
Animated instructions, Digital instructions	02	1	EC, SO
Energy relation chart	12	1	EN, EC
LCA (Life Cycle Assessment)	16	1	EN, EC
Line balancing	05, 07, 16	3	EN, EC, SO
Customer satisfaction surveys	03	1	EN, EC, SO
Diagram Pareto, Diagram Pareto-Lorenz	07, 16	2	EN, EC, SO
EMA (Environmental Management Accounting)	16	1	
Gembutsu, Gemba	07, 16	2	EN, EC, SO
Flow chart	16	1	EN, EC
Jidoka	16	1	EN, EC
Just In Time	07, 14	2	EN, EC, SO
Kanban	07	1	EN, EC, SO
LR (Lean Relations)	14	1	EN, EC, SO
MFCA (Material Flow Cost Accounting)	16	1	EN, EC
MHA (Material Handling Analysis)	16	1	EN, EC
MOO (Multi-objective optimization)	15	1	EN, EC
MOPSO (Multi-Objective Particle Swarm Optimization) algorithm	15	1	EN, EC
MTBF (Mean Time Failures)	07	1	EN, EC, SO
MTTR (Mean Time to Repair)	07	1	EN, EC, SO
OEE (Overall Equipment Effectiveness)	07	1	EN, EC, SO
Poka Yoke	02	1	EN, EC, SO
Process map	03, 04, 05, 06, 07, 14, 15, 16	8	EN, EC, SO
SCs (Closed loop supply chains)	14	1	EN, EC, SO
SIPOC (Suppliers, Input, Process, Output, Customer)	16	1	EN, EC
SLP (Systematic Layout Planning), U-shape layout	12	1	EN, EC
SMED (Single-Minute Exchange of Die)	07	1	EN, EC, SO
SMS (Sustainable manufacturing systems)	14	1	EN, EC, SO
SOO (The single objective optimization)	15	1	EN, EC
SOP (Standard Operation Procedure)	16	1	EN, EC
Spaghetti diagram	16	1	EN, EC
Standardisation	02, 03, 04, 06, 07	5	EN, EC, SO
String diagram	05, 16	2	EN, EC, SO
Takt time	06, 07, 14, 16	4	EN, EC, SO
Teamwork	02, 04, 07, 14, 16	5	EN, EC, SO
TQM (Total Quality Management)	07, 14	2	EN, EC, SO
Time study analysis	03, 06	2	EN, EC, SO
TPM (Total Productive Maintenance), TPM check-sheet	05, 07	2	EN, EC, SO
WFM (Waste Flow Mapping)	16	1	EN, EC
VSM (Value Stream Mapping)	05, 06, 07, 14, 16	5	EN, EC, SO
Visual Management	07	1	EN, EC, SO

their implementation just in assembly processes. They have rather given the positive effects on the companies. The obtained results can be compared to the work [7]. In the mentioned work the tools are analysed taking into account outcomes and effects of Lean Tools implementation on sustainability types. For example, standardization improves production rate what have positive influence on economic aspects and in the same time systematizes work, what, according to the authors, have additionally influence on environmental aspect. Moreover, standardization creates workforce driven collaborative environment what has positive influence on social aspects. The results obtained in this work confirm that standardization has positive influence on this three SD aspects also when assembly processes are discussed.

Conclusions and future work

The main goal of the paper was to identify, based on a systematic literature review, how Lean Tools can support SD. First, in the paper the sustainable development together with the sustainability goals were defined. Then, a review of Lean Tools and their possible application in assembly process was presented. Then, a systematic literature review, focused on Lean Tools implementation towards sustainability improvements in areas connected with assembly process was performed. It was identified, that really few papers touch this problem and it is not sufficiently discussed in the literature how Lean Tools can affect sustainability of assembly processes. The retrieved papers, which were connected with the analysed topic were studied. The connected areas of research presented in the papers as well as applied Lean Tools were identified. Moreover, the connections with the sustainability goals were identified.

