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D3.3 Mid-term progress report on pilot projects in aerospace manufacturing

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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 a 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 processing allows short-term visits between the EU and UA partners, in order to exchange knowledge, receive training and/or conduct feasibility studies. Two pilot projects are 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 original 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 performed potential analysis of the aerospace components manufacturing process, the consortium partners defined two scenarios: sensor controlled riveting process (scenario 1) and model-based assembly assistance and inspection (scenario 2).

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

Partner roles in scenario 2 are: 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 M18:</u>
- A potential analysis for the production technology riveting process was carried out.
- A potential analysis for the assembly process of high quality flight control systems was carried out.
- Test cases for the riveting and the assembly process were defined.
- Fasteners for the riveting process were selected.
- The requirements for a quality-controlled riveting process were defined.
- The requirements for a highly flexible assistance and testing system for assembly were defined.

Pilot Project 3.3b:
The original 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 purpose, 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. Curing of the work-piece was done approximately within 5 hours with turned on of vacuum unit and heating of surface 60°C, while full curing cycle lasted 24 hours. Stereo/optical and scanning electron microscopic characterisation was conducted on joints to study impact of insert design on quality of impregnation by infusion process and generated localised defect zones.

Metal inserts used in this case-study were manufactured by UA partner 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 M18:</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

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 have 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 have defined the technological topics that are of particular relevance for improving competitiveness in Ukrainian aircraft manufacturing.

As a result of this process, two scenarios have been 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 from the main kinds of permanent joints, which are used to assemble the constructions of aeronautical vehicles.

Under the quality of a riveted joint it should be understood the correspondence of the following list of conditions to the nominal values, namely: 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 rivet's intensive deformation; the saving of product's theoretical shape after the joint's creation. A failure in the implementation of any demand results in unavoidable rework of joint, which, in one's turn, results in considerable timetable (such a timetable is comparable to the timetable of 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 process. This characteristic puts some additional limitations on peculiarities of incoming, inside and outcoming inspection to warn timely against possible defects.

The technological process (Fig.2.1.a – 2.1.f) of a simple riveted (R) / bolt-riveted (BR) joint creation is the sequence of the following operations to be executed: 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; defects correction in the case of their presence.

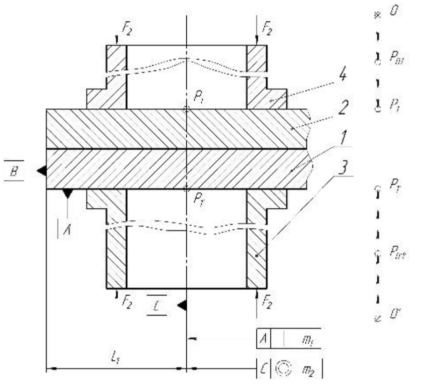


Fig.2.1.a Fixation

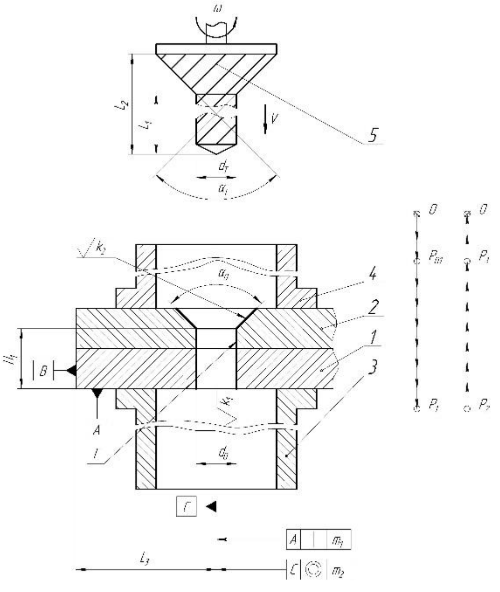


Fig.2.1.b Drilling-Countersinking

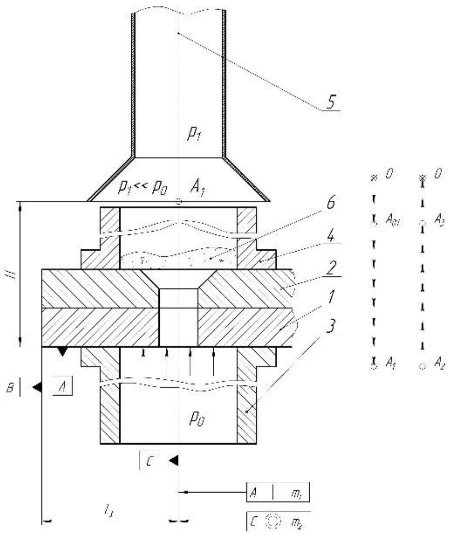


Fig.2.1.c Removing of shavings

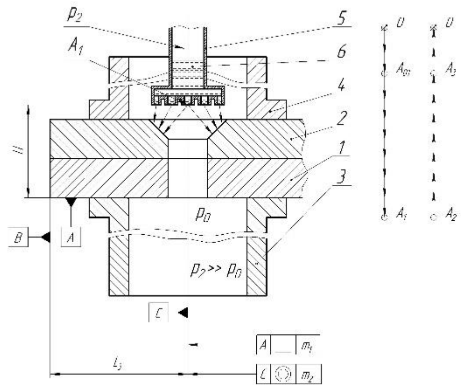


Fig.2.1.d Sealant spreading

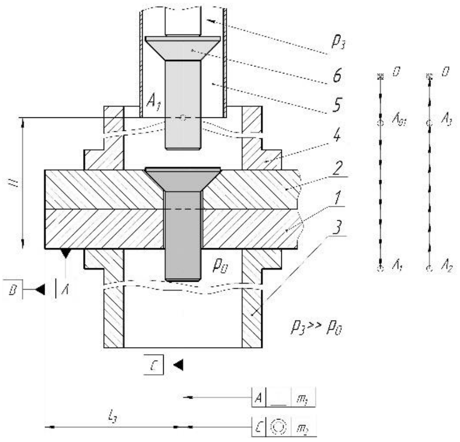


Fig.2.1.e Rivet installation

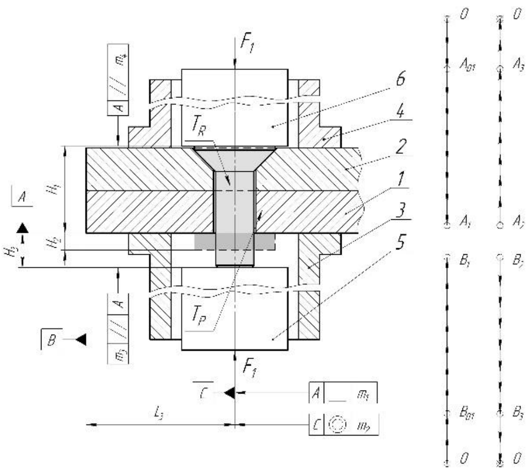


Fig.2.1.f Joint creation

The essence of control comes to collection of the data about the geometry of setting and closing heads of controlled rivets (Fig.2.2) and about the location of skin surface relatively to the rivet. Further the analytical comparison of collected data with the given data is providing. In case of controlled parameter oversteps the limits of values – the decision about following actions to exclude the defect makes.

