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D3.6 Final report on pilot projects in aerospace manufacturing

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PU	Public	X
PP	Restricted to other program participants (including the EC Services)	
RE	Restricted to a group specified by the consortium (including the EC Services)	
CO	Confidential, only for members of the consortium (including the EC)	

The overall aim of the AERO-UA project is to stimulate aviation research collaboration between the EU and Ukraine through strategic and targeted support. AERO-UA is focused solely on Ukraine, because the country has a huge aerospace potential but a low level of aviation research collaboration with the EU. Ukraine's aerospace sector spans the full spectrum of systems and components development and production with OEMs, Tier 1 and 2 suppliers, aeroengine manufacturers, control systems manufacturers, R&D institutions, aeronautic universities, and SMEs. This is also reflected in the sector's important contributor to the country's economy (e.g. aircraft production of €1,9 billion in 2011).

Ukrainian aerospace organisations possess unique know-how that can help Europe address the challenges identified in the ACARE SRIA / Flightpath 2050 Report. Furthermore, following the signing of the Agreement for the Association of Ukraine to Horizon 2020 in March 2015, Ukrainian organisations are eligible to participate in Clean Sky 2 and H2020 Transport on the same funding terms as those from EU member states. Equally, genuine commercial opportunities exist for European aviation organisations to help modernise Ukraine's aerospace sector.

The AERO-UA project will achieve its overall aim via four high-level objectives:

1. Identifying the barriers to increased EU-UA aviation research collaboration;
2. Providing strategic support to EU-UA aviation research collaboration;
3. Supporting EU-UA aviation research knowledge transfer pilot projects; and
4. Organising awareness-raising and networking between EU-UA stakeholders.

The AERO-UA consortium is comprised of key EU and UA aviation organisations that will implement WPs closely mapped to the high-level objectives. The consortium will be supported by an Advisory Board involving Airbus, DLR, Min. Education and Science of Ukraine, Ukrainian State Air Traffic Services Enterprise and retired Director of EADS Jean-Pierre Barthélemy.

Table of Contents

1. Introduction

This work package provides targeted support for EU-UA collaboration in aviation research in the form of knowledge transfer pilot projects (WP 3) to be implemented by the AERO-UA partners. The pilot projects are structured around three key areas relevant to the challenges of ACARE SRIA / Flightpath 2050: Aerostructures, Aeroengines and **Aerospace Manufacturing**.

Task 3.3 is focused on the key area Aerospace Manufacturing. The project allowed short-term visits between the EU and UA partners, in order to exchange knowledge, receive training and/or conduct feasibility studies. Two pilot projects were carried out in the field of aerospace manufacturing:

- Pilot Project 3.3a: Manufacturing joints (Leader: Fraunhofer; Support: UoM, UkrRIAT, FED, NASU and KhAI), and
- Pilot Project 3.3b: Manufacturing aerospace composite structures (Leader: UoM; Support: UkrRIAT, FED, NASU and KhAI).

Pilot Project 3.3a:

The main goal was to exchange knowledge and conduct a feasibility study concerning the development of manufacturing processes for high-load-transfer and high-lifetime joints for Ukrainian aerospace structures.

During the first potential analysis of the aerospace components manufacturing process performed, the consortium partners defined two scenarios: sensor controlled riveting process (scenario 1) and mode-based assembly assistance and inspection (scenario 2).

Partners in scenario 1: UkrRIAT (definition of practical end user requirements for high-load aircraft manufacturing and riveting tooling), KhAI (expertise in riveting technology), NASU – G.S.Pisarenko institute for problems of strength (tension testing and stress testing), Fraunhofer (contactless optical quality inspection).

Partners in scenario 2: FED (definition of practical end user requirements for the digital assistance and quality inspection during manual assembly process), Fraunhofer (technologies for visual assembly assistance using augmented realty methods and technologies for optical inspection of assembly quality).

<u>Milestones achieved until M36:</u>

- A potential analysis for the production technology riveting process.
- A potential analysis for the assembly process of high quality flight control systems.
- Definition of test cases for the riveting and the assembly process.
- Selection of fasteners for the riveting process.
- Definition of the requirements for a quality controlled riveting process.
- Definition of the requirements for a highly flexible assistance and testing system for assembly.
- Design of a virtual technology demonstrator »sensor controlled riveting process«.
- Design of a virtual technology demonstrator »model-based assembly assistance and inspection«.
- Testing of function modules for physical simulation of all relevant functions.

Discussion of gaps between state of the Art in Ukraine and European Union

The usage of modern sensor systems as a core technology of smart manufacturing is limited in Ukraine. Ukrainian researchers and engineering professionals are capable of understanding and employing these technologies. Nevertheless, due limited information available in Ukraine on those technologies and limited financial resources, modern sensor technologies are rarely employed in Ukraine.

A SWOT analysis was completed for this pilot project, to identify the internal strengths, weaknesses, external opportunities, and threats in relation to manufacturing joints, and to assess potential gaps and strategies. The qualitative findings of the SWOT analysis is detailed below:

Internal Strengths:

- Availability of advanced aircraft industry in Ukraine
- Availability of manufacturing processes and equipment, experience and personnel on the area of riveting
- Availability of research, design, test and manufacturing competences to implement Scenario 2
- Aim to modernize aircraft industry to achieve a high innovation level
- Relatively low labour costs
- Availability of advanced optical industry in Ukraine
- Availability of relations and experience of collaboration in the area of automatic riveting with leading European companies

Internal Weaknesses:

- Lack of balance in hand for the companies and research institutes
- Insufficient government incentives
- Fairly outdated aircraft production line technology
- Lack of experience in optical inspection of the riveted joint parameters
- Insufficiently developed system of manufacturing incentives and loans
- High risks in connection with problems of partial occupation of Ukrainian territory
- Long terms of innovation introduction
- Poor domestic market for aircraft production
- Unfavourable age structure

External Opportunities:

- Association Agreement and Science and Technology Cooperation Agreement between the EU and Ukraine
- Ukrainian companies are eligible to participate in the EU Framework Programme
- Availability of worked through technology of the riveted joint optical inspection and possibility of its transfer to Ukraine
- Availability of worked through technology and equipment of automatic riveting and its transfer to Ukraine
- In light of breakdown of cooperative relations with Russian companies there is an opportunity to re-orient science and technology cooperation to EU
- Availability of crediting mechanism for joint projects at acceptable conditions
- Market entry jointly with European companies

External Threats:

- Lack of investment funds for innovation project development in Ukrainian aircraft industry
- Lack of section in Association Agreement concerning aircraft industry
- Insufficient European corporate investment in unstable Ukrainian economy
- High competition at the aircraft market in Europe and other countries
- There is no admission in EU of certificates (production approval, aircraft type) issued in Ukraine

Pilot Project 3.3b:

The goal was to exchange knowledge and training between the EU (UoM) and UA partners in the field of integral composite structures production, using dry-fibre preforms and out-of-autoclave process, advanced characterisation and rational approach for testing of composite structures.

For training purposes, the main activity took place between KhAI (UA) and UoM (UK). A researcher from KhAI visited UoM and was trained by skilled staff on composite manufacturing by means of RTM and vacuum infusion processes (with/without heating) using dry-fibre preforms manufactured by 3D weaving and filament winding/braiding.

In the pilot project, the trainee also manufactured metal-CFR composite ‘Hybrid-joints’ by out-of-autoclave process using 3D woven fabrics and 2 different designs of metal inserts made of titanium alloy. The workpiece was cured for approximately 5 hours with a turned on vacuum unit and heating of surface 60 °C, with the full curing cycle lasting 24 hours. Stereo/optical and scanning electron microscopic characterisation was conducted on joints to study the impact of insert design on quality of impregnation by infusion process and localised defect zones generated.

The metal inserts used in this case-study were manufactured by UA partner Public Joint Stock Company FED by Electrical Discharge Machining (EDM). Mechanical testing of hybrid-joint specimens was done by NASU (Pisarenko). UkrRIAT supported this study by providing a review of research and technology in Ukraine concerning metal to composite joining.

<u>Milestones achieved until M36:</u>

- Identification of test case
- H1 Design of joints and manufacturing method
- H2 Manufacturing subcomponents (metal inserts, woven fibre preforms)
- Finalised analysis types to be performed
- H3 Hybrid metal-composite joint structures manufacturing
- Analysis and characterisation of manufactured joints
- Smart-sensor embedded structures manufacturing and analysis
- Publication on use of sensors for early crack investigations

Discussion of GAPs between state of the Art in Ukraine and European Union

UoM and KhAI have the facilities for the manufacture of composite materials from both dry fibres (fabrics, fibre mats, nonwovens) infused with liquid resin, and from pre-impregnated fibre materials. Electrical Discharge Machining (EDM) has been facilitated by FED for the manufacture of the metal inserts used in this hybrid joints study. The 3D woven fibre composites have been manufactured by UoM. KhAI, UoM and TECPAR have the capability to evaluate the hybrid joints that have been produced through non-destructive and destructive test methods. NASU (G.S. Pisarenko institute for problems of strength) has the facilities for mechanical testing of hybrid-joint specimens.

A SWOT analysis was completed for this pilot project, to identify the internal strengths and weaknesses in relation to manufacture and evaluation of hybrid joints, and to assess potential external opportunities and threats. These are detailed below.

<u>*Internal Strengths:*</u>

- UoM ability to manufacture 3-dimensional fibre preforms that are known to lead to more damage tolerant joints

- Experimental facilities are available in UA for mechanical testing of composites and hybrid joints for their evaluation
- NASU has the ability to produce modified adhesives and resins to further improve the strength of hybrid joints
- FED has the capability to machine metallic components, including inserts with pins, for the production of hybrid metal/composite joints

Internal Weaknesses:

- Lack of internal collaboration
- Capabilities of partners are very different – requiring extensive communication and posing a threat of misunderstandings and delays

External Opportunities:

- UA capability puts it in a good position to collaborate with EU and worldwide
- Potential to build a taskforce/workforce for advanced design, manufacture and evaluation of hybrid joints
- Potential for collaboration and support from UA on design processes in future aerospace projects

External Threats:

- Lack of government or private funds in UA for full-scale research on hybrid joints
- No interest in industry-academic collaboration
- Data sharing within some sectors (e.g. defence, military) on advanced design processes can be problematic due to security factors

2. Pilot Project 3.3a: Sensor controlled riveting process (scenario 1) and Model based assembly assistance and inspection (scenario 2)

The Pilot Project 3.3a partners carried out a potential analysis of the relevant manufacturing processes from the user and utilization point of view. Here, the representative end users FED and UkrRIAT defined the technological topics that were of particular relevance for improving competitiveness in Ukrainian aircraft manufacturing.

As a result of this process, two scenarios were defined: sensor controlled riveting process (scenario 1) and model based assembly assistance and inspection (scenario 2). For both scenarios test cases and the requirements for the process improvements were examined.

2.1 Background to the pilot project

2.1.1 Sensor controlled riveting process (scenario 1)

Riveted joints are one of the main kind of permanent joints used to assemble the constructions of aeronautical vehicles.

The quality of a riveted joint signifies the correspondence of the following list of conditions to the nominal values: the character and the value of distribution of interference along the generating line of rivet; the height and the diameter of closing head; the absence of scratches, tears and cracks in the area of the rivet's intensive deformation; the maintenance of the product's theoretical shape after the joint's creation. A failure in the implementation of any requirement results in unavoidable rework of joint, which, in turn, results in considerable delays (comparable to the time required for the main process of riveted joint creation) and in decrease of final strength and resource of the product.

The process of the riveted joint creation is a multifactor process. Moreover, insignificant alteration of each factor's value leads to significant alteration in behaviour and final results of the process. This characteristic puts some additional limitations on the ability of incoming, inside and final inspection to warn of possible defects in a timely manner.

The technological process (Fig. 1a – 1f) of a simple riveted (R) / bolt-riveted (BR) joint creation consists of a sequence of the following operations: creation of the through bore-hole in previously fixed assembly to install R or BR; installation of the R or BR itself; creation of the R / BR closing head; non-destructive check of made joint; correction of defects in the case of their presence.

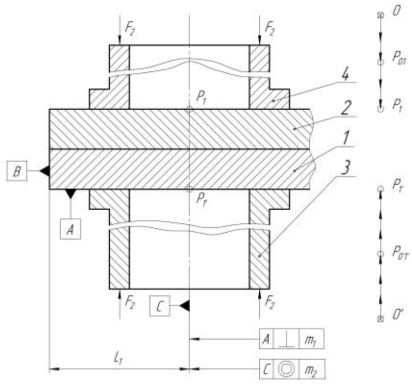


Figure 1a. Fixation

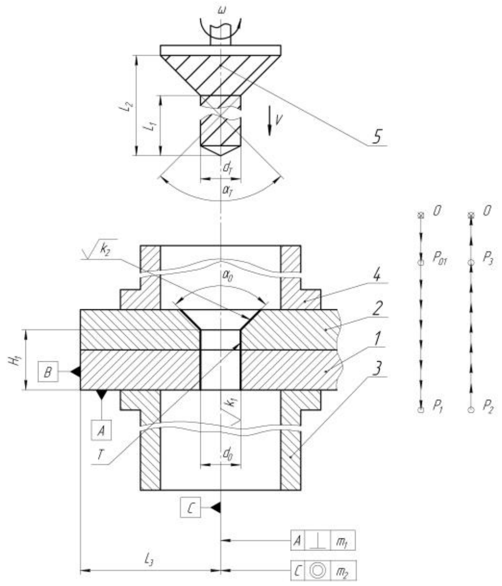


Figure 1b. Drilling-Countersinking

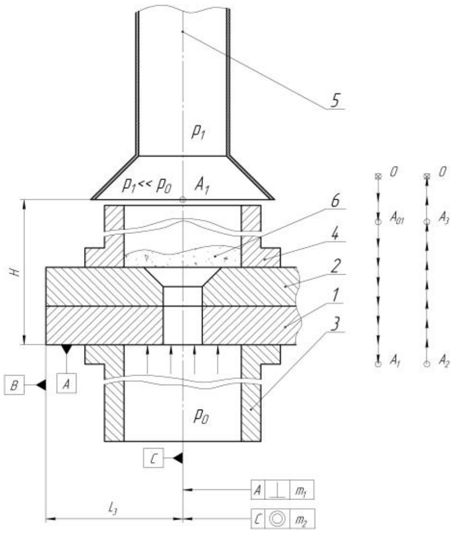


Figure 1c. Removing of shavings

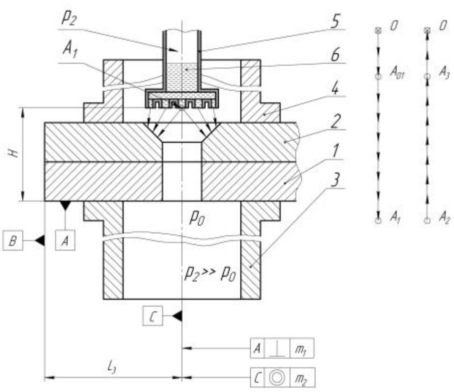


Figure 1d. Sealant spreading

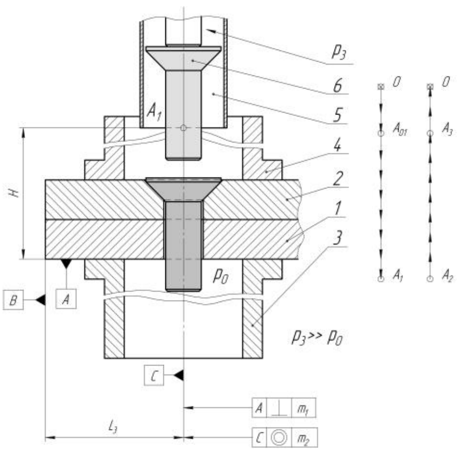


Figure 1e. Rivet installation

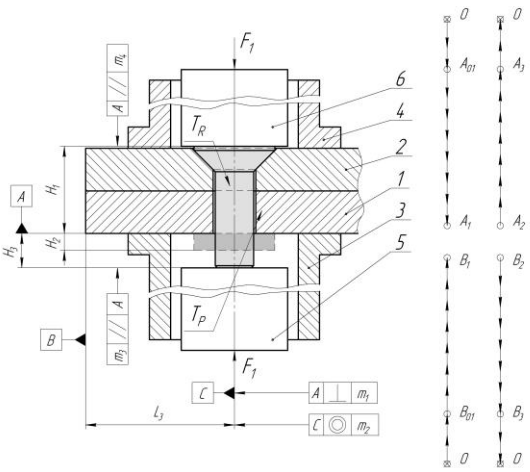


Figure 1f. Joint creation

The essence of control is the collection of data about the geometry of the setting and closing heads of the rivets tested (Fig. 2) and about the location of skin surface relative to the rivet. Subsequently, the analytical comparison of collected data with the given data is performed. If the controlled parameter oversteps the limits of values, a decision about following actions to exclude the defect is taken.