This paper contributes to the literature in presenting what Lean Tools are applied to improve manufacturing processes, especially assembly processes and how they can positively influence SD aspects. Moreover, it is presented what topics are discussed in the literature in this context. Additionally, it can be concluded that there is a gap discovered on the base of the performed systematic literature review which can be filled in future researches to present a set of tools which can be used in assembly process organization to improve positive effect of the Lean Tools implementation on assembly process SD.

Based on the performed analyses, it can be said that the topic needs to be further analysed. These few articles retrieved during the database search are not enough to present generalized conclusions concerning LT influence of assembly process sustainable development. The presented work is a part of a bigger studies. In future research the authors plan to analyse deeply what are the advantage of Lean Tools implementation for SD conducting researches in chosen assembly areas.

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

Sborka nr 10, 2019

1. Enhancement of technological opportunities of the passing cutter due to the application in the design of an additional assembly unit

Author: Kudryashov E. A., Smirnov I. M., Grishin D.V.

The device of a straight lathe tool, implementing the turning of surface of a complex profile under conditions of interrupted cutting, has been described. An additional assembly unit integrated into the body of the tool – a device damping impact loads, allows to maintain the set efficiency of a replaceable cutting multi-faceted plate made of super hard tool material composite, which has, along with unique physical and mechanical characteristics and cutting properties, high fragility. The use of the damping device has allowed to enlarge technological capabilities of the straight lathe tool by increasing stability of intermittent turning.

2. Development and use of acoustic-diagnostic installation for study of the parameters of acoustic emission signals in heat exchangers under various operating conditions

Author: Chmyihalo I.A., Medeljaev I.A., Chelnokov A.V., Spiryagin V.V.

The article presents an acoustic-diagnostic installation for studying and forming a database of parameters of acoustic emission signals in various operating modes of operation of heat exchangers.

3. Assembly of modules for air disinfection by ultraviolet radiation in ventilation systems

Author: Mikaeva S.A., Mikaeva A.S.

The aassembly of the module for air disinfection with ultraviolet radiation in ventilation systems is described. Presented technical characteristics and device module MEGALIT 2200F.

4. Multicomponent high-strength antifriction polyphenylene sulfide based composites

Authors: Panin S.V., Kornienko L.A., Le Thi Mi Hiep, Buslovich D.G., Nguen Dyik An.

The mechanical and tribotechnical properties of polyphenylene sulfide (PPS) based composites filled with polytetrafluoroethylene (PTFE), colloidal graphite (CGr) and milled (short) carbon microfibers (MCF, 200 μm long) were investigated. It is revealed that the multicomponent composite "PPS + 10 % PTFE + 10 % CGr + 10 % MCF" possesses the best values of strength and wear resistance properties. Loading of the polytetrafluoroethylene provides solid lubrication increasing the wear resistance of the composite by 18 times, reducing the friction coefficient by 3 times at metal-polymer friction pairs, while at ceramic-polymer one wear resistance increases by 14 times at the friction coefficient decreasing by 2.5 times. Reinforcement by the short carbon fibers (200 μm long) increases the flexural modulus by 1.5 times. Colloidal graphite particles due to higher heat conductivity ensure formation of more uniform polymer matrix with increased hardness. A multi-component PPS based composite is recommended for application in friction units in mechanical engineering for both metal-polymer and ceramic-polymer tribounits.

5. Size delta-criteria of the form of the origin of deformation depending on the parameters of the turning process of a round continuous profile

Authors: Gur'yanov G.N., Guryanov N.G.

The proposed indicators to assess the deformed state when drawing a round solid profile. The values of the delta-criteria are given: the criterion of the shape of the deformation zone and the proposed indicators for a fixed and optimal value of the drawing angle for different models of hardening of the material being processed and the values of drawing and friction coefficients, anti-tension stresses. Dependencies are proposed to assess the relationship between the criteria of the deformation zone and the indicators of the deformed state. Formulas for calculating the optimal value of the delta criterion are proposed. The dependences on the friction coefficient for axial stress, the safety factor I.L. Perlin, and the stress state indicator V.L. Kolmogorov at a fixed and optimal angle of dragging. Taking into account the criteria for the shape of the deformation zone and indicators of the deformed state contributes to the choice of rational modes of drawing a round solid profile.