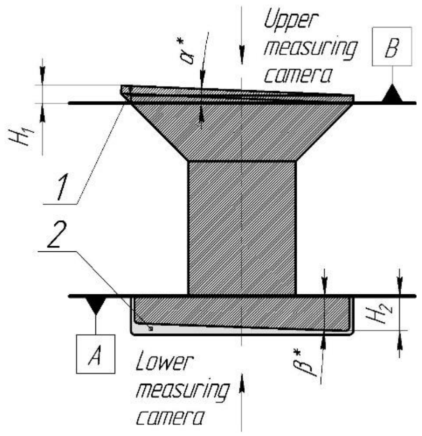


Fig.2.2 Evaluation

Prepared on the basis of Fraunhofer's experience with rivet head measurement systems designed for different types of BRÖTJE Automatic Riveting Machines, a technical concept has been prepared by Fraunhofer.

This technical concept of the »Rivet Head Measurement System« is modular designed. It can be adapted to different types of BRÖTJE Automatic Riveting Machines with low 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.2.3**).

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

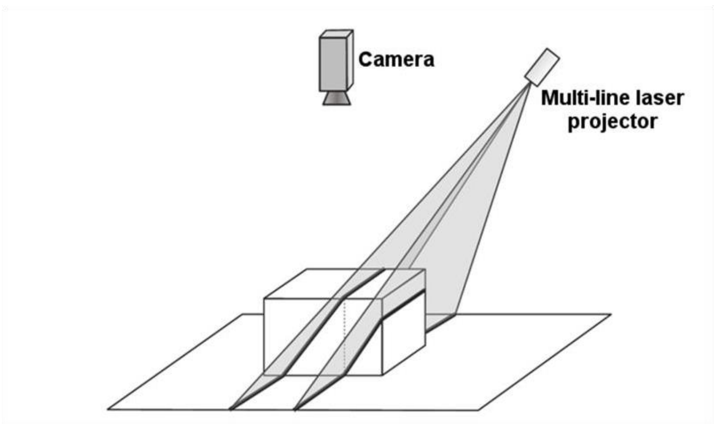


Fig.2.3 Principle of the height measurement for the setting head

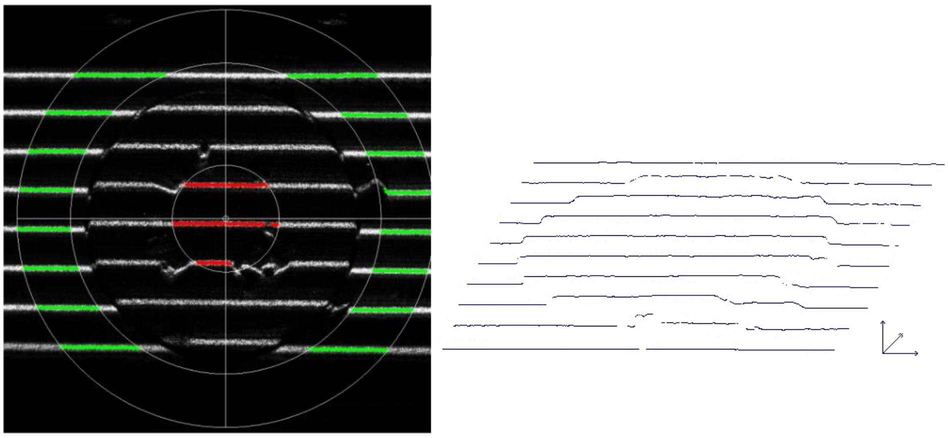


Fig.2.4 Measuring data for the height measurement

The position of the drilling axis and therefore the middle axis of the rivet is known out of the calibration, so that for the evaluation only these measuring points are used, which are closest to the middle of the rivet (red marked in figure 2.3). The reference to the fuselage shell will be made via measuring data outside of the rivet (green marked in figure 2.4). 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 cycle period of riveting machine is only extended minimally.

The measurement system has the ability due to its vertical assembled measuring camera above the work level to detect circular objects in the area of the pressure die bush and to calculate a correction value to a required position (look at figure 2.5). The measurement inaccuracy during the assignation of the centre point is less than ±0.05 mm.

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

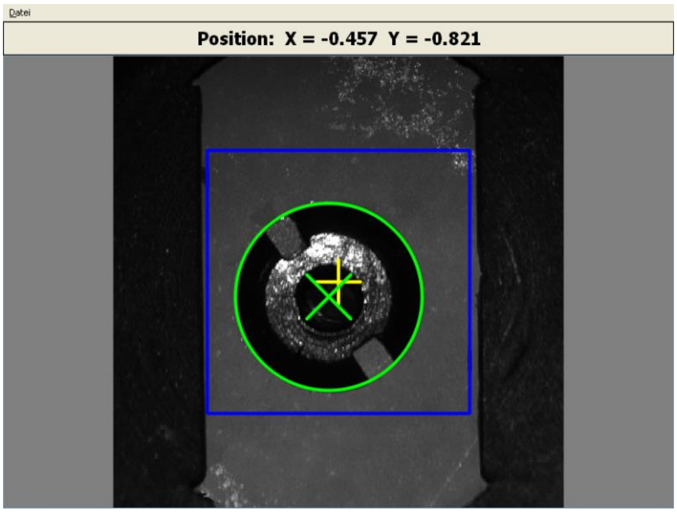


Fig.2.5 Reference position

The implementation of automatic control elements, which could realize in on-line mode the mathematical estimation of geometrical input parameters of fasteners and assembly units operatively to interfere in process by changing of process parameters, is one of the ways to improve the quality of a riveted joint.

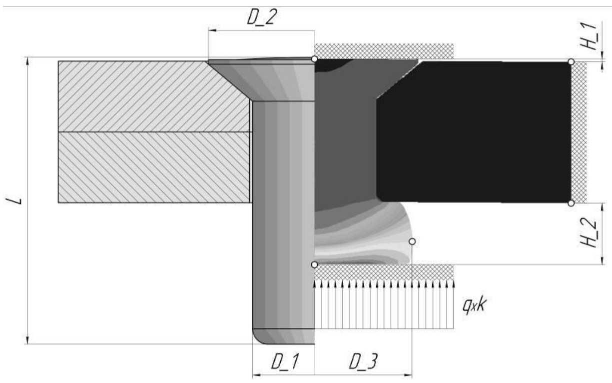
To create such control elements, it is necessary to have an exact mathematical description of the process which should be realized. This leads to a strict analytical forecast of process's behaviour during the changing of one or more input parameters within the bounds of known areas of possible variations.

On the base of the unknown character of values alteration of a-priori selected technological and design factors, which influence the process of creation of a riveted joint between two solid plates with small thickness, define the characteristic relations (F_1, F_2, F_3) 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 correspondently (Fig. 2.6).