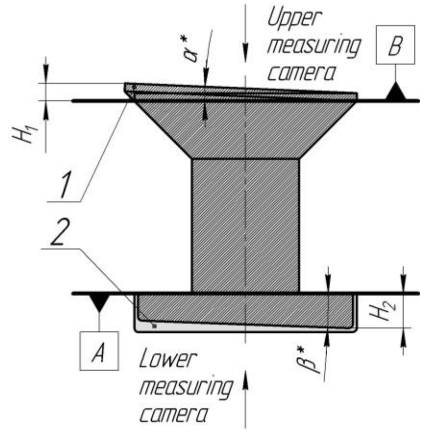


Figure 2. Evaluation

Prepared on the basis of Fraunhofer experiences with rivet head measurement systems designed for different types of BRÖTJE Automatic Riveting Machines, a technical concept was prepared by Fraunhofer.

This technical concept of the “Rivet Head Measurement System” is a modular design. It can be adapted to different types of BRÖTJE Automatic Riveting Machines with little effort.

The Rivet Head Measurement System uses the light sectioning principle. A laser projects a number of lines onto the rivet head and the measuring camera directly above captures a single image. By evaluating the offset of the lines in different image areas the height offset between the setting head and the fuselage shell is calculated (see Fig. 3).

The measurement uncertainty for the determination of the height of the rivets setting head with this method is ±0.010 mm.

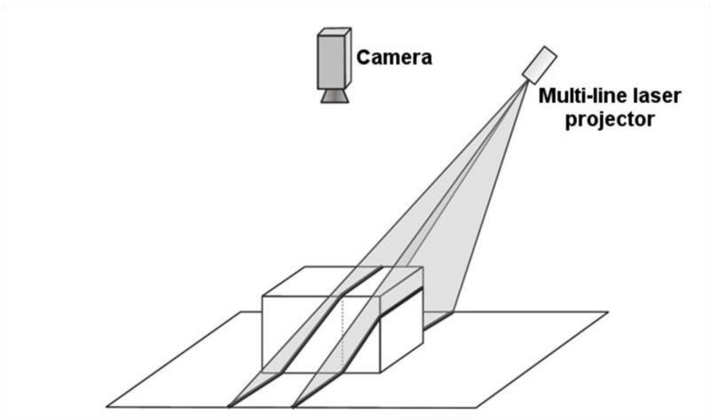


Figure 3. Principle of the height measurement for the setting head

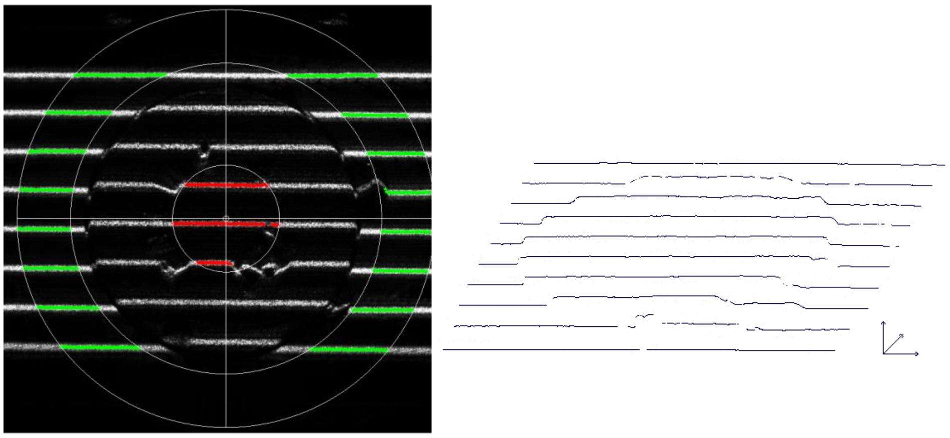


Figure 4. Measuring data of the for the height measurement

The position of the drilling axis and therefore the middle axis of the rivet is known from the calibration, so that for the evaluation only those measuring points are used which are closest to the middle of the rivet (marked red in Fig. 4). The reference to the fuselage shell will be made via measuring data outside of the rivet (marked green in Fig. 4). The lateral distance between the profile lines is approximately 1.5 mm.

The result evaluation is based on one single image acquisition, so that the riveting machine cycle period is only extended minimally.

Thanks to its vertical measuring camera assembled above the work level the measurement system has the ability to detect circular objects in the area of the pressure die brush and to calculate a correction value to a required position (Fig. 5). The measurement inaccuracy during the assignation of the centre point is less than ±0.05 mm.

The result of the centre point assignation is visualized on a screen for the machine operator and sent to the control system of the riveting machine. The camera image is shown parallel in real-time.

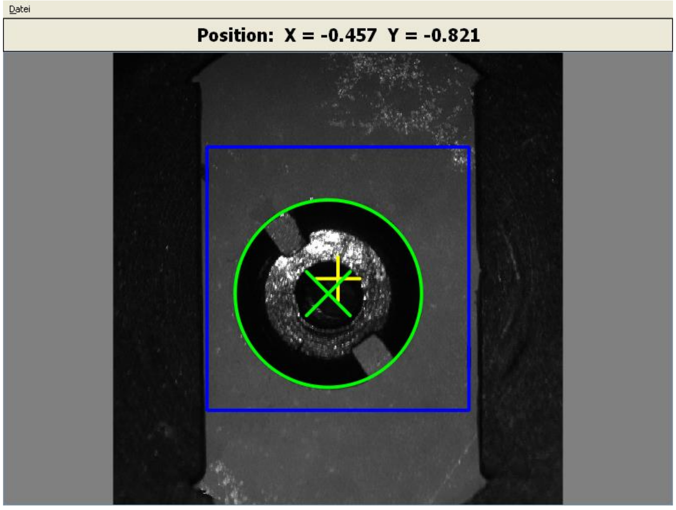


Figure 5. Reference position

One of the ways to improve the quality of a riveted joint is the implementation of automatic control elements that can perform the mathematical estimation of geometrical input parameters of fasteners and assembly units operatively to interfere in process by changing of process parameters in on-line mode.

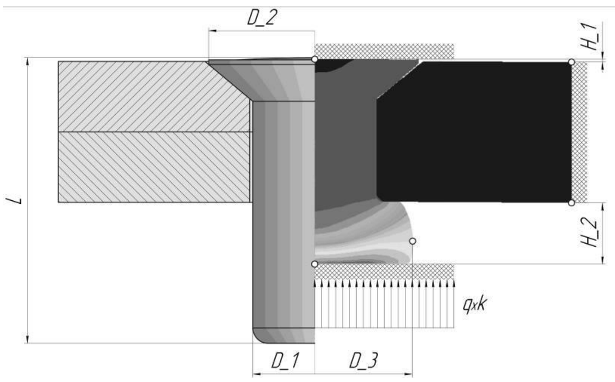
To create such control elements, it is necessary to have an exact mathematical description of the process which should be performed. This leads to a precise analytical forecast of the process's behaviour during the changing of one or more input parameters within the bounds of known areas of possible variations.

On the basis of the unknown character of value alteration of the technological and design factors selected a-priori, which influence the process of creation of a riveted joint between two solid plates with small thickness, define the characteristic relations (F1, F2, F3) of thickness (H_2), diameter (D_3) of closing head and value of protrusion (H_1) of setting head of rivet from the length (L), diameter (D_1) of pin, diameter (D_2) of setting head of rivet and the coefficient (k) of reduction of applied pressure correspondingly (Fig. 6).

The technological scheme of a riveted joint has two flat plates of known thickness, made from aluminium alloy with known physico-mechanical characteristics (the elasticity modulus, yield point, Poisson's coefficient, strengthening modulus are set). Both plates have an opening of known diameter. The opening in the upper plate has the countersink with known depth and opening angle. The plates touch one another by corresponding surfaces (the corresponding surfaces have the static friction coefficient, the friction process is described by Coulomb's law [1, 2]). The ends of the plates have a fixed bearing. In the opening of the plates there is the rivet made of aluminium alloy (the mechanical properties of the rivet's elastic-plastic material described by bilinear law of strengthening [1, 2]). The geometrical parameters of the rivet are known [7].

At the initial time state, the rivet leans on contact surface of the countersink in the upper plate. The top point of the setting head stays in contact with a rigid, flat and fixed tool. The bottom surface of the pin stays in contact with a rigid, flat and movable tool which can move towards the upper tool by means of applied pressure q (Fig. 6). The contact surfaces of the rivet have the static coefficients of friction.

In this special case it is necessary to define the total displacement of three referenced marks of the rivet (Fig. 6). The difference between the location of upper (bottom) referenced marks and referenced marks of fixed points of upper (bottom) plates (Fig. 6) defines the required values of protrusion of the setting and closing head of the rivet. The calculation of the diameter of the closing head is organized directly.



	D_2, mm	D_1, mm	L, mm	k, –
– *	08,310	04,730	11,600	00,800
– 1	08,350	04,745	11,800	00,900
0	08,390	04,760	12,000	01,000
+ 1	08,430	04,775	12,200	01,100
+ *	08,470	04,790	12,400	01,200
epsilon	00,040	00,015	00,200	00,100

	D_2, mm	D_1, mm	L, mm	k, –
H_1, mm	F_1	F_1	F_1	F_1
H_2, mm	F_2	F_2	F_2	F_2
D_3, mm	F_3	F_3	F_3	F_3

Figure 6. The description of initial and boundary conditions of the task with guidance of known and unknown parameters, character of their variations in asterisk-, core-, and central-points of plan, conditions of loading of finite-element model of process

The peculiarity of this problem's statement (the character of necessary variations, Fig. 6) stipulates the need to create a parametrical model. Adequate to the description of the physics of the process under consideration, the apparatus of contact mechanic of deformed solid body in nonlinear elastic-plastic statement on the base of finite element method [3, 4] was used. In order to reduce solution time, in consideration of axial geometrical and physical parameters (loads) symmetry, it was decided to reduce the basic dimension of task from three to two (in axially symmetrical statement).

The grid convergence of the created model was verified by means of data obtained from natural experiment [3], which was provided with the help of a highly sensitive optical system which measured the geometrical location of points of the deformable specimen with the necessary level of accuracy.

The ranges of variation of initially selected criteria (D_2, D_1, L, k) were corrected by means of statistical analysis [5] and by geometrical irregularity of fasteners used in active manufacturing line. The value of error in obtained test results does not exceed the level of 5%, so the created parametrical model should be recognized as satisfactory.

The numerical multi-factor experiment for definition of the equations (F1, F2, F3) was organized according to a full uniform-rotatable two-degreed plan. The quantity of independent variables k in (1.1) equals 4. The total number of provided numerical experiments equals 31 (notably: in core of plan – 16, in asterisk points of plan – 8, in centre of plan – 7). The values of independent variables (D_2, D_1, L, k) in central-, asterisk-, and core-levels are shown in Fig. 6. The matrix of full uniform-rotatable two-degreed plan is not shown because of a lack of space. The required functions are represented in the form of a two-degreed polynomial view [6]:

$$Y = b_0 + \sum_{1 \le i \le k} b_i x_i + \sum_{1 \le i < l \le k} b_{il} x_i x_l + \sum_{1 \le l = i \le k} b_{il} x_i^2 \qquad [1.1]$$

where:

Y – required value of function;
$b_{0,i,l}$ – coefficients of regression;
$x_{i,l}$ – independent variables.

The coefficients of regression b 0 ,i ,l were defined analytically according to [6] and placed in table:

Y	B0	B1	B2	B3	B4	B12	B13
H_1	+7,640	+0,002	+0,006	+0,007	+0,228	–0,004	+0,001
H_2	+0,128	+0,016	+0,000	+0,000	+0,000	+0,000	+0,000
D_3	+2,395	–0,007	+0,020	+0,075	–0,166	+0,000	+0,000

B14	B23	B24	B34	B11	B22	B33	B44
+0,003	+0,001	–0,003	+0,001	–0,011	–0,015	–0,013	–0,022
+0,000	+0,000	+0,000	+0,000	+0,000	+0,000	+0,000	+0,000
–0,001	+0,000	+0,001	–0,003	–0,005	–0,004	–0,003	+0,011

The final decoding of the obtained functions results in a complete view of the mathematical forecast of riveted joint behaviour (changing of technological parameters of process) by placing the values of independent variables $x_{i,l}$ in the following form:

$$x_1 = \frac{D\_2 - 8{,}39}{0{,}04} \quad [1.2]; \qquad x_2 = \frac{D\_1 - 4{,}76}{0{,}015} \quad [1.3];$$

$$x_3 = \frac{L - 12}{0{,}2} \quad [1.4]; \qquad x_4 = \frac{k - 1}{0{,}1} \quad [1.5].$$

The value of error of mathematical forecast in the area studied (Fig. 1) does not exceed the level of 5%, so the computed functions ($H\_1=F_1$ (D_1, D_2, L, k); $H\_2=F_2$ (D_1, D_2, L, k); $D\_3=F_3$ (D_1, D_2, L, k)) should be recognized as adequate.