6. Tribological characteristics of cutting tools with ion-modified surface

Authors: Migranov M.Sh., Shekhtman S.R., Migranov A.M.

Some ways of improving tribotechnical characteristics of wear-resistant coatings on high-speed steel cutting

tools after ion surface modification are considered. Coatings in two stages are formed: diffusion saturation of nitrogen (nitriding) and deposition (Ti, Cr)N solid coatings by cathode arc discharge plasma (CAPDP). The coating includes an additional ion-doped layer implanted on the previously nitrided surface of high-speed steel. This multi-layer coating significantly increases (2.1−2.4 times) the wear-bone of the cutting tool by expanding the stage of normal wear. The compromise between high wear resistance and reliability of the coating, which depend on the degree of adhesion with the sub-spoon, is achieved in a multi-layer coating, which contains a lower layer enriched with indium.

7. Some physical phenomena at friction
Author: Lerner YU.N.

Based on the results of studies of silicon niobium friction, the equation of forced vibrations of surface electrons is proposed. It is shown that friction with a covalent atomic bond is substantially less than with an ionic and metallic atomic bond

8. Simulation of magnetic hysteresis loop materials using interpolation linear fractional function
Authors: Vvedenskiy V.YU., Nuzhdin G.A., Frolov S.V.

TThe basic relations are derived and the ways of applying linear fractional functions for interpolating the descending and ascending branches of the magnetic hysteresis loop when assembling various magnetic products and electrical devices are presented. A new model is proposed that describes the magnetization as the sum of an irreversible contribution in the form of a fractional-linear function and a reversible contribution. Using the example of an amorphous soft magnetic alloy 30 KCP, the experimental data were compared with the results of calculations for several models.

9. Development of a mechanism for the management of industrial manufacturability aircraft engines
Authors: Sukhova N.A.

The problem of managing the manufacturability of aircraft gas turbine engines (GTE) in the early design stages is considered. Methods of control of manufacturability of aviation gas turbine engines, ensuring the rational use of existing resources of the enterprise, by reducing the labor intensity and ensuring the competitive cost of the engine being designed are presented. The control mechanism in the iterative procedure of situational analysis is proposed providing the choice of the best ways to achieve policy labor-intensiveness with the goal of rational use of the available resources of the enterprise. The proposed mechanism will significantly reduce the amount of work on the development of the product for manufacturability in a high level of uncertainty in the early design stages.

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Sborka nr 11, 2019

1. Model of the loss of efficiency of metal structures of the evaporator of refrigerating machine
Author: Spiryagin V.V., Medeljaev I.A., Chmyihalo I.A.

The article is devoted to the development of a model of the loss of efficiency of a shell-and-tube evaporator with intratube boiling of freon. It is established that the process of loss of the efficiency of the evaporator is associated with the development of local deformations of the heat exchange tubes caused by the freezing of coolant (water) in the radial gaps of the milling joints of the tubes with the tube sheet.

2. Phosphoromolyb date natrium polymeradditive for rail lubricants
Authors: Avilov V.V., Luneva E.I., Volyanik S.A., Savenkova M.A., Syichev A.P.

The results of tribotechnical tests of railway greases with additive NaPMoO6 are presented. Reduction of wear spots and smoothing rough edges of metal friction units is caused by the adsorption of the chains NaPMoO6 generated during opening trimethophosphoromolybdate cycles.

3. Analysis of the end-element modeling of the extension of surface waves of the private case of the Lemba problem
Authors: : Nizamaev T.M., Kuznetsov S.V.