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, the yield point, Poisson's coefficient, strengthening modulus are set). Both plates have an opening of known diameter. The opening in 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 law [1, 2]). The ends of the plates have a fixed bearing. In the opening of the plates there is the rivet, made from aluminium alloy (the mechanical properties of 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 countersink in upper plate. The top point of setting head stays in contact with a rigid, flat and fixed tool. The bottom surface of pin stays in contact with a rigid, flat and movable tool, which has an opportunity to move towards the upper tool by means of applied pressure q (Fig. 2.6). 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. 2.6). The difference between the location of upper (bottom) referenced marks and referenced marks of fixed points of upper (bottom) plates (Fig. 2.6) defines the required values of protrusion of setting and closing head of 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

Fig.2.6 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. 2.6) stipulates the necessity of the creation of 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. With the aim of reduction of solving time, in consideration of axial geometrical and physical parameters (loads) symmetry, there was made a decision 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, gained from natural experiment [3], which was provided with the help of a high-sensitive optical system. It measured the geometrical place of points of the deformable specimen with the necessary level of accuracy.

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

The numerical, multi-factor experiment for definition of noted equations (F_1, F_2, F_3) 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 at Fig. 2.6. The matrix of full uniform-rotatable two-degreed plan is not shown because of lack of space. The required functions are represented in form of a two-degreed polynomial view [6]:

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

Where

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

The coefficients of regression $b_{0,i,l}$ was defined analytically according to [6] and placed in table

Y	B0	B1	B2	B3	B4	B12	B13	B14	B23	B24	B34	B11	B22	B33	B44
H_1	+7,640	+0,002	+0,006	+0,007	+0,228	−0,004	+0,001	+0,003	+0,001	−0,003	+0,001	−0,011	−0,015	−0,013	−0,022
H_2	+0,128	+0,016	+0,000	+0,000	+0,000	+0,000	+0,000	+0,000	+0,000	+0,000	+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	−0,001	+0,000	+0,001	−0,003	−0,005	−0,004	−0,003	+0,011

The final decoding of the gained 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 following view:

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

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

The value of mistake of mathematical forecast in researched area (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.

Publications:

[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 Figure 2.7).

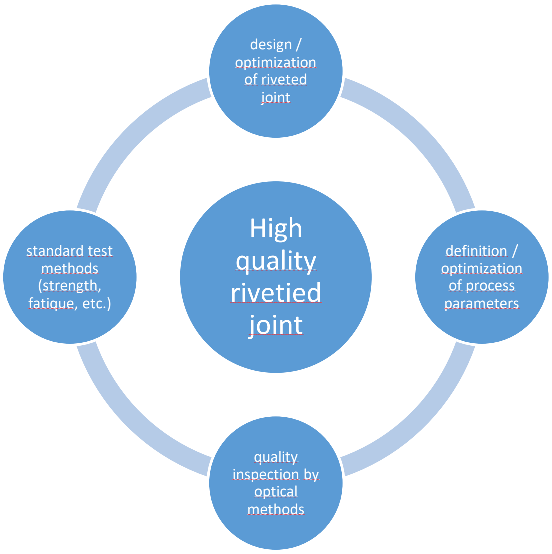


Fig.2.7 Model of quality-controlled riveting process

2.1.2 Model-based assembly assistance and inspection (Scenario 2)

The desire for customization in our society is also confronting industrial assembly with new challenges. 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.

<u>Flexibility through Digital Models</u>
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 delivers 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 much the same 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. Up to 40,000 rivets hold each of an airplane's twenty fuselage sections together. 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 extremely expensive at times.

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. 2.8). It generates high-resolution measured data on a real attached part's stage of assembly reliably from every position. The system extracts the requisite information from the 3D CAD data available for the fuselage section. They specify the intended outcome and contain 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.

Fig.2.8 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 green (fig. 2.9). It marks discrepancies red (fig. 2.10), and ambiguities yellow. The user can view different interactive evaluations in the test report. The system delivers not only photos of the parts but also coordinates to locate the part concerned quickly for rework.

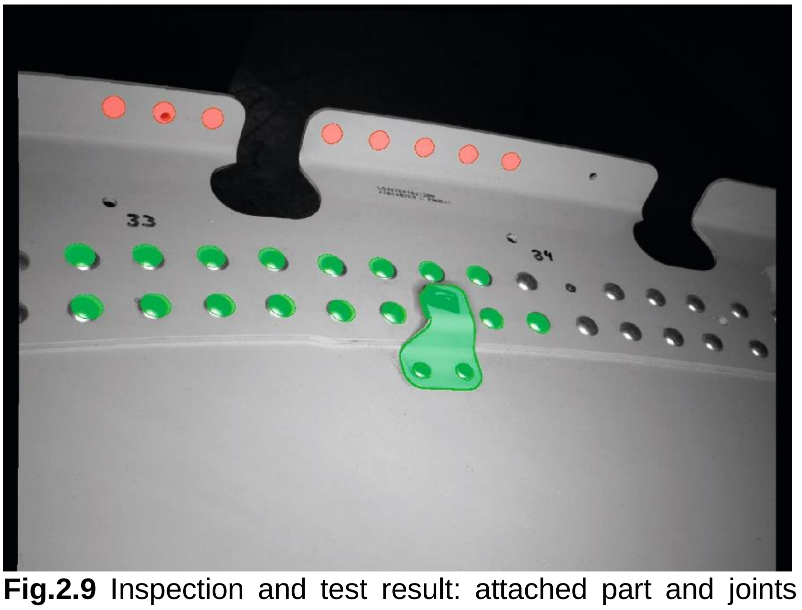


Fig.2.9 Inspection and test result: attached part and joints correct, some missing joints and missing boreholes

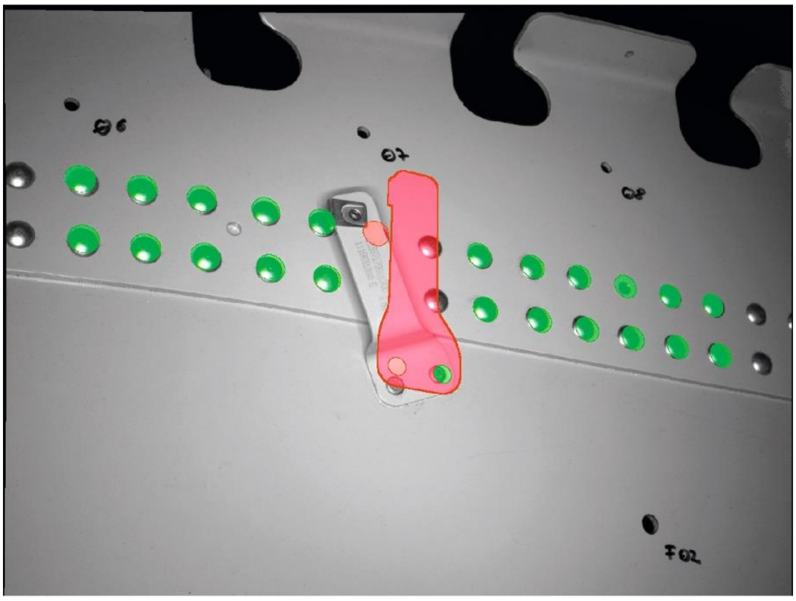


Fig.2.10 Inspection and test result: skewed attached part, correct joints

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 (TCF) 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 (see fig. 2.11) developed a manually guided inspection assistant. It 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, fourteen 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. An entire TCF has been inspected after approximately five minutes and twelve positions.