[1] *Hill, R., The Mathematical Theory of Plasticity, Oxford University Press, 1998, ISBN 978-0198503675, 366 p.*

[2] *Johnson, K. L., Contact Mechanics, Cambridge University Press, 1987, ISBN 978-0521347969, 468 p.*

[3] *Washizu, K., Variational Methods in Elasticity and Plasticity, Pergamon Press, 1982, ISBN 978-0080267234, 540 p.*

[4] *Zienkiewicz, O. C., Taylor, R. L., The Finite Element Method: Volume 2, Solid Mechanics, Butterworth-Heinemann, 2000, ISBN 978-0750650557, 480 p.*

[5] *Shao, J., Mathematical Statistics, Springer, 2007, ISBN 978-0387953823, 520 p.*

[6] *Cox, D. R., Reid, N., The Theory of the Design of Experiments, Chapman & Hall/CRC, 2000, ISBN 978-1584881957, 336 p.*

[7] *Tschaetsch, H., Metal Forming Practice: Processes – Machines – Tools, Springer, 2006, ISBN 978-3540332169, 405 p.*

Based on the prerequisites described above, a basic concept for a quality-controlled process control has been designed (see Fig. 7).

Figure 7. Model for the quality-controlled riveting process

In the first half of the project, the Pilot Project 3.3a partners carried out a potential analysis of the relevant manufacturing processes from the user and utilization point of view. As a result of this process, the scenario sensor controlled riveting process (scenario 1) was defined. Test cases and the requirements for the process improvements were examined and tests and training activities were carried out.

In the second half of the project, a virtual technology demonstrator for the scenario was designed and a proof of concept was performed. These modules of a virtual technology demonstrator were established as the basis for further training and education measures of the Ukrainian staff members of our end users in the AERO-UA project.

The virtual technology demonstrator is defined as follows: The functional sequence of a quality-controlled riveting process is presented. No physical components, tools, machines or measuring system are used for this purpose. Instead, the functional process is mapped digitally using simulation tools. For this purpose, digital geometry models of the component, tools, machines, measuring systems, etc. (3D-CAD) as well as mathematical-physical models of the process sequences of, for example, riveting and measuring process are used.

The following quality parameters are relevant for the tensile and shear strength as well as the aerodynamics of a riveted joint:

- diameter and height of closing head (important for life time of the joint),
- diameter and height of sat head,
- diameter of the hole,
- position of the riveted joint (centre of closing/sat head) relative to the edge off fuselage shell,
- deformation of the surface of fuselage shell around the riveted joint.

One important part of our virtual technology demonstrator is the functional step of “design/optimization of riveting joint” and “design/optimization of process parameters”. For this the FEM method was examined.

The finite element method is a numerical technique for finding approximate solutions of partial differential equations as well as of integral equations. The solution approach is based either on eliminating the differential equation completely (steady state problems), or rendering the partial differential equations into an approximating system of ordinary differential equations, which are then numerically integrated using standard techniques. In solving partial differential equations, the primary challenge is to create an equation that approximates the equation to be studied, but is numerically stable, meaning that errors in the input data and intermediate calculations do not accumulate and cause the resulting output to be meaningless. The Finite Element Method is a good choice for solving partial differential equations over complicated domains, when the domain changes (as during a solid state reaction with a moving boundary), when the desired precision varies over the entire domain, or when the solution lacks smoothness. While the theory of FEM can be presented in different perspectives or emphases, its development for structural analysis follows the more traditional approach via the virtual work principle or the minimum total potential energy principle.

Concerning scenario 1, the quality-controlled riveting process of fuselage shells, the aim was the definition of mathematical dependence of influence of variable geometrical and power process-parameters of riveting and bolt-riveting joint creation on the character of setting head protrusion in running flow and its optimization.

As a result of our work, it was possible - based on riveting process parameters, material parameters and design data of riveting tools - to calculate the geometry of a compressed rivet by applying the FEM simulation. Figures 8 and 9 illustrates the results.

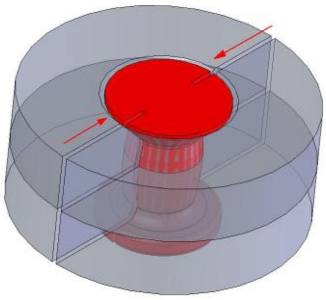


Figure 8. Deformed rivet in a riveting tool

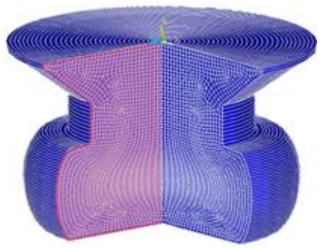


Figure 9. Finite element model of rivet for verification of material properties

Another important functional module is the simulation of "quality inspection by optical methods". For this purpose, a mathematical-physical measurement simulation of the Fraunhofer IFF was used. It enables the calculation and quality assessment of digitized 3D point clouds for optical sensors based on the principle of measurement of structured illumination with active triangulation. Prerequisites for this are a physical model of the optical sensor, a mathematical model for the sensor calibration and geometric models of the object to be measured. The object to be measured can be virtually arbitrary. Thus, in addition to aircraft structures and their rivets, for example, welded structures can also be measured virtually, see Fig. 10.

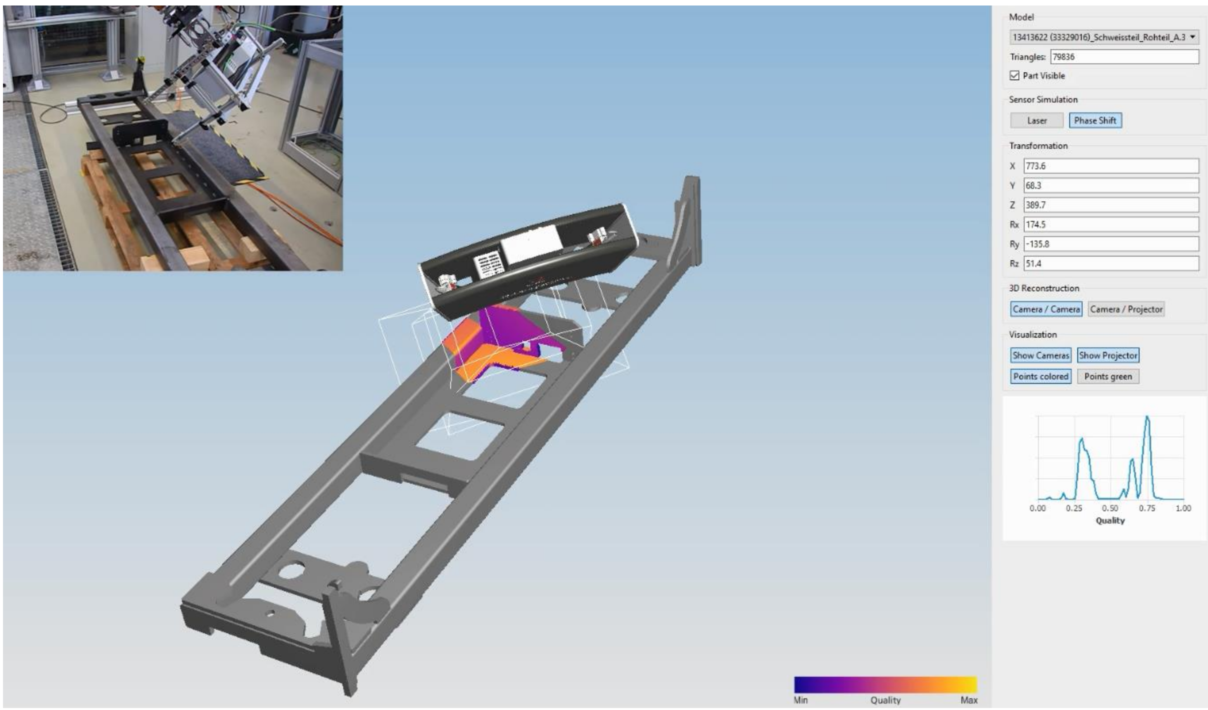


Figure 10. Simulation tool for the calculation of synthetic measuring data with optical sensors and the check of their quality

With the function modules described above, the virtual demonstrator could be fully realized.

2.1.2 Model based assembly assistance and inspection (scenario 2)

The desire for customization in our society also poses new challenges for industrial assembly. Rising demand for customized products is concomitant with steadily decreasing lot sizes, short product life cycles and a large variety of models. Advanced assembly processes in industrial manufacturing as well as quality assurance in assembly have to meet the associated challenges. This requires high flexibility without increasing labour for work preparation or diminishing quality.

Flexibility through Digital Models

A model-based approach can render such inspection systems flexible, i.e. cost effective to use even when the variety of models is large and lot sizes are as low as one. Digital geometry and physical function models of every interacting component and function modules are also employed. A function module can be used, for instance, to inspect the digital 3D CAD models of an inspected part and the probe itself as well as a physical function model of the probe in order to simulate inspection. This serves as the basis for executing steps such as planning tests and providing specified conditions fully automatically and, thus, efficiently (even for a quantity of one).

Standard inspection systems based on a golden sample or learning-driven approaches cannot do this efficiently. Continuous changes to inspection tasks would entail constant manual teaching of the underlying specifications with undue labour.

Model-Based Optical Assembly Inspection

Optical assembly inspection encompasses the inspection of different stages of a single part's assembly in relation to a complete assembly. Typical inspected stages of assembly are presence (i.e. the presence of some part at a targeted position), correctness (i.e. the presence of a specified part at a targeted position), and location (i.e. the part's position and orientation within a tolerance range).

A 3D CAD model defines the targeted stage of assembly. Optical sensors scan the actual stage of assembly. Systems that measure three dimensions, e.g. stereoscopic imaging, light sectioning or structured-light 3D scanning, are also employed. The resulting 3D point cloud can be compared with the 3D CAD model and provides information on the specific stage of assembly. Since cameras are usually employed in such optical sensor systems, oriented image data is also available for a variation analysis. Synthetic inspection data (synthetic images and synthetic 3D point clouds) is computed to ascertain the required reference data based on model data on the part (3D CAD model with contextual information) and on the inspection system's measuring function (mathematical and physical computational model).

Assembly Inspection in Aircraft Manufacturing with a Robotic Inspection System

Airliners are custom-made and thus hardly different from other capital goods such as custom machines or equipment. Every airline desires a custom interior and has aircraft modified for its specific needs. Whereas one airline installs as many rows of seats as possible, another stresses comfort and gives passengers more legroom. This is also the case with monitors, overhead bins and ventilation systems. All of these demands result in custom manufacturing with thousands of small and miniature parts that have to be positioned and mounted on the respective large parts time after time. This complicates assembly and subsequent quality control considerably. Workers get the specifications for this from paper documents and crosscheck every piece manually. The number of parts inspected in an aircraft is huge. Each of an airplane's 20 fuselage sections is held together by up to 40,000 rivets. In addition, the correctness and correct positioning of each of up to 2,500 attached parts have to be verified. Error detection is complex, and subsequent correction can be extremely expensive.

Fraunhofer developed a pilot system based on model-based assembly inspection. It autonomously inspects every attached part and joint on fuselage sections. The system consists of a six-axis industrial robot on a linear axis, which has a specially developed sensor head. The head is equipped with image sensors and 3D sensors and automatically scans several thousand test positions on the fuselage section and, thus, every inspected feature (see Fig. 11). It generates high-resolution measured data on an attached part's real stage of assembly reliably from every position. The system extracts the requisite information from the 3D CAD data available for the fuselage section. It specifies the intended outcome and contains all of the test positions' coordinates. The system also generates virtual measured data of inspected features from this data, specifically in the form of synthetic images and 3D point clouds. Every joint and every single attached part is represented exactly.

Figure 11. Fuselage section assembly inspection system

During inspection, the system overlays the real measured data with the virtual specification. It automatically factors in image section and camera angle. When the real and synthetic data match up, i.e. the imaged parts have been mounted correctly, the system marks correct parts in the test report in green (Fig. 12). It marks discrepancies in red (Fig. 13), and ambiguities in yellow. The user can view different interactive evaluations in the test report. The system delivers not only photos of the parts but also the coordinates to quickly locate the part concerned for rework.

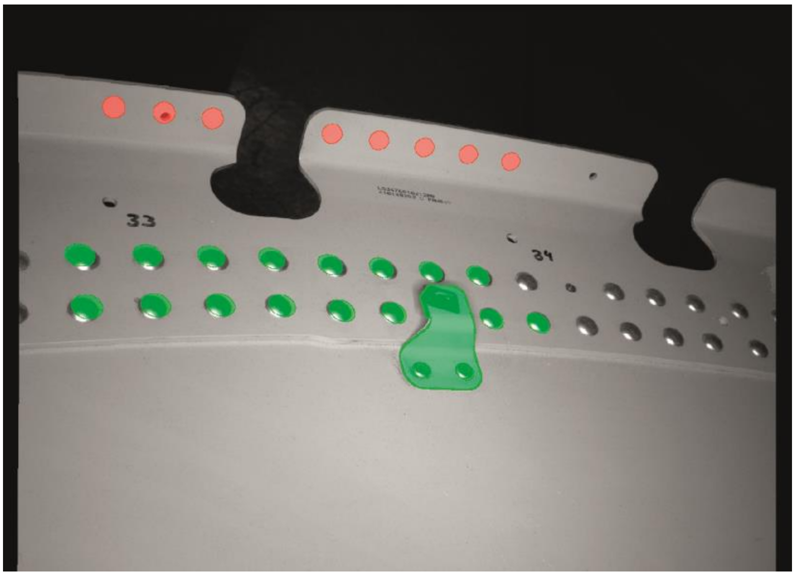


Figure 12. Inspection and test result: attached part and joints correct, some missing joints and missing boreholes

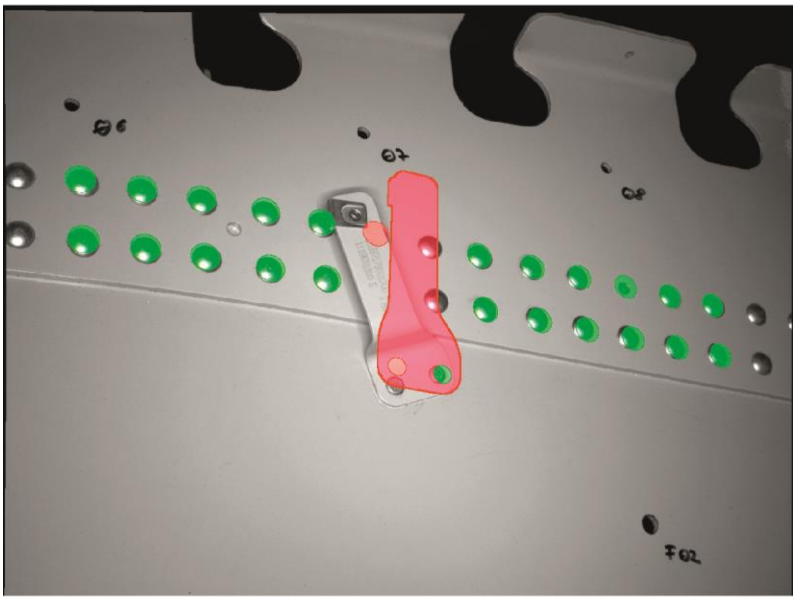


Figure 13. Inspection and test result: skewed attached part, correct joints

Assembly Inspection in Engine Manufacturing with a Manually Operated Inspection System

Early detection of defects is extremely important not only for the manufacture of fuselage sections but also for parts for aircraft turbines. Turbine centre frames (TCFs) are inspected based on similar principles of model-based optical assembly inspection. Once they are fully assembled, the tapered TCFs with diameters of approximately 1.40 m are packed in containers and shipped to customers that install them in engines. Assembly errors are intolerable for such a safety-related part and must be prevented.