Experimental computer simulation of a particular case of the Lamb problem is considered, when a pair of concentrated loads moves along an elastic half-space. The surface deformation is analyzed using a series of points that are perpendicular to the axis of motion of the

loads. This case of the Lamb problem is not amenable to numerical simulation, therefore complexes using in which computer-aided finite element modeling is implemented. The change in the oscillations of surface points depending on the speed of movement of loads and the distance between them was studied. The results are presented in the form of a series of graphs that allow you to choose the optimal distance and speed of movement of loads for analyzing the reduction of surface oscillations, since this task in practice is a demonstration of the propagation of the wave field from the transport stream.

4. About intermittent sliding
Authors: Lerner YU.N.

This is a study of the electric surface resistance of crossed metal samples in static, previously shifted, and sliding modes. An increase in the resistance was discovered for the sliding mode. An explanation is also given to the inequality between static and dynamic friction.

5. Investigation of the similarity of gravitational and dispersive forces as contactless communication capabilities
Authors: Nozhenkov M.V.

The phenomenon of similarity of gravity and dispersion forces is considered. A similarity between interactions has been established. The possibility of contactless transmission of interactions between dissipative systems is investigated. A number of similar phenomena were detected (contactless transfer of pulse energy or information), the similarity criteria were determined as a ratio of the number of two phases (in the form of particle flows) with different properties.

6. Solution of a balance problem of contact heat transfer between two bodies: braking pad and the rotating braking disk in the braking process
Author: Yanyushkin YU.M.

Analytical dependence of proportion of heat, incoming in each part depending on breaking time, is established on the basis of equilibrium of average integral contact temperature of braking pad and rotating breaking disk. The received dependence is used for determination of contact temperatures of bodies depending on time.

7. A new approach to the choice of the initial contour of gears offset coefficients
Authors: Timofeev B.P., Dang N.T.

A method for calculating the displacement coefficients considering the lateral clearance using the multicriterial gearing (blocking contour) method using the COMPAS-3D program is proposed. The methods of assigning an additional offset of the original contour are analyzed. The recommendations on the choice of displacement coefficients of spur gears of cylindrical gears are offered.

8. Synthesis of adaptive friction clutches of the second generation a bifunctional control device
Authors: Shishkarev M.P.

It is shown that the rated load capacity of the developed adaptive friction clutch of the second generation with a bifunctional control device is higher than that of the basic version with all leading friction pairs of the main friction group, with the values of the ratio of the tension force of the spring closing the friction pair of the additional friction group to the force of the tangential spring of the bifunctional control device exceeding the set value.

9. Manufacturability of the design of the drive stand for testing the drive axle of trucks
Authors: Dubovik E.A.

The proposed modernization of the stand for testing the drive axle of trucks in order to reduce its energy consumption. The highly specialized direction of the stand will allow for the connection of the driveshaft to the main transmission flange is not used adapter flanges, but a quick-coupling.

10. Lubricants for frictional units of mechanisms and machines
Authors: Buyanovsky I.A., Samusenko V.D., Scherbakov YU.I.

The article reviewed the most widespread and most economically reasonable method of ensuring decrease power losses in frictional units which are present practically at all modern machines and mechanisms, and wear of the contacting details of these knots — introduction lubricants between the rubbing surfaces of details of these frictional units. Lubricants are products of organic or inorganic origin which, reduce losses by friction, prevent scuffing and reduce wear of the rubbing bodies. Methods of the choice of lubricants for frictional units of different function are described.

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ABSTRACTS:

1. A conceptual scale model of mobile drilling robot

Authors: Dongmin Li, Yuanzhi Zhao, Shiming Zhu, Hengxuan Luan

This paper aims to propose a conceptual scale model of mobile drilling robot according to the actual drilling rig and working conditions to improve the safety and automation of drilling in tunnel construction and coal mining applications.

A couple of pinion and rack serves as the support mechanism driven by a motor with low rotation speed at high power, and these components are assembled in the center of the robot to tightly fasten the whole body together. The drilling rod and the sleeve are connected through a hole with screw thread so that the rod feeds and rotates simultaneously along with the sleeve. The robot model is automatically controlled by a single-chip microcomputer, and the anti-disturbance circuit is designed as well. A five-step rule obstacle avoidance method is proposed to ensure safe and reliable movement.