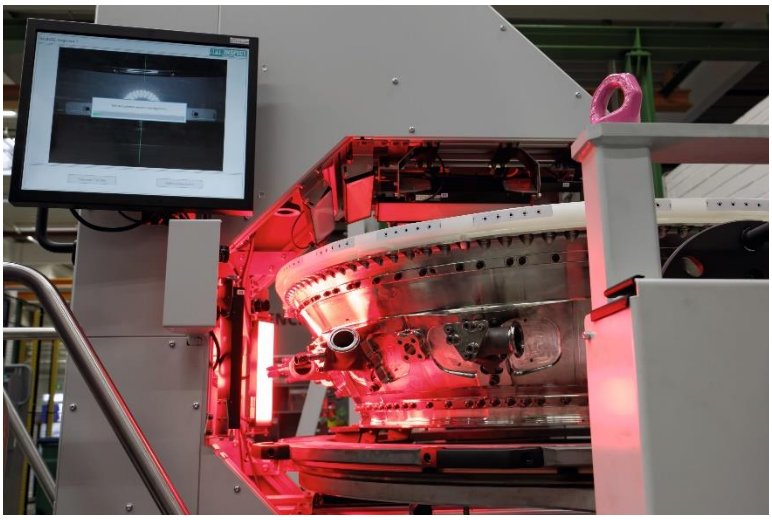


Fig.2.11 Assistant for TCF module assembly inspection

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 lock wires. 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 and, if so, where rework is still required (see fig. 2.12 and 2.13).

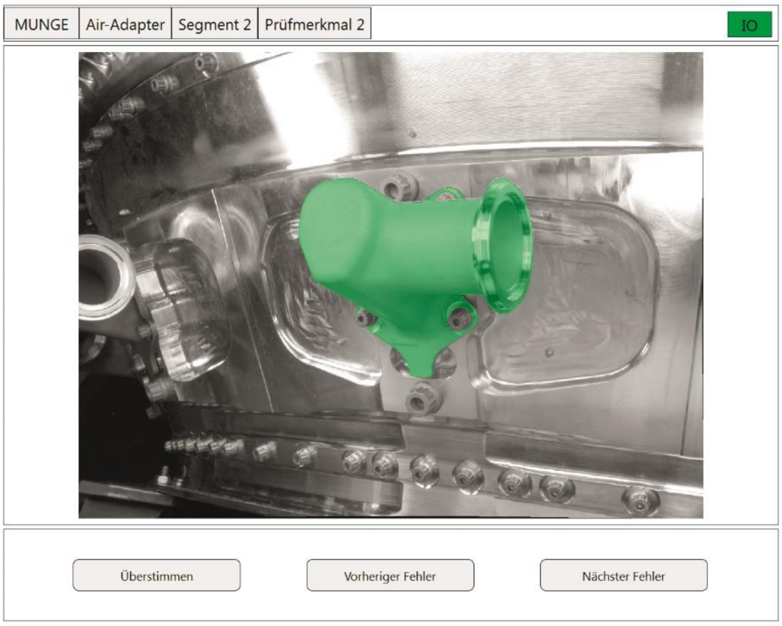


Fig.2.12 Inspection and test result: correct assembly

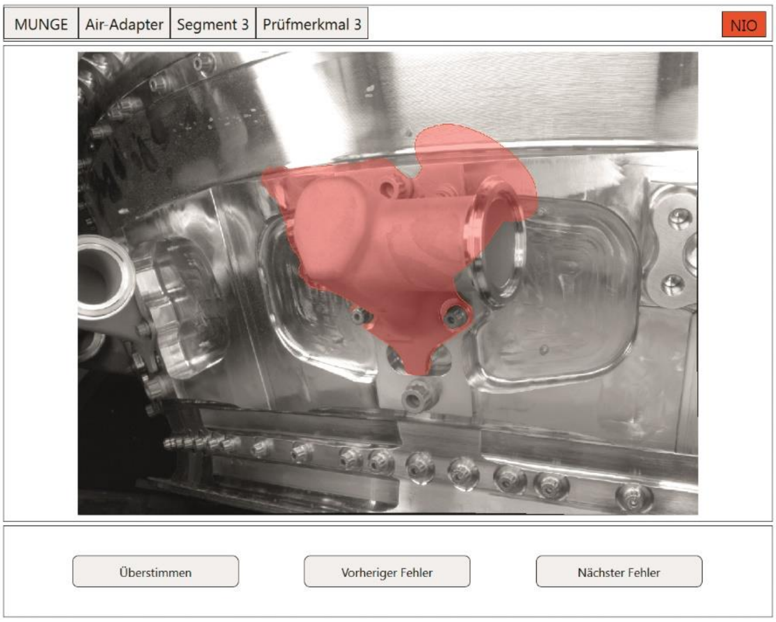


Fig.2.13 Inspection and test result: faulty assembly

<u>Conclusion</u>

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 documented as changes in the CAD model, for instance. 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%.

2.2 Knowledge exchanged

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

- Kick-off meeting (11th & 12th October 2016), Hamburg
- Meeting between KhAI and Fraunhofer (29th November 2016, morning session) concerning scenario 1, Kharkiv
- Meeting between FED and Fraunhofer (29th November 2016, afternoon session) concerning scenario 2, Kharkiv
- Meeting between IPS and Fraunhofer (30th November 2016) concerning scenario 1, Kyiv
- Meeting between UkrRIAT and Fraunhofer (1st 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 (6th March 2017), Magdeburg
- Networking Conference “13th International Scientific Conference AVIA 2017” hosted by the National Aviation University (19th April 2017) for the presentation of scenario 1 and 2 of pilot project 3.3a, Kyiv
- Consortium Meeting and tour of Antonov (20th April 2017, morning session), Kyiv
- Technical Workshop for further work and knowledge exchange/transfer in the pilot consortium 3.3a (20th April 2017, afternoon session), Kyiv
- Consortium Meeting (21th September 2017), Warsaw
- Technical Workshop for further work and knowledge exchange/transfer in the pilot consortium 3.3a (22th September 2017), Warsaw
- Technical Workshop for further work and knowledge exchange/transfer in the pilot consortium 3.3a (19th January 2018), Magdeburg

The continuous cooperation of the partners was aimed at a continuous exchange of information, the continuous development of the defined concepts 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 summary of impressions is scripted here below.

Fig. 2.14 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.