Unlike assembly inspection in aircraft manufacturing, Fraunhofer developed a manually guided inspection assistant (Fig. 14) which makes a motorized handling system and an external reference measurement system unnecessary. The worker positions a C-shaped inspection system on rollers at an initial position above the TCF module so that it “looks” into the tapered TCF module above and below a bit. Based on the measuring principle of structured-light 3D scanning, 14 cameras and two 3D sensor systems capture images and 3D measured data of the attached parts from different perspectives and compare them with the inspection data generated synthetically from CAD model data. Measured data acquisition lasts approximately five seconds, the evaluation another five seconds per position. Once the initial position has been completed, the worker rotates the TCF module in the inspection system to the next specified position and the procedure begins anew. After approximately five minutes and 12 positions an entire TCF has been inspected.

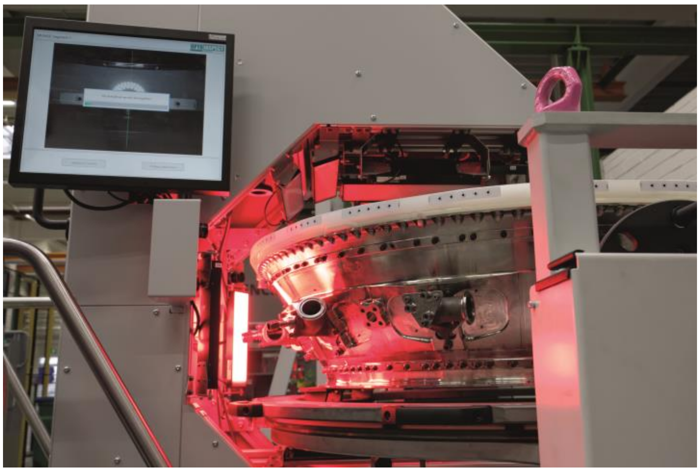


Figure 14. Assistant for TCF module assembly inspection

The optical system verifies the presence, correctness and location of attached parts, e.g. connectors, the correct assembly of joints, and the correct assembly of bolted connections and lockwires. More than 500 different parts are inspected per TCF module. Defects are usually hidden in the many specific details of the outwardly virtually axisymmetric part and some are hard to detect in a visual inspection. The inspection system detects them reliably, though. The test report shows the worker at a glance whether what and, if so, where rework is still required (Fig. 15 and 16).

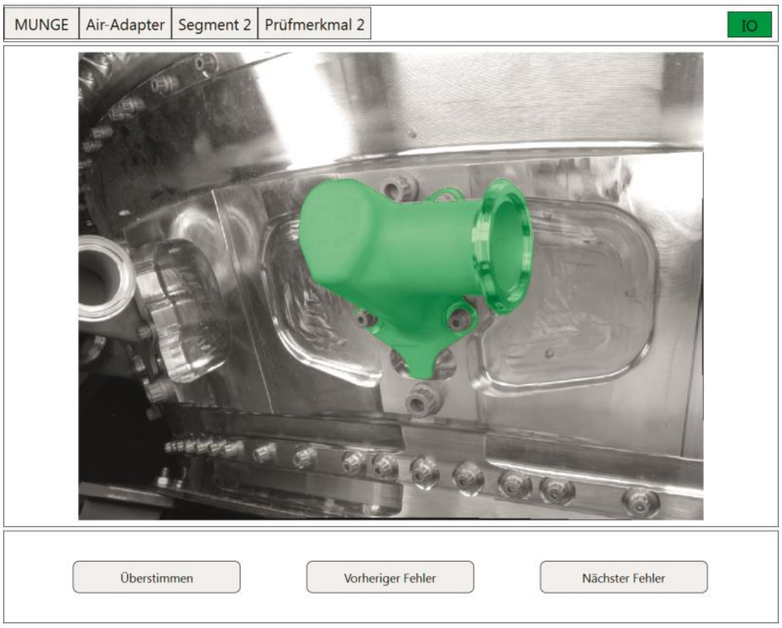


Figure 15. Inspection and test result: correct assembly

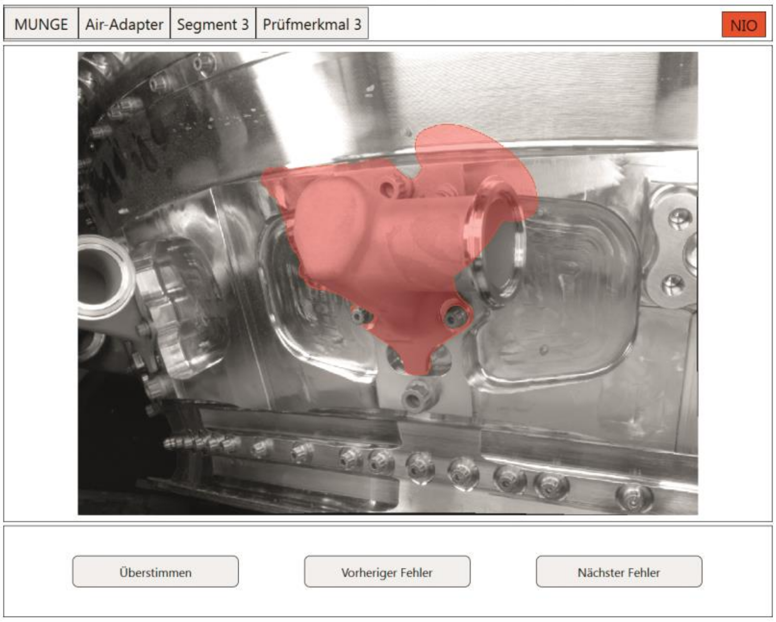


Figure 16. Inspection and test result: faulty assembly

Conclusion

Resource efficiency and flexibility are demands relevant to competitive industrial manufacturing. Model-based technology modules use integrated digital process chains to make optical inspection systems highly flexible.

New specifications for a manufactured product are for instance documented as changes in the CAD model. This model data is the basis for all other steps in the preparation and execution of optical inspection. This automates the generation of inspection and test programs, the supply of reference data and the performance of a variation analysis. Changes in the CAD model automatically result in an adaptation of the inspection and test process. Another benefit is the elimination of the need to teach specified conditions, as is often common for inspection technologies in mass production. This makes it possible to use inspection technologies cost-effectively even for small lot sizes.

The potential of the model-based assembly test was examined in close cooperation between FED and Fraunhofer. Then the assembly of high-quality assemblies is largely carried out manually. There is a potential of improving the quality by 5-10% and reducing time for assembly up to 30%.

In the second half of the project, a technology demonstrator for the scenario was designed and a proof of concept was performed. These modules of a technology demonstrator shall be the basis for further training and education measures of the Ukrainian staff members of our end users in the AERO-UA project.

The assembly of control cabinets was chosen as an application scenario. It has the advantage of being used in many areas of industrial automation (in aviation as well as in many other industries). This ensures a high degree of dissemination of the project results.

The demonstrator was set up at a hand assembly workstation. On the assembly table there was an assembly panel with DIN rails, on which various switching devices were mounted. Above the assembly table were camera systems to record the scene. An image processing software evaluates the images in the sense of a quality inspection. Behind the assembly table were touch screens which allowed a representation of an assembly instruction (assembly assistance system) and results of the quality inspection, see Fig. 17.

Figure 17. Assembly assistance system

Based on the model data of the switching devices, interactive 3D models of the target situation (Fig. 18), augmented reality-based templates for the target position in the assembly (Fig. 19) and optical assembly inspection functions can be provided.

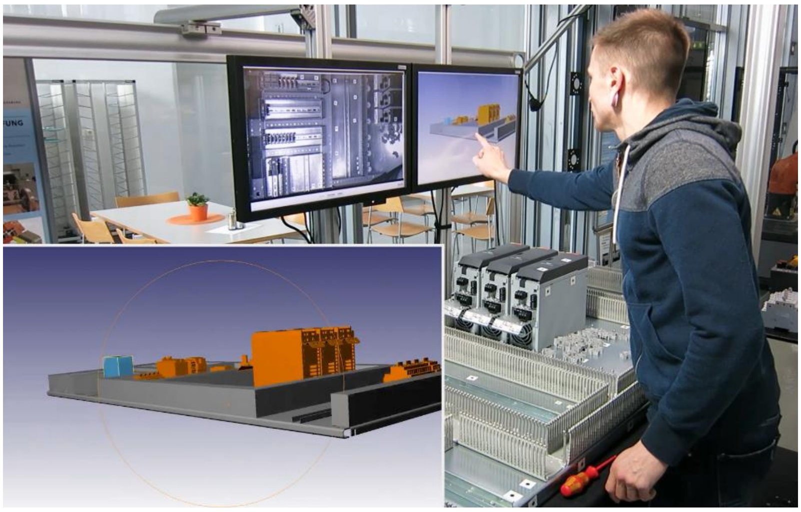


Figure 18. Interactive 3D models of the target situation

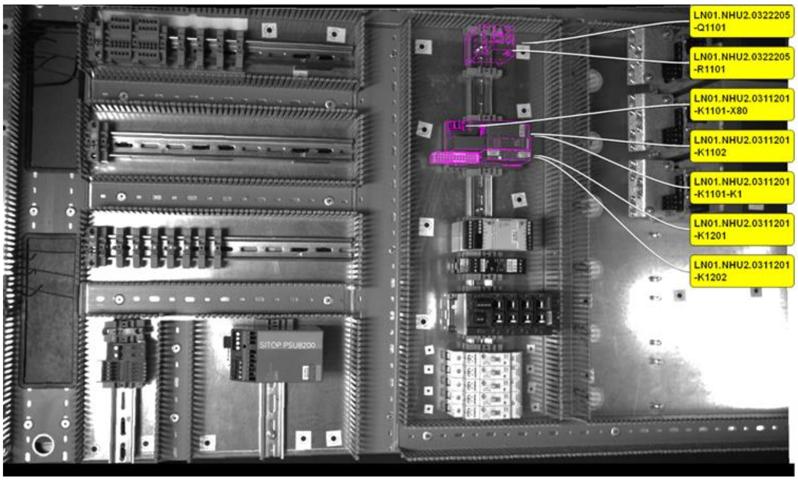


Figure 19. AR based assembly instruction

2.2 Knowledge exchanged

The following is a list of significant meetings and visits that have taken part within Pilot Project 3.3a:

- Kick-off meeting (11 - 12 October 2016), Hamburg
- Meeting between KhAI and Fraunhofer (29 November 2016, morning session) concerning scenario 1, Kharkiv
- Meeting between FED and Fraunhofer (29 November 2016, afternoon session) concerning scenario 2, Kharkiv
- Meeting between IPS and Fraunhofer (30 November 2016) concerning scenario 1, Kyiv
- Meeting between UkrRIAT and Fraunhofer (1 December 2016) concerning scenario 1, Kyiv
- Meeting between Fraunhofer, UkrRIAT, FED and UoM for presenting Fraunhofer technologies and working out technical concepts for the defined use cases (6 March 2017), Magdeburg
- Networking Conference "13th International Scientific Conference AVIA 2017" hosted by the National Aviation University (19 April 2017) for the presentation of scenario 1 and 2 of Pilot Project 3.3a, Kyiv
- Consortium Meeting and tour of Antonov (20 April 2017, morning session), Kyiv
- Technical Workshop for further work and knowledge exchange/transfer in Pilot Project 3.3a (20 April 2017, afternoon session), Kyiv

- Consortium Meeting (21 September 2017), Warsaw
- Technical Workshop for further work and knowledge exchange/transfer in Pilot Project 3.3a (22 September 2017), Warsaw
- Technical Workshop for further work and knowledge exchange/transfer in Pilot Project 3.3a (19 January 2018), Magdeburg
- Sprint Review Meeting "Factory of the Future in the Aeronautics Industry" – Presentation of the AERO-UA Project (17 April 2018), Hamburg
- International Aviation Trade Fair (ILA), Aviation Session, Presentation of the AERO-UA Project (25 April 2018), Berlin
- Meeting with R&D director of Airbus, Presentation of AERO-UA Cooperation with Ukrainian Partners (29 May 2018), Hamburg
- Consortium Meeting, Training Sessions with Ukrainian Partners (30 May-1 June 2018), Kharkiv
- European Machine Vision Association, Business Conference, Poster Session with results of AERO-UA Project (7-9 June 2018), Dubrovnik
- AERO-UA midterm review meeting (13 June 2018), Brussels
- Workshop with UkrRIAT, KhAI, NASU to design the virtual demonstrator on scenario 1 (16-17 August 2018), Kyiv
- European Machine Vision Association, Machine Vision Conference, Presentation of scientific results on model-based inspection of AERO-UA Project (6-7 September 2018), Bologna
- Sprint Review Meeting "Factory of the Future in the Aeronautics Industry" – Presentation of the AERO-UA Project (25 September 2018), Hamburg
- Web-Conference with FED to design the demonstrator in scenario 2 (12 October 2018)
- Web-Conference with Ukrainian partner concerning the working progress of demonstrator realization (7 December 2018)
- Presentation of AERO-UA project results at Rockwell Automation (11 February 2019), Edinburgh
- Webinar with Ukrainian Partner to train technology skill using the demonstrators of scenarios 1 and 2 (8 March 2019)
- European Machine Vision Association, Business Conference, B2B talks with European Companies about AERO-UA Project results (17-18 May 2019), Copenhagen
- Webinar with Ukrainian Partner to train technology skill using the demonstrators of scenarios 1 and 2 (14 June 2019)

The continuous cooperation of the partners was aimed to ensure a constant exchange of information, the continuous development of the concepts defined in scenarios 1 and 2 as well as the definition of possible collaborative research topics which can be applied for in the framework of European research funding.