The results of simulation experiments on drilling operation do indicate that the mechanism and control method are feasible and effective.

The robot is nearly complete but indeed remains only an experimental machine.

The design of the mechanism structure for the conceptual robot is novelty. The method of five-step rule obstacle avoidance can improve reliability of obstacle avoidance according to the experimental results, which can meet the requirements of complex working conditions underground coal mine.

2. Dynamic characteristics of a jumping robot with coordinated quadruped legs

Authors: Jun Zhong, Ruqi Ma

This paper aims to analyze features of jumping process and to present the kinematic and dynamic models of a novel sole-type quadruped jumping robot with variable coordinated joints.

Jumping robots with coordinated multiple legs have been a hot research subject during the past years because of their excellent abilities in fast moving and obstacle-climbing. However, dynamics of jumping process of these coordinated legged robots are complex because of collisions between coordinated legs and the ground.

A complete jumping period of is divided into several subphases according to contact status of different coordinated legs to the ground. Continuous dynamics and discrete dynamics are established in different subphases. Simulations are performed in MATLAB software and ADAMS environment.

Comparison between two-set simulated results acquired from ADAMS and MATLAB demonstrates the validity of kinematic and dynamic equations.

The established dynamics establish the foundation of further research in motion planning and controller design of coordinated multiple legs.

3. Identification of nonlinear state-space time-delay system

Authors: Xin Liu, Hang Zhang, Pengbo Zhu, Xianqiang Yang, Zhiwei Du

This paper aims to investigate an identification strategy for the nonlinear state-space model (SSM) in the presence of an unknown output time-delay. The equations to estimate the unknown model parameters and output time-delay are derived simultaneously in the proposed strategy.

The unknown integer-valued time-delay is processed as a latent variable which is uniformly distributed in a priori known range. The estimations of the unknown time-delay and model parameters are both realized using the Expectation-Maximization (EM) algorithm, which has a good performance in dealing with latent variable issues. Moreover, the particle filter (PF) with an unknown time-delay is introduced to calculated the Q-function of the EM algorithm.

Although amounts of effective approaches for nonlinear SSM identification have been developed in the literature, the problem of time-delay is not considered in most of them. The time-delay is commonly existed in industrial scenario and it could cause extra difficulties for industrial process modeling. The problem of unknown output time-delay is considered in this paper, and the validity of the proposed approach is demonstrated through the numerical example and a two-link manipulator system.

The novel approach to identify the nonlinear SSM in the presence of an unknown output time-delay with EM algorithm is put forward in this work.

4. An end-to-end learning method for industrial defect detection

Authors: Yupei Wu, Di Guo, Huaping Liu, Yao Huang

Automatic defect detection is a fundamental and vital topic in the research field of industrial intelligence. In this work, the authors develop a more flexible deep learning method for the industrial defect detection.

The authors propose a unified framework for detecting defects in industrial products or planar surfaces based on an end-to-end learning strategy. A lightweight deep learning architecture for blade defect detection is specifically demonstrated. In addition, a blade defect data set is collected with the dual-arm image collection system.

Numerous experiments are conducted on the collected data set, and experimental results demonstrate that the proposed system can achieve satisfactory performance over other methods. Furthermore, the data equalization operation helps for a better defect detection result.

An end-to-end learning framework is established for defect detection. Although the adopted fully convolutional network has been extensively used for semantic segmentation in images, to the best knowledge of the authors, it has not been used for industrial defect detection. To remedy the difficulties of blade defect detection which has been analyzed above, the authors develop a new network architecture which integrates the residue learning to perform the efficient defect detection. A dual-arm data collection platform is constructed and extensive experimental validation are conducted.

5. One-shot gesture recognition with attention-based DTW for human-robot collaboration

Authors: Yiqun Kuang, Hong Cheng, Yali Zheng, Fang Cui, Rui Huang

This paper aims to present a one-shot gesture recognition approach which can be a high-efficient communication channel in human–robot collaboration systems.