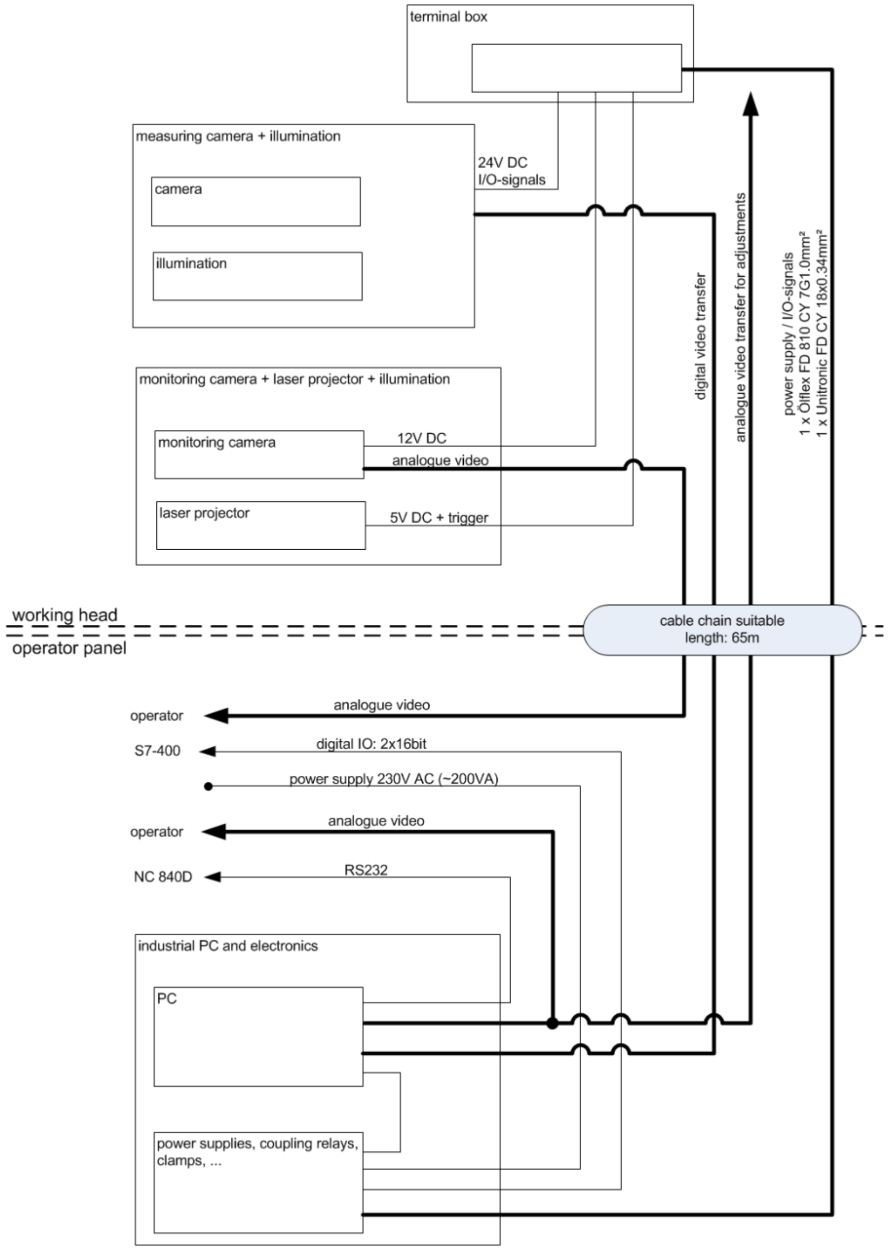


Fig.2.14 Inspection overview of wiring of the system components

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. Subsequent an image acquisition of 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 bush has to be dismounted for the calibration of the height measurement. On the level of the workline a calibration pattern shall be placed (figure 2.15). On the basis of the image acquisition automatically all necessary parameters will be calculated for the later on measurement procedure.

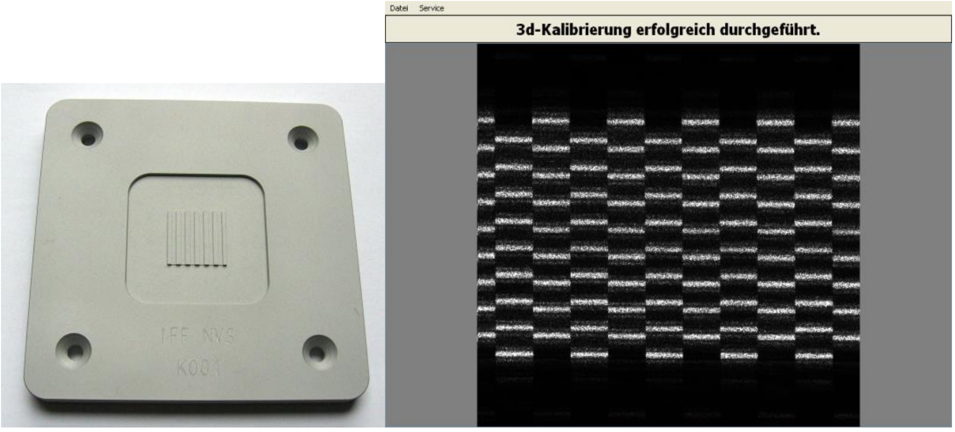


Fig.2.15 Calibration pattern for the measurement of the height of the rivet head

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 summary of impressions is scripted here below.
Training measures were carried out at a reference workplace (see fig. 2.16) using technologies of a stationary augmented reality-based assembly assistance system. Subject matter was the structure, functionality and implementation of representative assembly steps.

Fig.2.16 Reference workplace for manual assembly operations

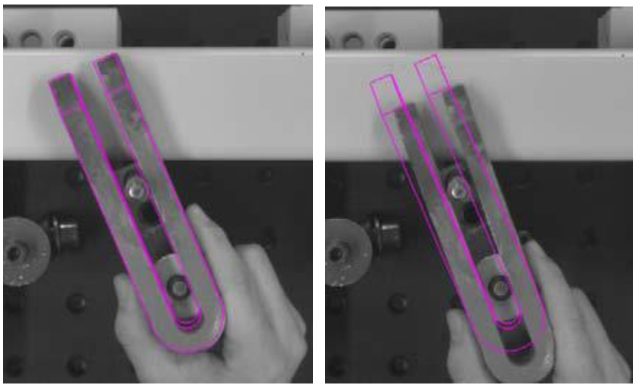


Fig.2.17 Assembly assistance using augmented reality technology

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 are the basis for feasibility studies to be carried out in the next step 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 industry standards OST 1 (transliteration from Ukrainian codding OCT 1). These standards prescribe materials and geometry for different types of rivets (solid-shank, tubular, semi-tubular, blind rivets etc.) to be used for joints manufacturing by means of manual and/or automated rivets 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. Riveting of composite structures is produced using steel rivets or rivets made 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. Last ones can vary by angle of countersunk head (90 and 120 degrees) depending of external plate thickness.

Load-carrying seams that are not located in the aerodynamic flow are performed preferably with universal-head rivets. For the rest part of the outer skin rivets should have countersunk head to guarantee necessary aerodynamic quality of the skin. If the sheet thickness of outer skin is less than the height of the countersunk head, then rivets with 120°-countersunk head should be used only or rivets with 90°-countersunk head with reduced height. 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 that 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 aircrafts protrusion of countersunk head over the outer surfaces of skin should not exceed 0.05 mm.