2.3 Training provided

A researcher from UkrRIAT visited Fraunhofer and was trained in the functionality and usage of the optical rivet inspection system. A description of the visit is provided below.

Fig. 20 illustrates the electrical gateway of the different components of the measurement system among each other as well as to the riveting machine. The researcher was trained concerning the electrical functionality und interface technology.

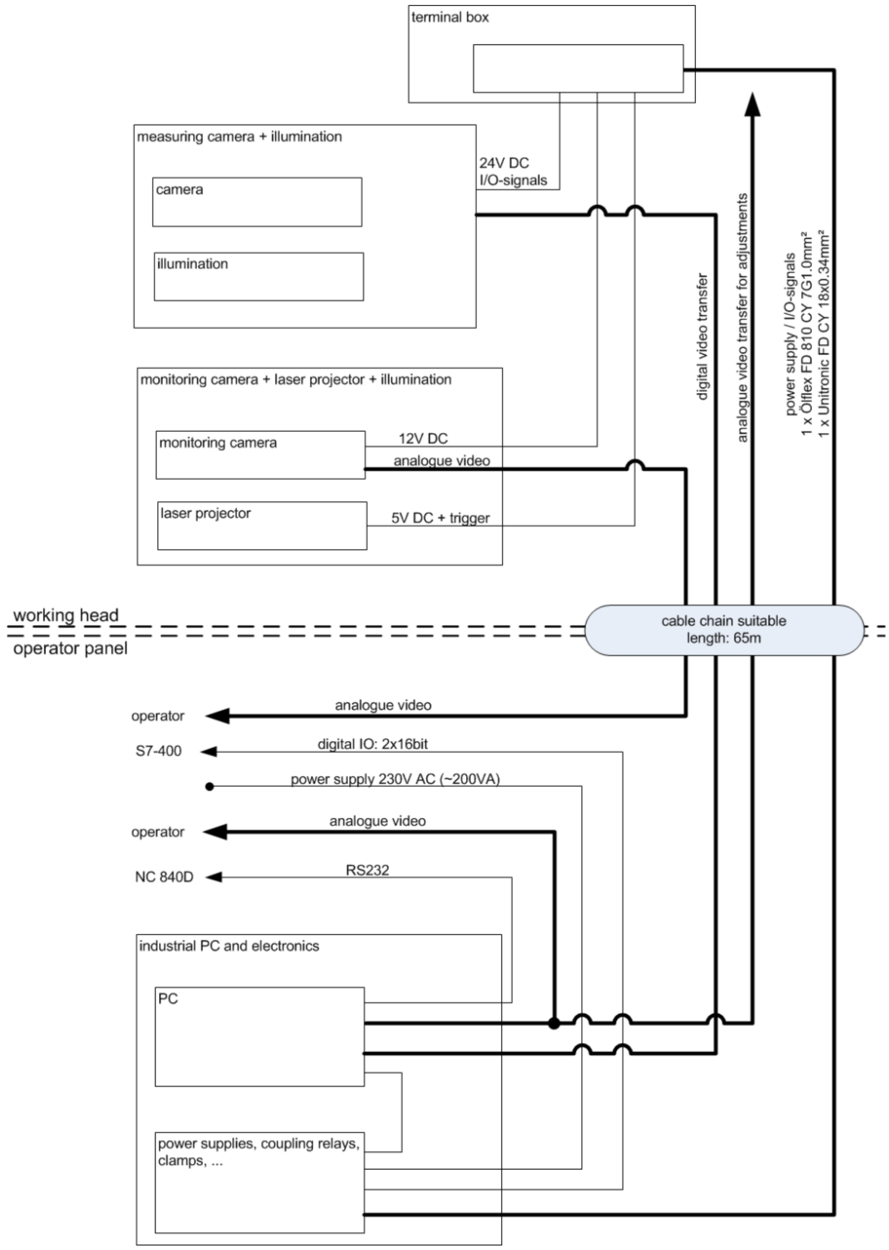


Figure 20. Inspection overview of wiring of the system components

Further training was carried out in the field of the calibration of the sensor system.

For the task “Zero point & tack rivet detection” a geometrically precise manufactured hole grid is aligned relative to the drilling axis and paraxial to the machine coordinate system. Subsequently an image acquisition by the measuring camera is executed. From this the software calculates the distortion of the camera image, the position of the drilling axis in the image and the image scale.

Alternatively, the position of the drilling axis can be measured after drilling a hole into a test panel and subsequent measurement of the hole position in the camera coordinate system (“Fine Calibration“).

The pressure die brush has to be dismounted for the calibration of the height measurement. A calibration pattern was placed at the workline level (Fig. 21). On the basis of the image acquisition all necessary parameters were calculated automatically for the later on measurement procedure.

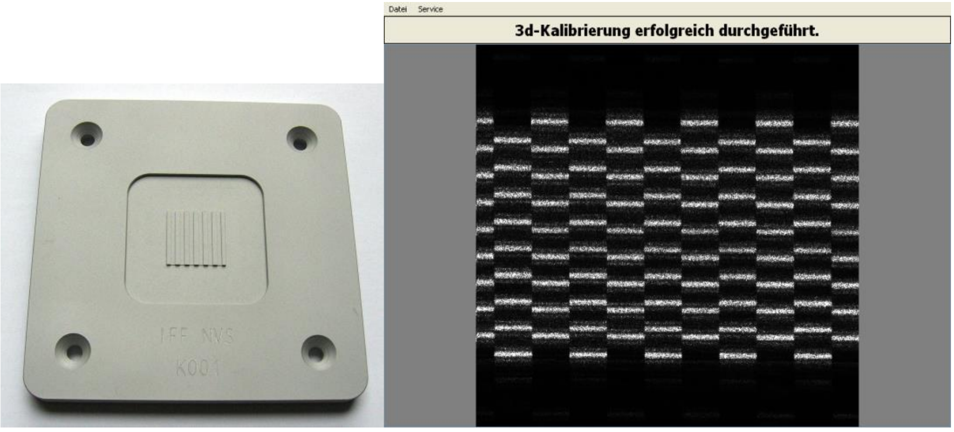


Figure 21. Calibration pattern for the measurement of the height of the rivet head

Furthermore, patterns are part of scope of delivery for the monitoring of the measurement function. The calibration patterns can also be used for identical systems, so that this is a one-time investment.

A researcher from FED visited Fraunhofer and was trained in model-based visual assistance systems as well as inspection methods for manually assembled modules. A description of the visit is provided below.

Training activities were carried out at a reference workplace (Fig. 22) using technologies of a stationary augmented reality-based assembly assistance system. Subject matter was the structure, functionality and implementation of representative assembly steps.

Figure 22. Reference workplace for manual assembly operations

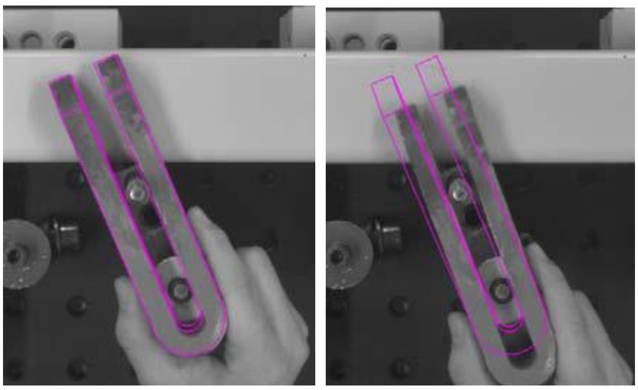


Figure 23. Assembly assistance using augmented reality technology

Two Webinars with Ukrainian Partner to train technology skill using the demonstrators of scenario 1 and 2 were conducted in March and June 2019.

2.4 Scientific and technical results

2.4.1 Sensor controlled riveting process (scenario 1)

Test panels with typical rivet joints for highly stressed joints under experimental conditions were produced. In this process, the process factors were varied in order to produce representative quality levels of the riveted joints. These were the basis for feasibility studies carried out on the applicability of optical technologies for quality testing of riveted joints as well as the further detailing of the developed concept of the quality-controlled riveting process.

Assembly of aircraft structures at Ukrainian aerospace enterprises is performed using fasteners which meet the requirements of OST 1 industry standards. These standards prescribe materials and geometry for different types of rivets (solid-shank, tubular, semi-tubular, blind rivets etc.) to be used for joint manufacturing by means of manual and/or automated rivet installation.

According to OST 1, general types of solid-shank rivets are made of steel, aluminium and titanium alloys, brass or copper and have different types of manufactured heads depending on the joint purposes. Rivets made of special aluminium alloys are used for joining of aluminium structural elements. Composite structures are riveted using rivets made steel or of titanium alloys.

Aluminium solid rivets specified by OST 1 have different types of manufactured heads. The most commonly used solid-shank fasteners are universal-head rivets and countersunk-head rivets. The latter can vary by angle of countersunk head (90 and 120 degrees) depending on external plate thickness.

Load-carrying seams that are not located in the aerodynamic flow are produced preferably with universal-head rivets. Other outer skin rivets should have a countersunk head to guarantee the necessary aerodynamic quality of the skin. If the sheet thickness of the outer skin is less than the height of the countersunk head, only rivets with 120°-countersunk head or rivets with 90°-countersunk head with reduced height should be used. At the same time, head sinking is unacceptable, and maximal protrusion over the outer surface of the structure should not exceed 0.15 mm. For primary zones of aircraft responsible for creation of lifting force this requirement can be even more rigid. For example according to the specifications for external surface quality of Antonov aircraft, protrusion of the countersunk head over the outer surfaces of skin should not exceed 0.05 mm.

A significant disadvantage of countersunk head rivets is low fatigue strength of joints subjected to cyclic loading. To extend fatigue life of riveted joints, special countersunk head rivets with compensator are used, providing increased technical service life of the joint and its sealing due to a good radial tightness in the transition zone of the head to the core (shank). To produce high-strength and reliable riveted joints of the airframe elements, special rivets with countersunk heads were developed by the Ukrainian aviation industry which have various compensators: crown-shaped, cylindrical, conical, etc. Below are examples of national code for rivets that are commonly used in Ukrainian aviation industry for producing riveted joints [1, 2]:

- d–L–Ан.Окс–ОСТ 1 34052-85 – anodized aluminium rivet with diameter **d** (mm) and length **L** (mm) with reduced 90°-countersunk head with crown-shaped compensator for automatic riveting;
- d–L–Ан.Окс–ОСТ 1 34055-92 – anodized aluminium rivet with diameter **d** (mm) and length **L** (mm) with reduced 90°-countersunk head with cylindrical compensator for automatic riveting.

The second is preferable due to significantly less protrusion of head above plate surface and does not require additional finishing operations (milling of manufactured head).

Riveted joints which are universally used in aircraft structures can be of different types depending on their purpose (strong, tight and strong-tight joints) and position of connected elements (lap and butt joints with in-line and staggered arrangements of rivets).

For example, longitudinal (line) joint of two sheets of fuselage skin is commonly produced by a double or triple riveted lap joint with adhesive sealing of seams (Fig. 24a).

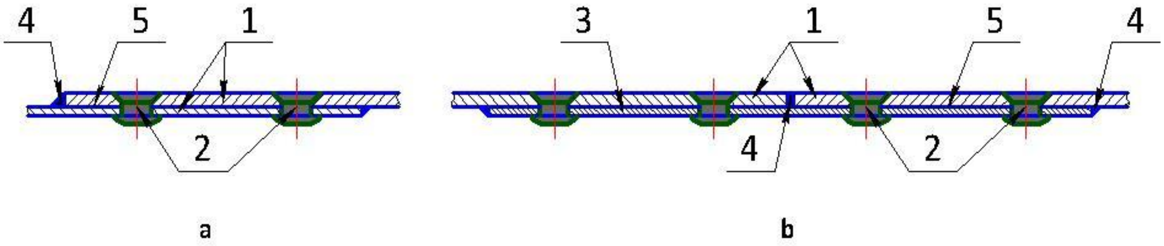


Figure 24. Strong-tight riveted joints

a – double riveted lap joint; b – double riveted butt joint with single cover plate

1 – joined plates (skin); 2 – rivets; 3 – cover plate; 4 – sealant; 5 – sealant or adhesive layer

In the case of triple riveted lap joints, the middle row is used for stringers joining. A transversal (circumferential) joint of two fuselage sections is also adhesively sealed and produced by double or triple riveted butt joint with single inner cover plate (Fig. 24b). The maximum number of rows in multi-row riveted joints of thin-walled aerospace structures is three.

The design procedure of riveted joints requires the joined plates and rivets to fulfil strength constraints. Typical failures of riveted joints subjected to shear load are: shear-out of rivets, tensile failure of joined plates, shear tear-out of plates and bearing of rivet on joined member (or bearing of joined member on rivet). Once the minimally required numbers of rivets, their diameters, and rivet pitch in row and between rows are defined, they are compared with standardized values and accepted as the final parameters. In the Ukrainian aviation industry rivet pitch in row is accepted according to requirements listed in OST 1.00016-71 [3]. The distance between rows in two- or multi-row riveted joints is accepted as 0.6...0.8 of rivet pitch in row.

Typical fuselage skin, stringers, skin reinforcements, cover plates, etc. in Ukrainian airplanes are made of aluminium alloy sheets with a thickness from 1.0 mm to 1.8 mm. The diameter of rivets according to common practice should be meet the value defined as $\sqrt{2}s$, where s is the total thickness of the joined plates. Rivets used in load-bearing joints are no less than 3 mm in diameter. Thus, the frequently used aluminium solid rivets in fuselage structures have the shank diameter of 3.5 and 4.0 mm (rarely 5.0 mm) depending on total thickness of the joined elements.

The length of rivets also depends on the total thickness of joined plates s and can be selected through the certain equation or using recommendation of industry standards OST 1 34102-80 [4] and OST 1 34041-79 [5]. The latter is used for selection of rivet length for the automatic riveting process.

Quality control of riveted joints starts with inspection of rivets and joined parts and finishes with quality control of riveted joints after assembly. Procedures of rivet quality control are described in technical requirements and specified in the national industry standard [4, 6]. Quality control of rivets is carried out by visual inspection, instrumental measurements and mechanical tests. Visual inspection is used to detect mechanical damage and cracks, validate the quality of surface treatment, etc. Instrumental measurements are carried out to validate correspondence of rivet parameters to requirements of the national industry standards.

Requirements on geometry of solid-shank aluminium rivets with countersunk head before and after upsetting as well as on drilled hole of joined plates are listed in the Ukrainian industry standard [4, 6] and in manufacturing guidelines for riveting of metallic structures PI 249-2000 [7] (transliteration from Ukrainian codding ПИ 249-2000) and summarized in table below.

Analysis of quality control of requirements of riveted joints shows that one of the important parameters is the protrusion of manufactured head above the outer surface. Generally, the countersunk heads of rivets with compensator after riveting process protrude above the surface of the joined elements by a value significantly exceeding the maximum allowable by technical requirements and require additional finishing operations.