This paper applies dynamic time warping (DTW) to align two gesture sequences in temporal domain with a novel frame-wise distance measure which matches local features in spatial domain. Furthermore, a novel and robust bidirectional attention region extraction method is proposed to retain information in both movement and hold phase of a gesture.

The proposed approach is capable of providing efficient one-shot gesture recognition without elaborately designed features. The experiments on a social robot (JiaJia) demonstrate that the proposed approach can be used in a human–robot collaboration system flexibly.

According to previous literature, there are no similar solutions that can achieve an efficient gesture recognition with simple local feature descriptor and combine the advantages of local features with DTW.

6. Wirerope-driven exoskeleton to assist lower-limb rehabilitation of hemiplegic patients by using motion capture

Authors: Longhan Xie, Ledeng Huang

The purpose of this paper is to design a lower limb exoskeleton to enhance hemiplegic patient's muscle strength and help the affected side return to normal gait after a long period of training.

A wire rope-driven exoskeleton that combines rigid bracket and flexible driven method was presented to assist the patients with rehabilitative walking training. By using three noncontact cameras, the patient's gait was captured and the target trajectory of the affected side was analyzed. Meanwhile, a controlling strategy of the affected side, which mimics the gait of the healthy side, was developed to help hemiplegic patients with varying degrees of hemiplegic gait obtain personalized walking rehabilitation training.

The results show that the hemiplegic gait of hip excessive abduction and strephenopodia was prevented. After wearing the exoskeleton, the movement trajectories of both sides of the lower limb were approximately identical. Based on the controlling strategy, the exoskeleton can correct the impaired gait and provide assistance for patients during walking. The exoskeleton has great benefits in walking rehabilitation training for hemiplegic patients.

This work improves the efficiency of the patient's individualized training in the room. The presented exoskeleton provides great benefits in walking rehabilitation training for hemiplegic patients.

7. Effective anti-collision algorithms for RFID robots system

Authors: Honggang Wang, Shanshan Wang, Jia Yao, Ruoyu Pan, Qiongdan Huang, Hanlu Zhang, Jingfeng Yang

The purpose of this paper is to study how to improve the performance of RFID robot system by anti-collision algorithms. For radio frequency identification (RFID) robots operating in mobile scenes, effective anti-collision algorithm not only reduces missed reading but also enhances the speed of RFID robots movement.

An effective anti-collision algorithm is proposed to accelerate tag identification in RFID robots systems in this paper. The tag collisions in the current time slot are detected by a new method, and then further resolve each small tag collision to improve system throughput, rather than the total tags number estimation. After the reader detected the collision, three different collision resolution

methods were described and studied, and the situation of missing tag caused by reader moving is also discussed.

The proposed algorithm achieves theoretical system throughput of about 0.48, 0.50 and 0.61 and simulates to show that the proposed algorithm performance is significantly improved compared with the existing ALOHA-based algorithm.

The proposed RFID anti-collision algorithm is beneficial to improve the moving speed and identification reliability of the RFID robots in complex environments.

8. ASPW-DRL: assembly sequence planning for workpieces via a deep reinforcement learning approach

Authors: Minghui Zhao, Xian Guo, Xuebo Zhang, Yongchun Fang, Yongsheng Ou

This paper aims to automatically plan sequence for complex assembly products and improve assembly efficiency.

An assembly sequence planning system for workpieces (ASPW) based on deep reinforcement learning is proposed in this paper. However, there exist enormous challenges for using DRL to this problem due to the sparse reward and the lack of training environment. In this paper, a novel ASPW-DQN algorithm is proposed and a training platform is built to overcome these challenges.

The system can get a good decision-making result and a generalized model suitable for other assembly problems. The experiments conducted in Gazebo show good results and great potential of this approach.

The proposed ASPW-DQN unites the curriculum learning and parameter transfer, which can avoid the explosive growth of assembly relations and improve system efficiency. It is combined with realistic physics simulation engine Gazebo to provide required training environment. Additionally with the effect of deep neural networks, the result can be easily applied to other similar tasks.