A significant disadvantage of countersunk head rivets is the low fatigue strength of joints subjected to cyclic loading. To extend fatigue life of riveted joints the special countersunk head rivets with compensator are used, that provide 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 perform high-strength and reliable riveted joints of the airframe elements, special rivets with countersunk heads were developed by Ukrainian aviation industry which have various compensators: crown-shaped, cylindrical, conical, etc. Below, example of national code is listed for rivets that are commonly used in Ukrainian aviation industry for performing of riveted joints [1, 2]:

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

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

Riveted joints, which are generally used in aircraft structures, could be of different types according to the 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 performed by double or triple riveted lap joint with adhesive sealing of seams (fig. 2.18, a).

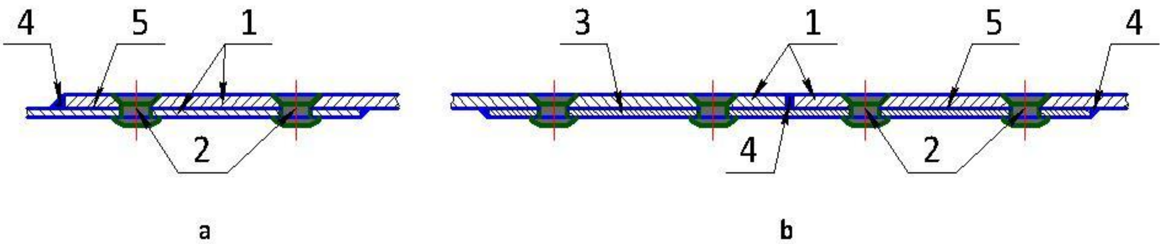


Fig.2.18 strong-tight riveted joints
a – double riveted lap joint; b – double riveted butt joint with single cover plate
1 – joined plates (skin); 2 – rivets; 3 – cover plate; 4 – sealant; 5 – sealant or adhesive layer

In the case of triple riveted lap joint, the middle row is used for stringers joining. Transversal (circumferential) joint of two fuselage sections is also adhesively sealed and performed by double or triple riveted butt joint with single inner cover plate (fig. 2.18, b). Maximum number of rows in multi-row riveted joints of thin-walled aerospace structures is not exceeding three.

Design procedure of riveted joints supposes fulfilment of strength constraints for joined plates and rivets. 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, rivet pitch in row and between rows are defined, they compared with standardized ones and accepted the final parameters. In 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 up to 1.8 mm. Diameter of rivets according to common practice should be meet to value defined as $\sqrt{2s}$, where **s** is summary thickness of joined plates. In load-bearing joints rivets less than 3 mm in diameter are not used. 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 joined elements.

The length of rivets also depends 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 last one is used for selection of rivets length applying for 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 damages and cracks, validate 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 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 over 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 that requires 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 in milling of excess material of protruded countersunk heads, which leads to removal of protective anticorrosion coating from the rivet heads and does not exclude of their damaging as well as of skin on the adjacent zones to the heads due to the tightening of skins during riveting.

On the base of this analysis for the case study forwarded to determining parameters and features of the measurement system for quality control of riveting process it is proposed to select double riveted lap joint (see fig. 2.19) of two aluminium sheets with thickness 2 mm joined by anodized aluminium rivets in diameter 4 mm with reduced 90°-countersunk head with cylindrical compensator (OST 1 34055-92). Diameter of countersunk head is 6.4 mm, requirement on maximum protrusion of countersunk head above plate surface – 0.05 mm.

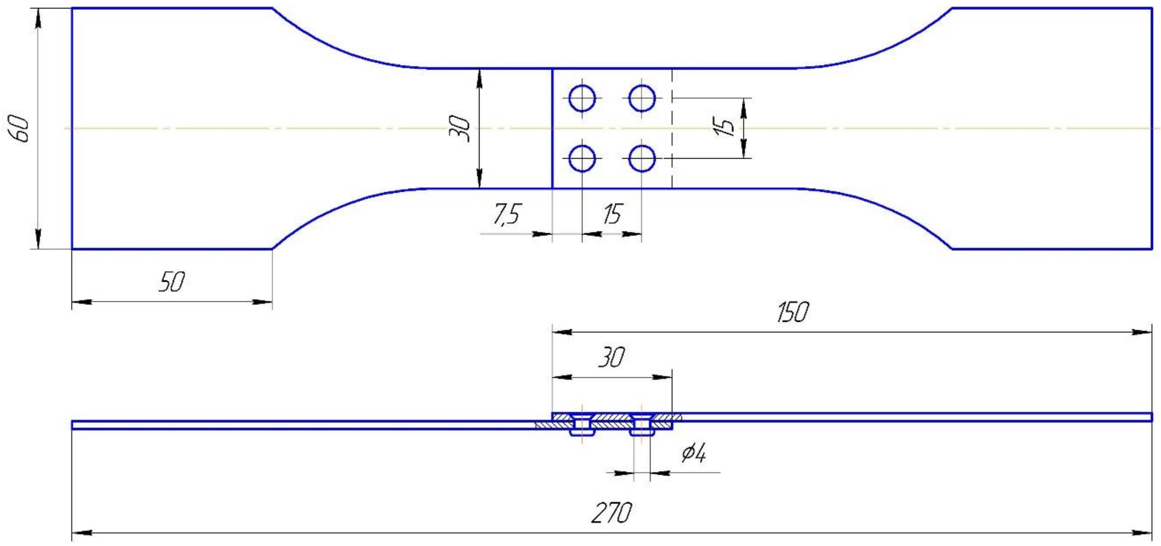


Fig.2.19 Standard specimen of double riveted lap joint (all dimensions in mm)

Dimensions of hole in joined plates for installation of rivets with reduced 90□-countersunk head are shown on fig. 2.20

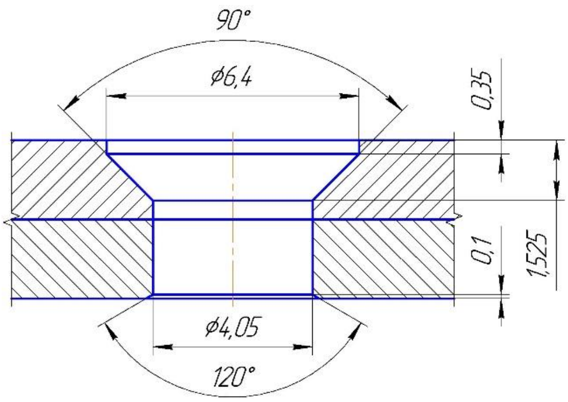


Fig.2.20 Dimensions of hole for installation of rivets (all dimensions in mm)

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.2.18) which were manufactured in accordance with the 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 specimens 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 servo-hydraulic testing system INSTRON 8802 (Fig.2.21a) and servo-hydraulic Universal testing machine BiSS (Fig.2.21b).

The tests were carried out in accordance with [8]. Accordingly, to this document, it is obligatory to perform the 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 not less than 5 pieces of the specimens should be provided. Each specimen should be numbered. Not 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

Fig.2.21 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 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;
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- determination of the static strength of the specimens;
- determination of stiffness of the specimens.

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. On this basis, a largely automatic calculation of assembly sequences, visual assembly assistance functions and synthetic target states was possible.