Ukrainian industry standards requirements on geometry of rivets and riveted joints

Parameter	Rivet diameter *d*, mm	Tolerance
Rivets		
Circularity of shank, mm	3.5 ÷ 5	+ 0.10
Circularity of manufactured countersunk head, mm	3.5 ÷ 5	+ 0.10
Tolerance on angle of countersunk head, degrees	3.5 ÷ 5	± 1.0
Reduction of tail diameter (within length 2 mm), mm	3.5 ÷ 5	0.20 (min)
Perpendicularity of free face of countersunk head with diameter ***D***, mm	3.5 ÷ 5	0.0087***D***
Perpendicularity of free face of tail, mm	3.5 ÷ 5	0.0524***d***
Joined plates		
Tolerance on diameter of drilled hole*, mm	3.5 ÷ 5	+ 0.12
Misalignment of holes in plates with total thickness up to 5 mm, mm	3.5 ÷ 5	± 0.10
Misalignment of holes in plates with total thickness more than 5 mm, mm	3.5 ÷ 5	± 0.15
Joints		
Tolerance on diameter of shop-head**, mm	3.5	± 0.30
	4	± 0.40
	5	± 0.50
Offset of shop-head axis relatively to shank axis, mm	3.5 ÷ 4	± 0.30
	5	± 0.40
Minimal protrusion of countersunk head above plate surface, mm	3.5 ÷ 5	0.01
Maximum protrusion of countersunk head above plate surface, mm	3.5 ÷ 5	0.15
* Diameter of drilled hole for installation of solid rivets with diameter up to 5 mm is ***d+0.1 mm.*** ** Dimensions of shop-head for solid rivets with diameter up to 5 mm: diameter = ***1.5d***, height ≥ ***0.4d.***		

Finishing operations consist of milling excess material of protruding countersunk heads, which leads to removal of protective anticorrosion coating from the rivet heads and risks damaging them as well as the skin on the zones adjacent to the heads due to the tightening of skins during riveting.

Based on this analysis for the case study used for determining parameters and features of the measurement system for quality control of riveting process, it was proposed to select double riveted lap joint (see Fig. 25) of two aluminium sheets with a thickness of 2 mm joined by anodized aluminium rivets 4 mm in diameter with reduced 90°-countersunk head with cylindrical compensator (OST 1 34055-92). The diameter of countersunk head is 6.4 mm, requirement on maximum protrusion of countersunk head above plate surface – 0.05 mm.

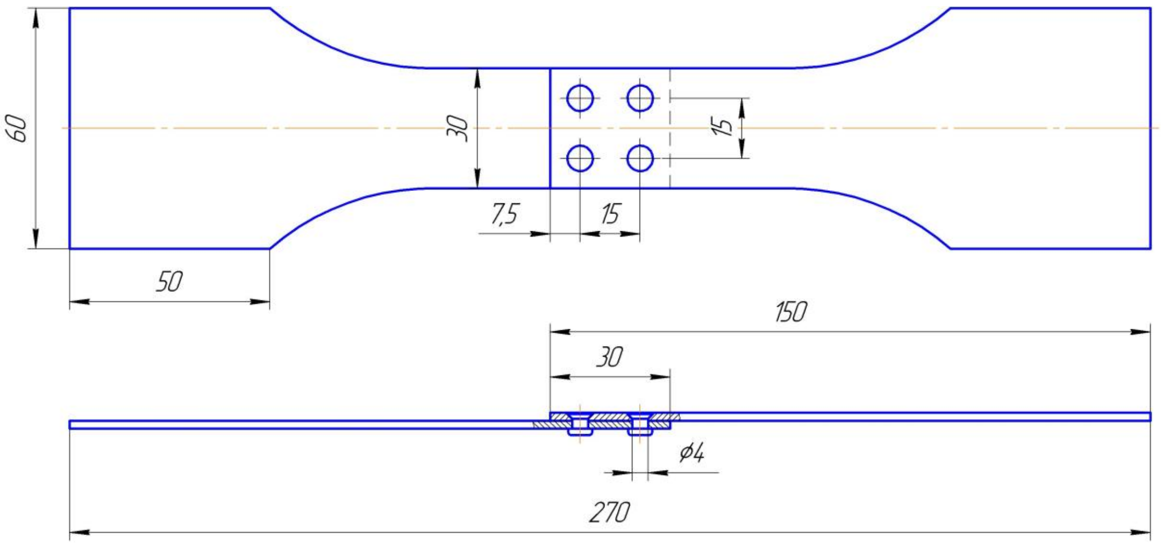


Figure 25. Standard specimen of double riveted lap joint (all dimensions in mm)

Dimensions of the hole in joined plates for installation of rivets with reduced 90°-countersunk head are shown in Fig. 26.

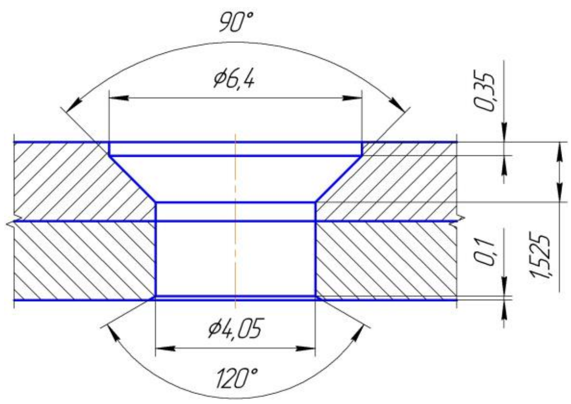


Figure 26. Dimensions of hole for installation of rivets (all dimensions in mm)

For the purpose of a standardized check of the mechanical load capacity of a riveting joint, destructive test series were carried out on selected test sheets (Fig. 27) which were manufactured in accordance with the following requirements [8]:

- The workpieces for the plates and straps of one lot should be produced from one sheet and cut along the rolled metal.
- The workpieces cut across the rolled metal have to be registered in the test report for the specimens and employed in the test data reduction.
- The layout of workpieces of the plates and straps should be conducted in compliance with the requirements of special industry documents.
- The rivets for the joints formation should be selected from the same lot.
- The specimens should be manufactured at the certain (unchanged) adjustment of the equipment and the instrument.
- The following parameters of the produced lot of the specimens should be verified: the specimens’ dimensions, the state of the unriveted rivets, the state of the surfaces of the plates and straps within the joints' zone and at the places of the specimen attachment in the testing machine.

- The state of the unriveted rivets, surfaces of the plates and straps should meet the requirements of the corresponding documentation.

The tests were conducted on the INSTRON 8802 Servohydraulic testing system (Fig. 27a) and BiSS Servohydraulic Universal testing machine (Fig. 27b).

The tests were carried out in accordance with [8]. This document requires the performance of strength tests for the mass adoption of new structures of rivets, the changed joint parameters as well as the riveted joints manufactured using new technologies in the process of production.

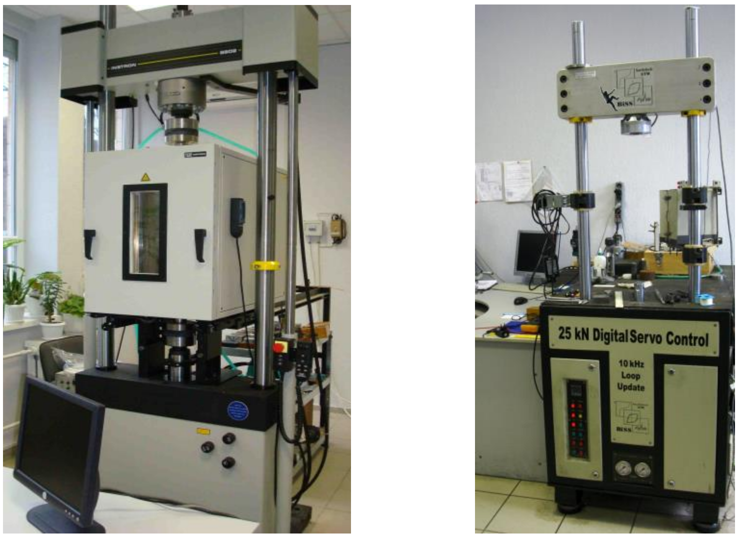
According to [8], for each static testing, no less than 5 pieces of the specimens must be provided. Each specimen must be numbered. No less than 7 pieces of the specimens at each stress level have to be manufactured to perform each type of fatigue testing.

The standard [8] establishes the methods for shear testing of engineering specimens of riveted joints for the unified assessment of the strength factors for joints formed by various types of rivets. The standard covers the following testing methods:

- static shear behaviour testing of the specimens of riveted joints;
- shear fatigue testing of the specimens of riveted joints.

The methods of shear fatigue testing of the specimens of riveted joints are assigned for the determination of endurance of the specimens under the action of alternating loads. The shear testing methods of the specimens involve the following types of tests:

- determination of the static strength of the specimens;
- determination of stiffness of the specimens.



a b

Figure 27. Test machines for standardized strength testing

The fatigue testing methods include the following types of tests:

- fatigue testing of the specimens;
- low-cycle fatigue testing of the specimens.

The fatigue testing of the specimens is aimed at the determination of fatigue limit of joints in the testing up to $1*10^7$ cycles. The low-cycle fatigue testing of the specimens is devoted to the determination of endurance of the joints within the range of large alternating stresses with $2*10^5$ cycles.

2.4.2 Model based assembly assistance and inspection (scenario 2)

For the use of digital model technologies for the highly flexible application of assistance and test functions in the assembly of technical assemblies, the digital product models of a representative assembly were imported into a test framework. This enables a largely automatic calculation of assembly sequences, visual assembly assistance functions and synthetic target states.

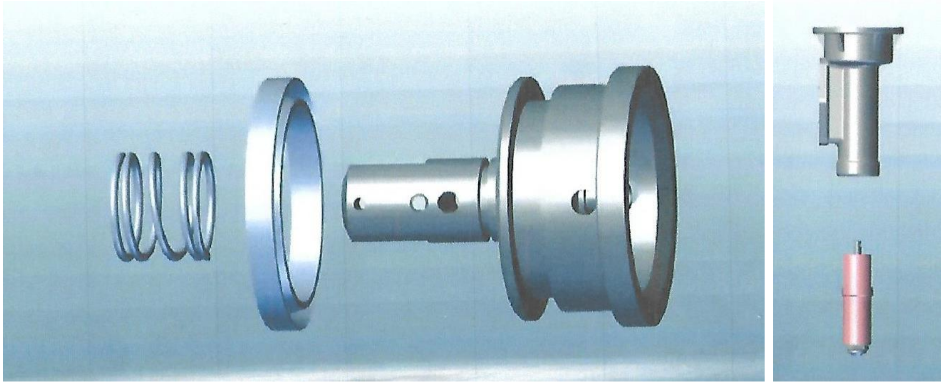


Figure 28. Assembly analysis of digital model information on FED assemblies

PJSC FED defined critical issues and presentations: “Assembly visualization”, “Assembly automation” in aviation industry.

The current development work focuses on organising the assembly process management through ERP-system and the implementing modules for the accounting of flows in assembly production and management of assembly production.

The “Visualization of assembly” was realized in different ways: augmented reality overlay of a wire frame of 3D CAD model with real-time camera image, interactive 3D visualization of a 3D model of the current assembly target state, instructions, feedback of deviations after optical inspection of the current assembly state. These functions were implemented in the technology demonstrator scenario 2 for the use case control cabinet assembly.

Publications:

[1] OST 1 34052-85. Countersunk head rivets ∠90° with crown-shape compensator. [In Russian].

[2] OST 1 34055-92. Reduced countersunk head rivets ∠90° with cylindrical compensator. [In Russian].

[3] OST 1.00016-71 Pitch of rivets in riveted seams. [In Russian].

[4] OST 1 34102-80 Rivets. Diameter of the holes, dimensions of shop head and selection of length. [In Russian].

[5] OST 1 34041-79 Riveted joints for automatic process. Radial tightness and selection of rivets length. [In Russian].

[6] OST 1 34104-80. Rivets. Technical requirements. [In Russian].

[7] PI 249-2000. Riveting of metallic structures. – Moscow: RIAT, 2000. – 151 p.

[8] OST 1 00872-77. Riveted joints. Test methods. [In Russian].

3. Pilot Project 3.3b: Manufacturing aerospace composite structures

3.1 Background to the pilot project

Leader: Fraunhofer, Support: UoM, UkrRIAT, FED, NASU and KhAI

The topic of the pilot project was to conduct a feasibility study of innovative hybrid metal-composite joints; including manufacturing, inspection, and mechanical characterisation. The specific novelties of the study are; the use of Electrical Discharge Machining (EDM) for the manufacture of metal parts, by FED, and use of the 3D woven fibre composites, by UoM. Activities involve definition and evaluation of test-case hybrid-joint specimens by KhAI, UoM and TECPAR. Mechanical testing of hybrid-joint specimens by NASU (G.S. Pisarenko institute for problems of strength). UkrRIAT will support this study by providing a review of research and technology in Ukraine concerning metal to composite joining. A parallel study is being considered to evaluate the compatibility of corrosion resistant aluminium and carbon fibre, using NASU (Frantsevich) developed materials.

Pilot Project 3.3b has assumed the working name of ‘Hybrid-joints’.

Description of Hybrid-joints

Detailed plan of activities within project 3.3b was discussed and agreed on July at UoM and after was corrected on project meeting on September in Warsaw.

According to plan KhAI was involved in manufacturing of surface structured metal inserts, hybrid joint specimens in cooperation with UoM and testing. Definition of the parameters of hybrid joint was performed in concordance with geometry of metal inserts and architecture of 3D woven preform.

Parameters of 3D fabric which was used for manufacturing of CFRP-metal hybrid joint are given in Table 3.1 and Fig. 29 as supplied by UoM.