9. Cooperative multi-agent search using Bayesian approach with connectivity maintenance

Authors: Hu Xiao, Rongxin Cui, Demin Xu

This paper aims to present a distributed Bayesian approach with connectivity maintenance to manage a multi-agent network search for a target on a two-dimensional plane.

The Bayesian framework is used to compute the local probability density functions (PDFs) of the target and obtain the global PDF with the consensus algorithm. An inverse power iteration algorithm is introduced to estimate the algebraic connectivity $\lambda 2$ of the network. Based on the estimated $\lambda 2$, the authors design a potential field for the connectivity maintenance. Then, based on the detection probability function, the authors design a potential field for the search target. The authors combine the two potential fields and design a distributed gradient-based control for the agents.

The inverse power iteration algorithm can distributed estimate the algebraic connectivity by the agents. The agents can efficient search the target with connectivity maintenance with the designed distributed gradient-based search algorithm.

Previous study has paid little attention to the multi-agent search problem with connectivity maintenance. Our algorithm guarantees that the strongly connected graph of the multi-agent communication topology is always established while performing the distributed target search problem.

10. An extended DMP framework for robot learning and improving variable stiffness manipulation

Authors: Feifei Bian, Danmei Ren, Ruifeng Li, Peidong Liang, Ke Wang, Lijun Zhao

The purpose of this paper is to present a method which enables a robot to learn both motion skills and stiffness profiles from humans through kinesthetic human-robot cooperation.

Admittance control is applied to allow robot-compliant behaviors when following the reference trajectories. By extending the dynamical movement primitives (DMP) model, a new concept of DMP and stiffness primitives is introduced to encode a kinesthetic demonstration as a combination of trajectories and stiffness profiles, which are subsequently transferred to the robot. Electromyographic signals are extracted from a human's upper limbs to obtain target stiffness profiles. By monitoring vibrations of the end-effector velocities, a stability observer is developed. The virtual damping coefficient of admittance controller is adjusted accordingly to eliminate the vibrations.

The performance of the proposed methods is evaluated experimentally. The result shows that the robot can perform tasks in a variable stiffness mode as like the human dose in the teaching phase.

DMP has been widely used as a teaching by demonstration method to represent movements of humans and robots. The proposed method extends the DMP framework to allow a robot to learn not only motion skills but also stiffness profiles. Additionally, the authors proposed a stability observer to eliminate vibrations when the robot is disturbed by environment.

11. 11. Cooperative control of dual-arm robots in different human-robot collaborative tasks

Authors: Xinbo Yu, Shuang Zhang, Liang Sun, Yu Wang, Chengqian Xue, Bin Li

This paper aims to propose cooperative control strategies for dual-arm robots in different human–robot collaborative tasks in assembly processes. The authors set three different regions where robot performs different

collaborative ways: “teleoperate” region, “co-carry” region and “assembly” region. Human holds the “master” arm of dual-arm robot to operate the other “follower” arm by our proposed controller in “teleoperation” region. Limited by the human arm length, “follower” arm is teleoperated by human to carry the distant object. In the “co-carry” region, “master” arm and “follower” arm cooperatively carry the object to the region close to the human. In “assembly” region, “follower” arm is used for fixing the object and “master” arm coupled with human is used for assembly.

A human moving target estimated method is proposed for decreasing efforts for human to move “master” arm, radial basis functions neural networks are used to compensate for uncertainties in dynamics of both arms. Force feedback is designed in “master” arm controller for human to perceive the movement of “follower” arm. Experimental results on Baxter robot platform show the effectiveness of this proposed method.

Experimental results on Baxter robot platform show the effectiveness of our proposed methods. Different human-robot collaborative tasks in assembly processes are performed successfully under our cooperative control strategies for dual-arm robots.

12. Reinforcement learning for human-robot shared control

Authors: Yanan Li, Keng Peng Tee, Rui Yan, Shuzhi Sam Ge

This paper aims to propose a general framework of shared control for human–robot interaction.