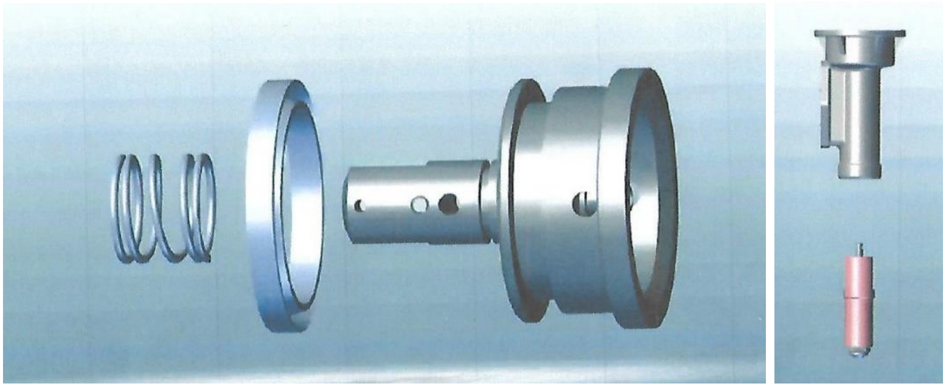


Fig.2.22 Assembly analysis of digital model information on FED assemblies

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

The development work at present is to organize the assembly process management through ERP-system and the implementation of modules for the accounting of flows in assembly production and management of assembly production.

The “Visualisation of the assembly” is scheduled for 2018.

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 is 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 figure 3.1 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

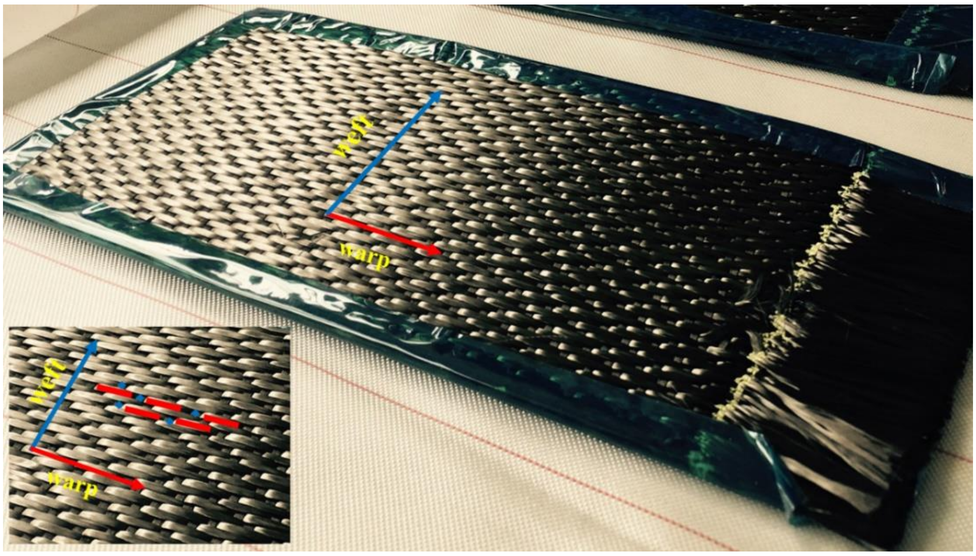


Figure 3.1: Woven 3D carbon fibre fabric used for Hybrid-joints

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 (figure 3.2, a) 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 Figure 2,a.

The second type of metal insert (Figure 3.2, b) 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 3.2: 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).

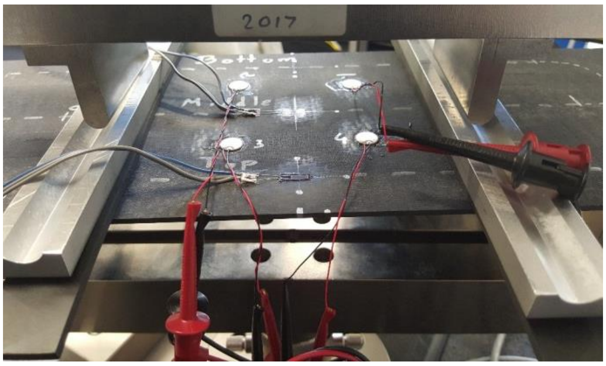


Figure 3.3: Embedded sensors during composite manufacturing for damage/stress-strain studies induced during manufacturing or later in service.

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

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, The 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, The University of Manchester.

Attendees:

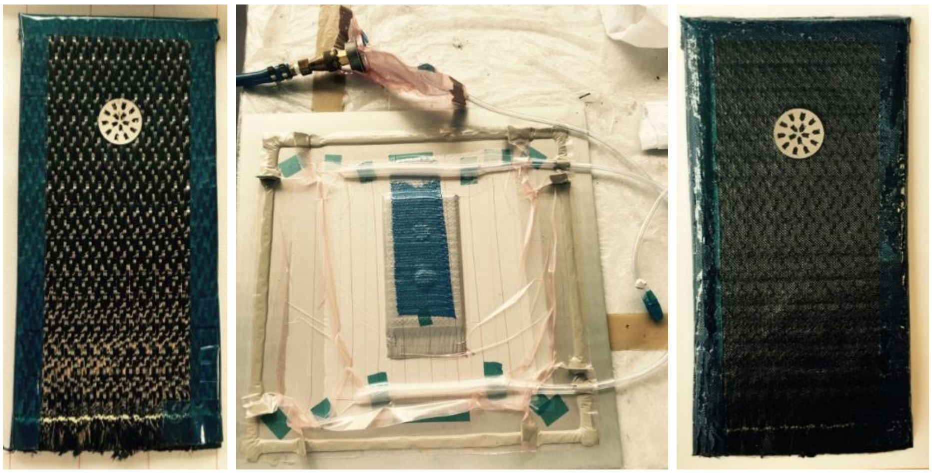
Prof Mojtaba Moatamedi	Aerospace Research Institute (UoM)
Dr Adam Joesbury	Aerospace Research Institute (UoM)
Dr Matthieu Gresil	Composites Lab (UoM)
Prof Prasad Potluri	Northwest Composites Centre (UoM)
Prof Constantinos Soutis	Aerospace Research Institute (UoM)
Dr. Georgii Kryvov	Ukrainian Research 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 (Figure 3.4) 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 3.4: 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 (Figure 3.5) with different cut-out sections of metal pins. Preliminary preparation of cross-section surfaces was carried out by cutting, grinding and polishing.