Table 3.1: Properties of 3D fabric

Fibre type 0° direction	IM7 12K
Fibre type 90° direction	IM7 12K
Fibre type Z direction	IM7 12K
Type of interlock	Layer-to-Layer
Yarn count, warp	5
Yarn count, weft	6
Areal weight	3260 gm^2
0/90 ratio	50:50

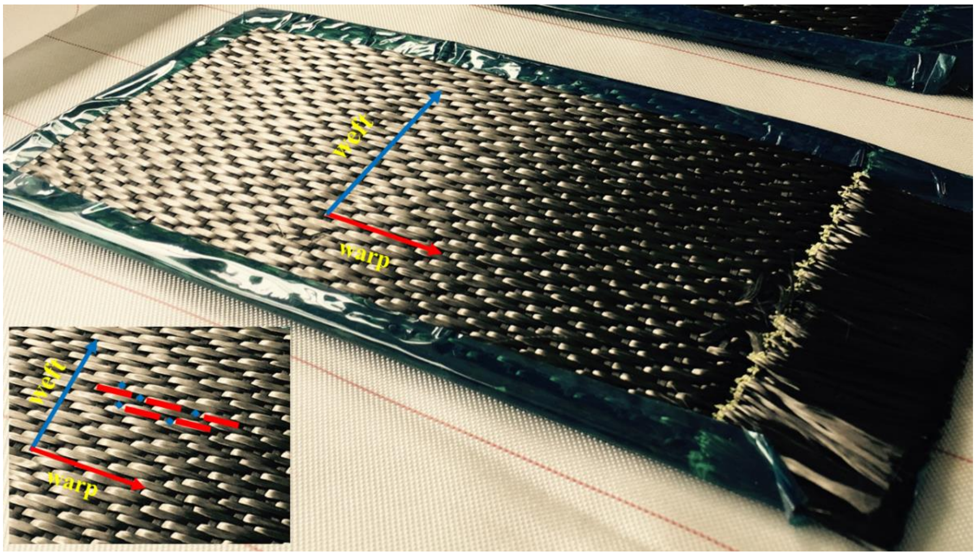


Figure 29. Woven 3D carbon fibre fabric used for Hybrid-joints

In current research various configurations of metal inserts were used, which allowed to investigate possible fibre damage during pin-embedding, the quality of impregnation by resin and abilities of pins to embed in tight 3D fabric architecture.

The first type of metal insert (Fig. 30a) was made of titanium alloy sheet of thickness 0.25 mm and consisted of a flat round base with two rows of pins placed in staggered arrangement along the edge of base. Pins are represented by simple rectangular section twisted along height of pin up to 50 degrees. Twisted shape of pins allows to increase the ultimate value of pull-out force value. Geometry of metal insert is shown in Fig. 30a.

The second type of metal insert (Fig. 30b) was made of a similar material. Pins were located inside the round base (instead on the edge of base like 1st type) and had a flat shape (not twisted along the height). The base of insert and pins had 4 times increased thickness (1 mm compared to 0.25 mm of 1st type). According to this, metal insert of second type had higher density of pin arrangement compared to first one, which affects the process of pins embedding into fabric.

a)

b)

Figure 30. Titanium inserts with twisted (a) and flat (b) pins (supplied by KhAI)

UoM is conducting research on crack detection in composite structures by acoustic emission methods and the use of optical fibres integrated into composites during manufacturing. A combination of studies, which will lead to improved defects monitoring and overcome the challenges arising during composite manufacturing as well as the life of the composite structures, by using optical fibre and piezoelectric sensors embedded in the structures at manufacturing stage.

Smart sensors like optical fibres and PZT transducers can be embedded or attached during the fabrication process for monitoring the resin infusion, capturing the residual strains (thermal strains) developed and measuring the strains and possible damage when in service.

Advanced methods improved by UoM will benefit collaborative UA partners to implement knowledge for crack and damage investigations under the topic structural health monitoring (SHM).

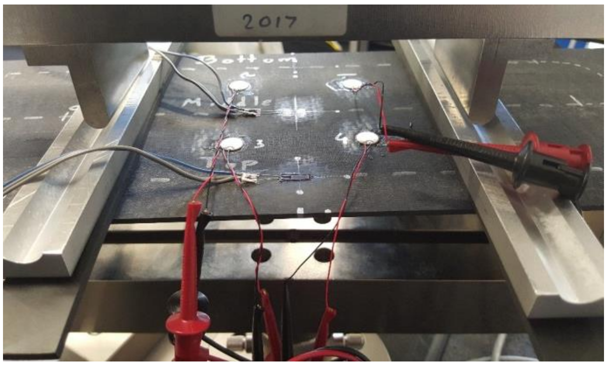


Figure 31. Embeded sensors during composite manufacturing for damage/stress-strain studies induced during manufacturing or later in service.

3.2 Knowledge exchanged

The following is a list of significant meetings and visits that have progressed Pilot Project 3.3b [composites manufacturing]:

- Kick-off meeting (11th & 12th October 2016), Hamburg
- Meeting between KhAI and UoM (10th December 2016), as part of British Council in Ukraine funded visit of KhAI to UoM
- Meeting at Fraunhofer IFF and tour (6th March 2017), Magdeburg
- Teleconference (27th March 2017)
- Consortium Meeting and tour of Antonov (19th & 20th April 2017), Kyiv
- UoM representative visits to NASU institutes: Frantsevich Institute for Problems of Materials Science, Pisarenko Institute for Problems of Strength, Paton Electric Welding Institute (21st April 2017), Kyiv
- Teleconference (6th June 2017)
- Working meeting hosted at UoM (3rd & 4th July), Manchester
- Working meeting hosted at UoM (21st & 22nd August), Manchester
- Skype meeting (17 July 2018) UoM, KhAI, IMC-NASU, IPMS-NASU, IPS-NASU - discussing upcoming workshop activity, topics and to know interests of partners
- “Composites in Action” workshop (18-25 November 2018), Manchester
- Consortium meeting and factory tour (May 2019), Zaporizhzhya
- Pilot projects meeting and tour of Ivchenko Progress (May 2019), Zaporizhia

The majority of effort towards Pilot Project 3.3b [composites manufacturing] has been to identify specific skills and interests of each partner and as well as a challenging project to come to a consensus between project partners as to a specific topic, scope of work, and work share, which will yield sufficient research output to generate at least one journal publication and one conference attendance.

AERO-UA Pilot Projects 3.1a, 3.1b, and 3.3b Working meeting, 3rd – 4th July, University of Manchester.

Attendees:

Prof Mojtaba Moatamedi	Aerospace Research Institute (UoM)
Dr Adam Joesbury	Aerospace Research Institute (UoM)
Dr Matthieu Gresil	i-Composites Lab (UoM)
Prof Prasad Potluri	Northwest Composites Centre (UoM)
Prof Constantinos Soutis	Aerospace Research Institute (UoM)
Dr Lina Smovziuk	National Aerospace University (KhAI)
Dr Fedir Gagauz	National Aerospace University (KhAI)
Dr Valeriy Fadeyev	Public Joint Stock Company (FED)
Dr Krzysztof Dragan	Air Force Institute of Technology (Tecpar)
Dr Michal Dziendzikowski	Air Force Institute of Technology (Tecpar)
Dr Iryna Bilan (via Skype)	Frantsevich Institute for Problems of Material Science (NASU)

AERO-UA Pilot Project 3.3b Working meeting, 21st – 22nd August, University of Manchester.

Attendees:

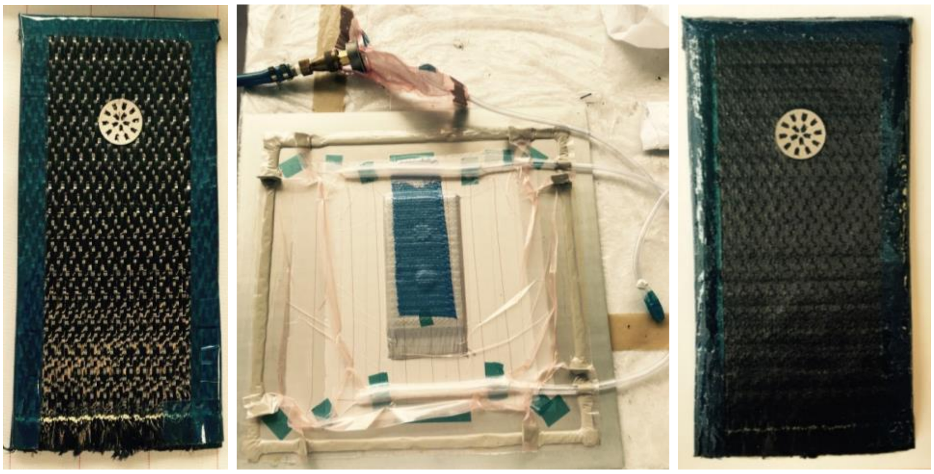
Prof Mojtaba Moatamedi	Aerospace Research Institute (UoM)
Dr Adam Joesbury	Aerospace Research Institute (UoM)
Dr Matthieu Gresil	Composites Lab (UoM)
Prof Prasad Potluri	Northwest Composites Centre (UoM)
Prof Constantinos Soutis	Aerospace Research Institute (UoM)
Dr. Georgii Kryvov	Ukrainian Research Institute of Aviation Technology (UkrRIAT)
Victor Shulepov	Ukrainian Research Institute of Aviation Technology (UkrRIAT)

3.3 Training provided

A researcher from KhAI visited UoM and was trained in facility on braiding, fibre placement and resin infusion manufacturing techniques. He also manufactured and further characterised samples of hybrid-joints as pilot project. A summary of the activity is scripted here below.

Manufacturing

Specimens (Fig. 32) were made at UoM with direct participation of KhAI team. Impregnation of 3D fabric with installed metal inserts was performed by the method of vacuum-infusion by resin RS-L135 with hardener RS-H137 mixed with weight ratio of 100:35. Pins of metal inserts were embedded into dry fabric on both (top and bottom) surfaces of 3D woven preform. Curing of the work-piece was done approximately within 5 hours with turned on of vacuum unit and heating of surface 60°C. Full curing cycle lasted 24 hours.



a) b) c)

Figure 32. Manufacturing of specimens: dry fabric with installed metal inserts (a), prepared tool for vacuum-infusion (b), impregnated specimen (c)

Microstructure analysis

Behaviour of metallic pins during the process of embedding into 3D fabric as well as analysis of the quality of subsequent impregnation by vacuum-infusion process, were carried out using a stereoscopic and scanning electron microscope (SEM). Microstructure analysis was performed at UoM and results are given in next section.

3.4 Scientific and technical results

Results of Hybrid-joints

Microstructure analysis was performed on 4 specimens (Fig. 33) with different cut-out sections of metal pins. Preliminary preparation of cross-section surfaces was carried out by cutting, grinding and polishing.

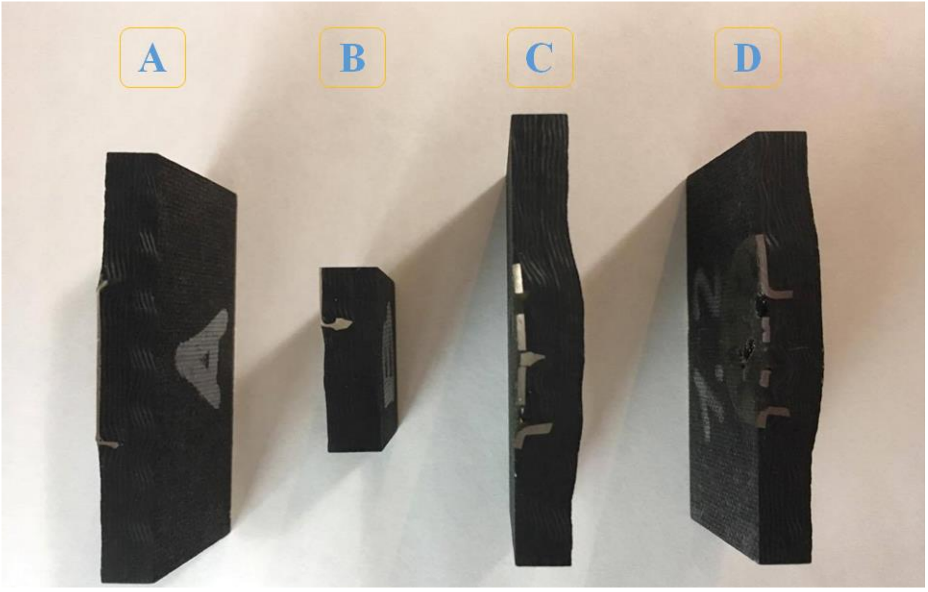
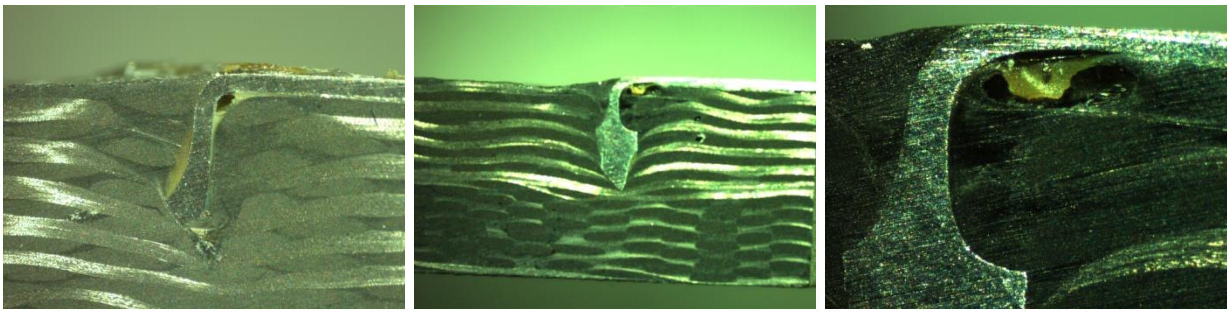
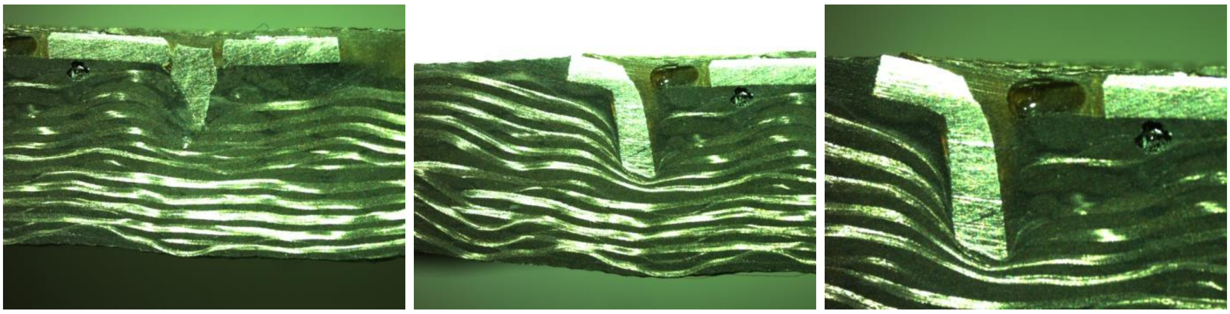


Figure 33. Cross-sections of hybrid metal-CFRC joint specimens in the zone of pin embedding

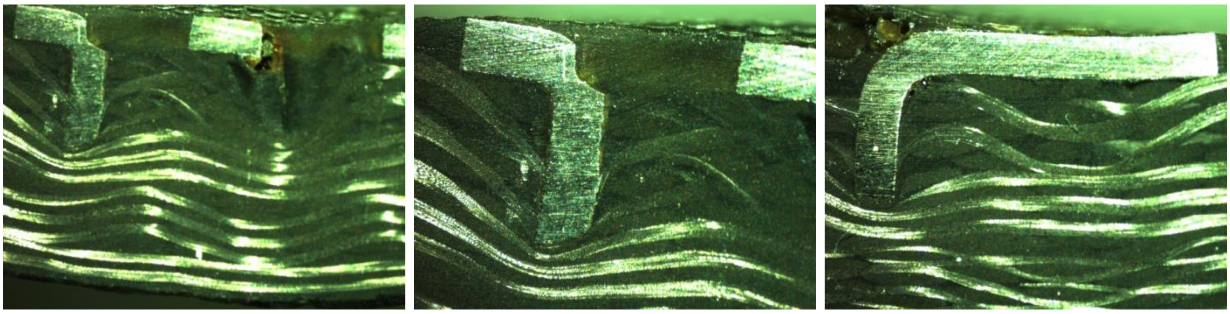
Stereoscopic images of specimens' sections are presented in Fig. 34. Section (a) shows the zone of 3D fabric with embedded pins of type 1. It should be noted, that embedded pin have been bent due to low stiffness (Fig. 34a). Although, small thickness allows penetration into the fabric without significant resistance and dissect the yarns (fibres) encountered on the path, which does not cause curving of fabric layers.