Human dynamics are considered in analysis of the coupled human–robot system. Motion intentions of both human and robot are taken into account in the control objective of the robot. Reinforcement learning is developed to achieve the control objective subject to unknown dynamics of human and robot. The closed-loop system performance is discussed through a rigorous proof.

Simulations are conducted to demonstrate the learning capability of the proposed method and its feasibility in handling various situations.

Compared to existing works, the proposed framework combines motion intentions of both human and robot in a human–robot shared control system, without the requirement of the knowledge of human’s and robot’s dynamics.

13. On stability for learning human control strategy by demonstrations using SVM

Authors: Zhiyang Wang, Yongsheng Ou

This paper aims to deal with the trade-off of the stability and the accuracy in learning human control strategy from demonstrations. With the stability conditions and the estimated stability region, this paper aims to conveniently get rid of the unstable controller or controller with relatively small stability region. With this evaluation, the learning human strategy controller becomes much more robust to perturbations.

In this paper, the criterion to verify the stability and a method to estimate the domain of attraction are provided for the learning controllers trained with support vector machines (SVMs). Conditions are formulated based on the discrete-time system Lyapunov theory to ensure that a closed-form of the learning control system is strongly stable under perturbations (SSUP). Then a Chebychev point based approach is proposed to estimate its domain of attraction.

Some of such learning controllers have been implemented in the vertical balance control of a dynamically stable, statically unstable wheel mobile robot.

14. A novel active balance assistive control strategy based on virtual stiffness model of XCoM

Authors: Wei Guo, Shiyin Qiu, Fusheng Zha, Jing Deng, Xin Wang, Fei Chen

This paper aims to propose a novel balance-assistive control strategy for hip exoskeleton robot.

A hierarchical balance assistive controller based on the virtual stiffness model of extrapolated center of mass (XCoM) is proposed and tested by exoskeleton balance assistive control experiments.

Experiment results show that the proposed controller can accelerate the swing foot chasing XCoM and enlarge the margin of stability.

As a proof of concept, this paper shows the potential for exoskeleton to actively assist human regain balance in sagittal plane when human suffers from a forward or backward disturbing force.

15. Dynamic stability analysis of a tracked mobile robot based on human–robot interaction

Authors: Chengguo Zong, Zhijian Ji, Haisheng Yu

This paper aims to provide a theoretical principle for the stability control of robot climbing stairs, autonomously based on human–robot interaction. Through this research, tracked mobile robots with human-robot interaction will be extensively used in rescue in disaster, exploration on planetary, fighting in battle, and searching for survivors in collapsed buildings.

This paper introduces the tracked mobile robot, based on human–robot interaction, and its six moving postures. The dynamic process of climbing stairs is analyzed, and the dynamic model of the robot is proposed. The dynamic stability criterion is derived when the tracked mobile robot contacts the stairs steps in one, two and more points. A further conduction of simulation on the relationship of the traction force and bearing force vs the velocity and acceleration in the three cases was carried out.

This paper explains that the tracked mobile robot, based on human–robot interaction, can stably climb stairs so long as the velocity and acceleration satisfy the

dynamic stability criterion as noted above. In addition, the experiment tests the correctness of dynamic stability analysis when the tracked mobile robot contacts the stair steps in one, two or more points.

16. Disturbance observer-based coordinated control for three dimensional formation of unmanned autonomous helicopter

Authors: Rong Mei

This paper aims to study the issue of the three-dimensional formation coordinated control for the unmanned autonomous helicopter (UAH) by using the sliding mode disturbance observer. Under the designed formation coordinated controller, the desired formation can be maintained and the closed-loop system stability is analyzed by using the Lyapunov theory.

Considering the unknown time-varying external 10; disturbance in formation flight of UAHs, a sliding mode disturbance observer has been employed to estimate them.

A sliding mode disturbance observer has been designed to estimate the unknown time-varying external disturbance in formation flight of UAHs. Aiming at the leading UAH maneuver in three-dimensional space during the formation flight progress, the formation coordinated controller has been proposed based on the output of the disturbance observer to maintain the formation.

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