(a)



(b)



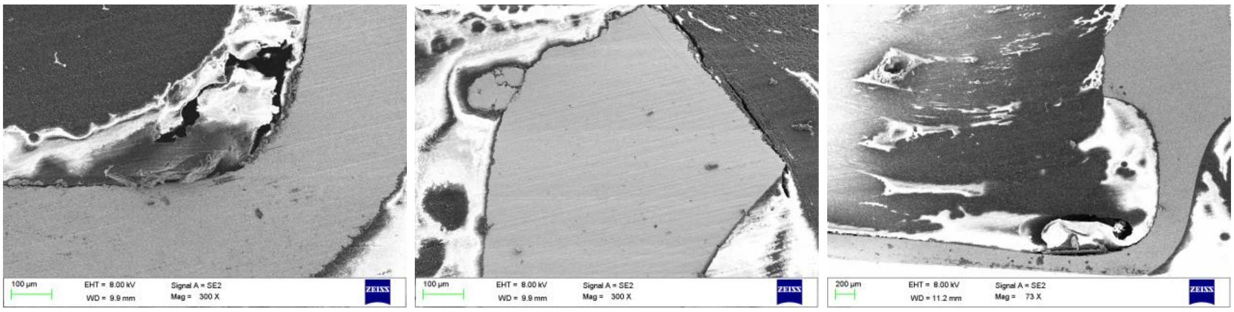
(c)

Figure 34. Stereoscopic microphotographs of pin's sections

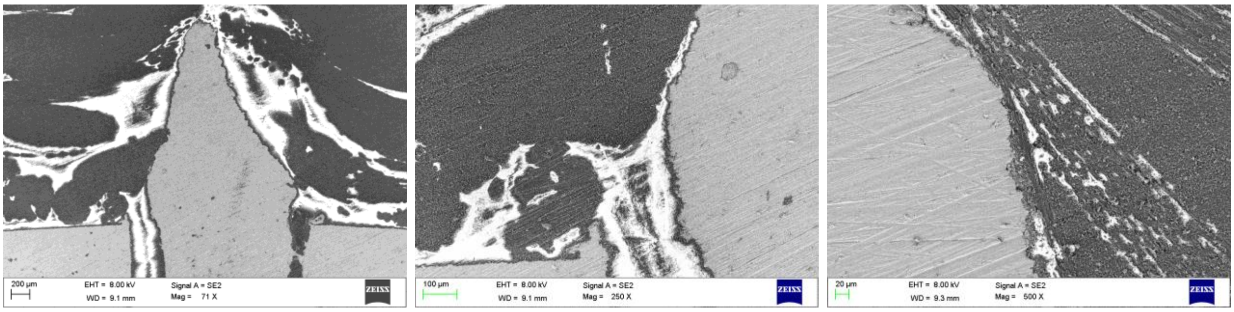
Defective zone localized at the base of pin (see Fig. 34a) is the air microscopic bubble formed in consequence of insufficient moulding as well as shape of pin. The twisted shape makes it an obstacle for moving the resin and caused a local inhibition, resulting in non-impregnated areas. Another reason of such defect (air cavity) can be higher impregnation speed and the presence of air in the vacuum system (in tubes and vacuum bag).

For the second type of pins (Fig. 34b & 34c), the deformation of the fibres is characteristic (pulling of layers out of plane). This is due to the high arrangement density of the pins on the base and their increased thickness. As a result, the only parts of the fibres are dissected and the remaining ones are deflected. When there is a lack of space in the volume of material, the fibres protrude outward (see Fig. 34b & 34c).

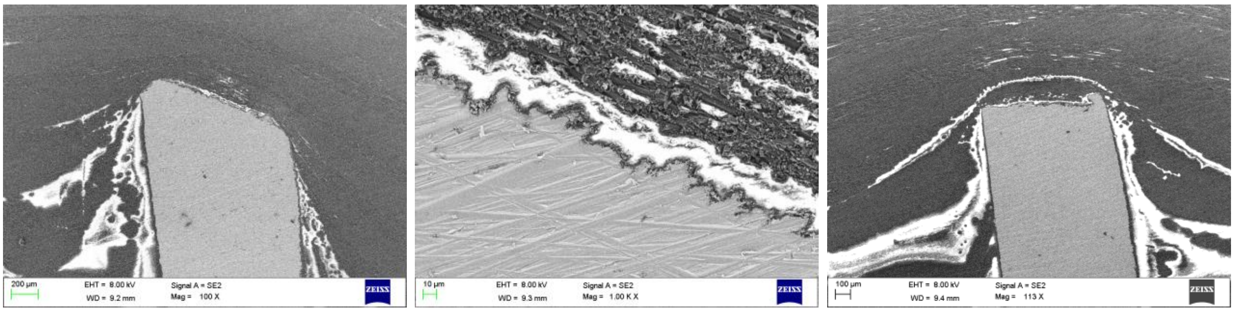
Inspection with SEM studies also demonstrates the presence of air cavities at the base of pins, as well as local damage of pin-CFRP interface at the tip of pin (Fig. 35a). In SEM analysis, it is clearly visible interlayer which represents the surface treatment of metal inserts by special adhesive for increasing of metal-to-CFRP adhesion (Figures 35b).



(a)



(b)



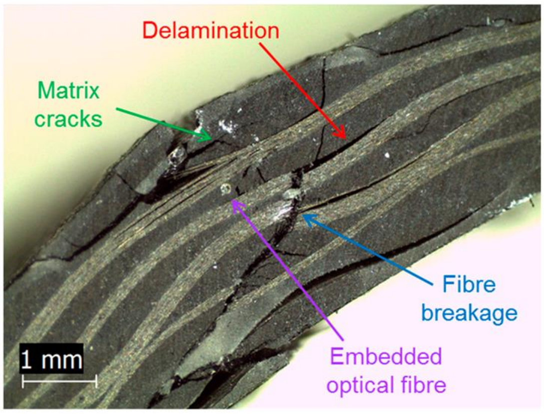
(c)

Figure 35. SEM microphotographs of pins' cross-sections

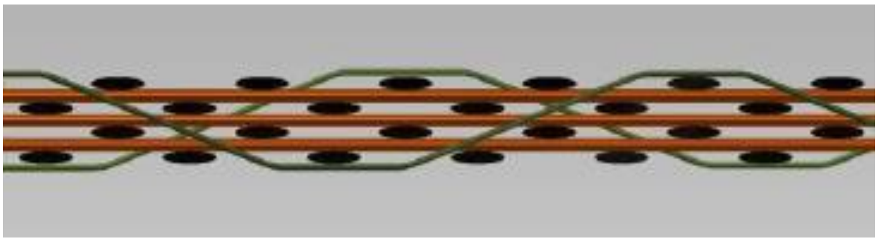
Section of pin (type 2) shows the absence of micro-cracks between the metal and composite. The pin is in tight contact with fibres, which should positively affect the electrical conductivity of the joint with such shape of pin. This effect can be explained by the sharp tip of pin and non-twisted configuration. The disadvantage is the tightening of the fibres along the pin (not the dissection), in consequence of which the deflection of reinforcing material is occurred.

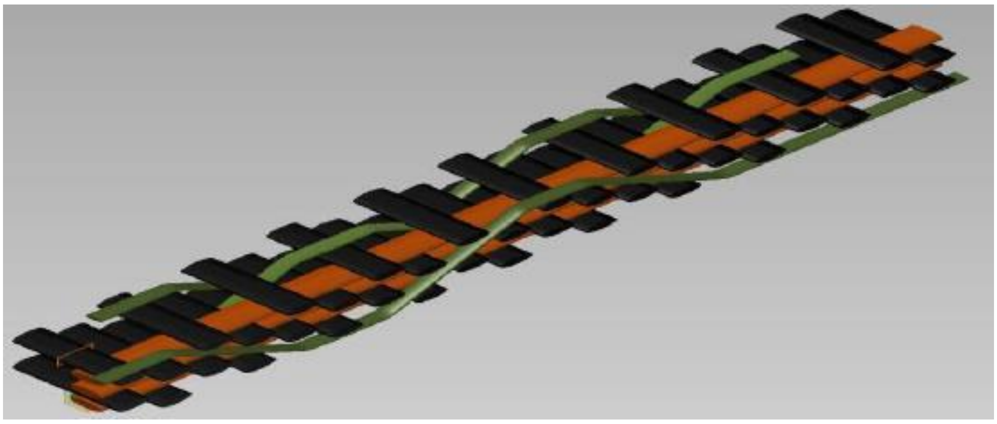
Other Publications:

1) *Early damage detection in composites during fabrication and mechanical testing*, N. Chandarana, D. M. Sanchez, C. Soutis and M. Gresil. Materials. 10, 7, DOI:10.3390/ma10070685



2) *Matrix crack detection in 3D angle interlock GFRP using acoustic emission (manuscript), M. Gresil, M. N. Saleh, C. Soutis.*





3D Angle Interlock Woven Composite (through thickness and planar view)

3.5 Dissemination

After completion of the manufacture of hybrid joints, two papers have been accepted for presentation at the 9th EASN conference, which will take place on 3-6 September 2019 in Athens, Greece. The two pieces of work are a joint effort between EU-UA partners. The abstracts for both presentations are provided below.

Characterisation of CFRP-titanium local reinforcement

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The use of fibre reinforced polymer (FRP) composites is widely accepted as an approach for reducing aircraft structural weight. However, current design and production trends suggest that FRP composites may never entirely supersede metals due to many reasons, such as their inability to withstand high concentrated loads in mechanical (bolted or riveted) joints because of their low interlaminar and bearing strength. The use of 3D fabric preforms for manufacturing composites is one method of improving the interlaminar strength. It is also possible to produce different fibre architectures in this way. A commonly used approach for increasing the bearing strength of composites in the regions in which fasteners, such as bolts and rivets, would be installed is the inclusion of metal foils within the laminate, resulting in hybridisation of the structure. This is an effective method, but requires the fabrication of composites from discrete fibre layers, such as dry or pre-impregnated materials. In the case of 3D fabric preforms, it is not possible to insert these metallic foils.

A more appropriate method to improve the local bearing strength of 3D woven composites is through installation of metal washers with transverse micropins during the lay-up process. Following this, the composite can be cured; bonding the metal insert in position. There are a number of possible problems that can arise during the manufacture of this type of "locally hybrid" material by resin infusion associated with poor-quality impregnation of the fabric in the region where metal micropins have been embedded, due to tight packing of the 3D-fabric architecture under vacuum. The present work, therefore, will focus on characterisation of the quality of this type of 3D reinforced hybrid composite/metal joint.

Two specimens were manufactured by embedding metal inserts into the surface of 3D-woven carbon-fibre preforms. The hybrid specimens were consolidated with epoxy resin using vacuum-assisted resin infusion. Titanium inserts were used to form these mechanical joints. Two different types of metal washers are considered in this work, with varying thickness (0.25 mm or 1 mm), shape of micro-pins (twisted or untwisted), and arrangement of pins (along the edge of the washer or covering the full surface). After curing, stereoscopic and scanning electron microscopy were used to analyse the effect on fabric architecture of embedding these micro-pins into the 3D preform, as well as to study of the quality (homogeneity) of subsequent impregnation by the resin infusion process.

Keywords: *Composite materials, 3D-woven fabric, hybrid joints, micro-pins*

Adhesive strength characterisation of titanium-composite joints

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The use of composite materials in primary aircraft structures, such as the fuselage and wings, represents one of the most efficient methods for weight reduction in the aerospace industry. At the same time, in the mentioned constructions there is still a significant amount of metallic elements. Titanium and its alloys are used commonly in the industry, so it is crucial to develop suitable methods for fabricating hybrid structures that combine the metallic and composite elements, to replace the classic non-detachable joints such as welding and rivets.

In the present study, two types of joints are manufactured and tested: titanium/titanium and hybrid titanium/composite adhesively bonded specimens. The shear strength of the adhesive bond is measured during lap-shear testing. Improvements in shear strength are achieved by the inclusion of mechanical surface treatments prior to bonding. The improved adhesive strength led to a 30% increase in the maximum stress of the joint.

Keywords: *Hybrid joints, shear strength, lap shear, adhesive bond*

4. Progress with respect to WP3 performance indicators

Work Package (High-Level Objective)	Performance indicators	Amount achieved by project end (M36)	Target by end of project (M36)
WP3. EU-UA aviation research knowledge transfer pilot projects **(High-Level Objective 3)**	• No. of short term staff exchanges about manufacturing joints • Feasibility study on manufacturing joints • No. of short term staff exchanges about manufacturing aerospace composite structures • No. of trainings on manufacturing aerospace composite structures	17 1 21 28	> 8 1 > 8 > 5

Completed visits:

- **11-12.10.2016, Hamburg** - ***AERO-UA Project Kick-off Meeting***
- **19-20.04.2017, Kyiv** - AERO-UA Project Meeting, visit to Antonov factory airport , 401 plant and PIPS NASU
- **20-22.09.2017, Warsaw** - AERO-UA Project Meeting, visit to ITWL, WZL-4, Warsaw University of Technology
- **29.05-1.06.2018, Kharkiv** - AERO-UA Project Meeting
- **19-23.11.2018 Manchester** - Ivchenko specialists visited the University of Manchester and participated in the “Composites in Action” workshop and in a workshop on the dynamics of machines, in particular aircraft engines, aimed at getting acquainted with the achievements of the dynamic analysis group of the University of Manchester and to initiate research cooperation
- **4-7.12.2018, Toulouse** - AERO-UA Project Meeting;
- **24-26.04.2019, Zaporizhia** - AERO-UA Project Meeting;
- **1-2.09.2019, Athens** - ***AERO-UA Final Project Meeting***.