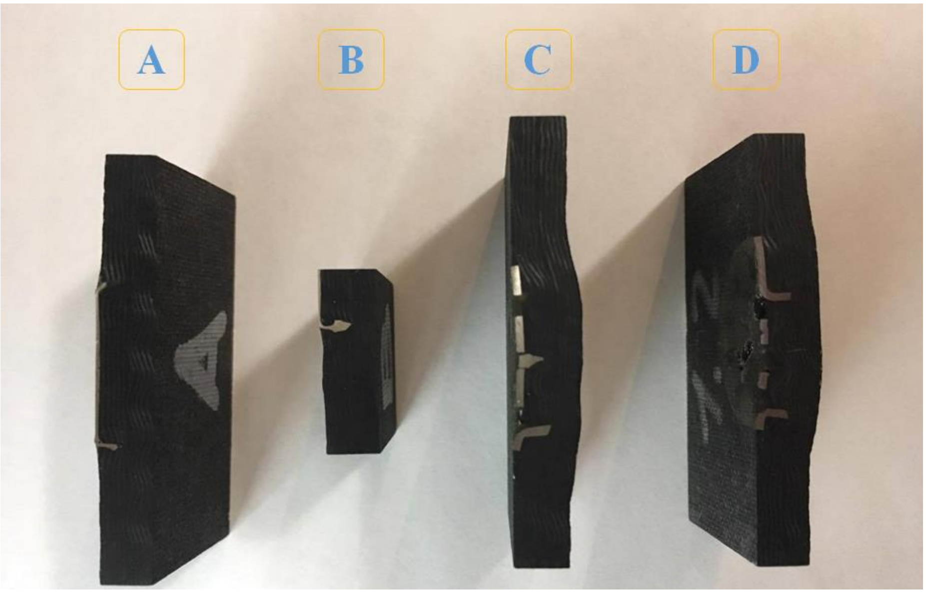
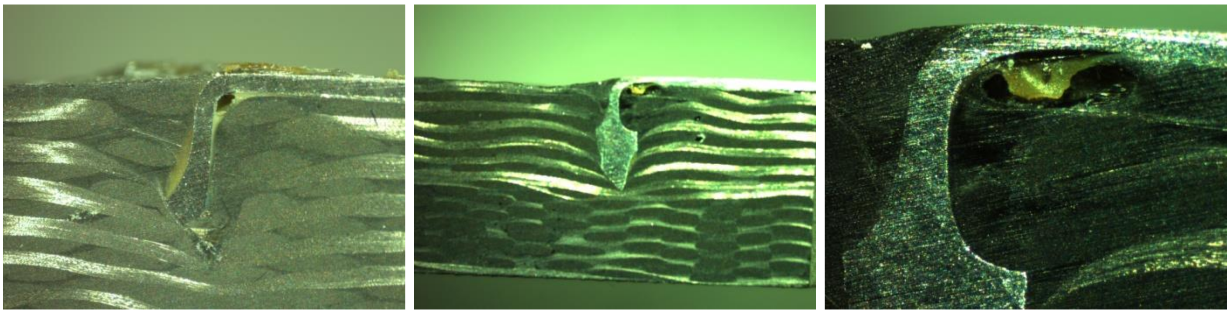
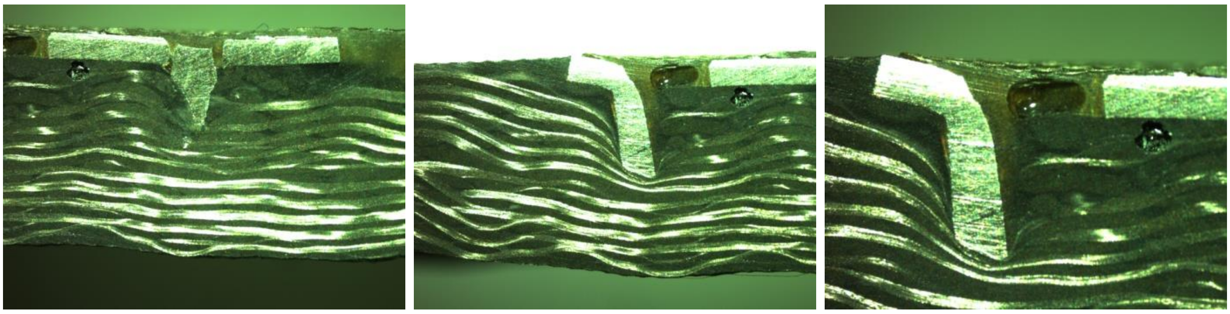


Figure 3.5: Cross-sections of hybrid metal-CFRC joint specimens in the zone of pin embedding

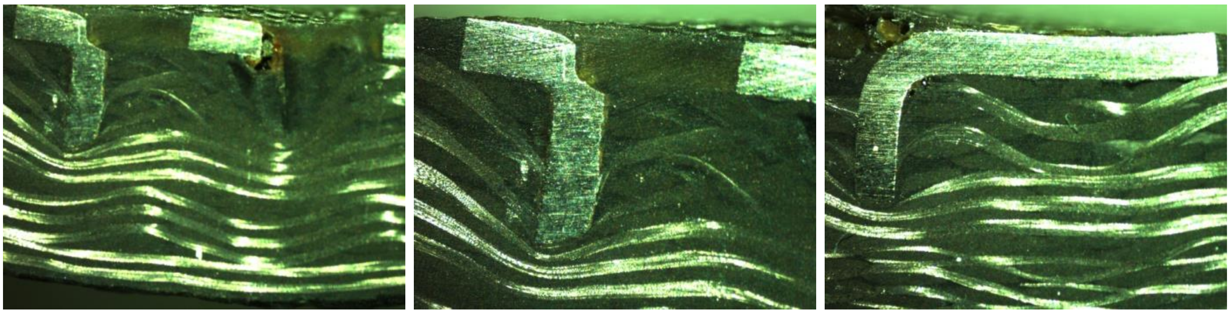
Stereoscopic images of specimens' sections are presented in figures 5. Section (a) shows the zone of 3D fabric with embedded pins of type 1. It should be noted, that embedded pin have been bent due to low stiffness (Figure 5, a). Although, small thickness allows penetration into the fabric without significant resistance and dissect the yarns (fibres) encountered on the path, which does not cause curving of fabric layers.



(a)



(b)



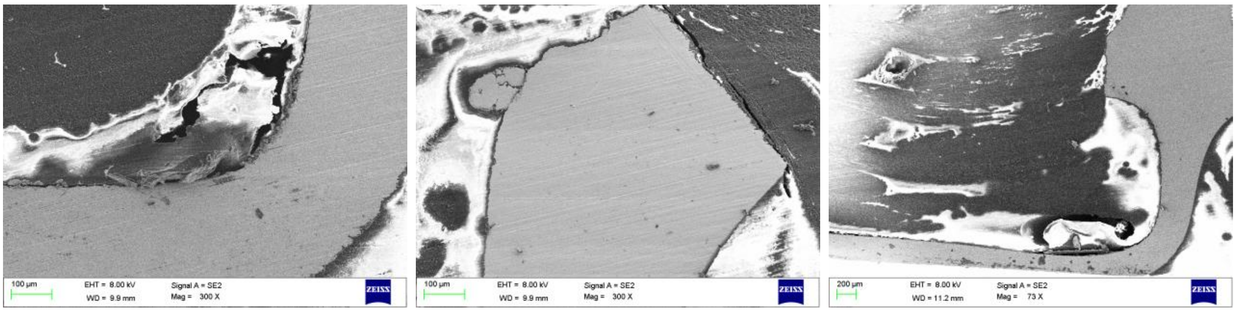
(c)

Figure 3.6: Stereoscopic microphotographs of pin's sections

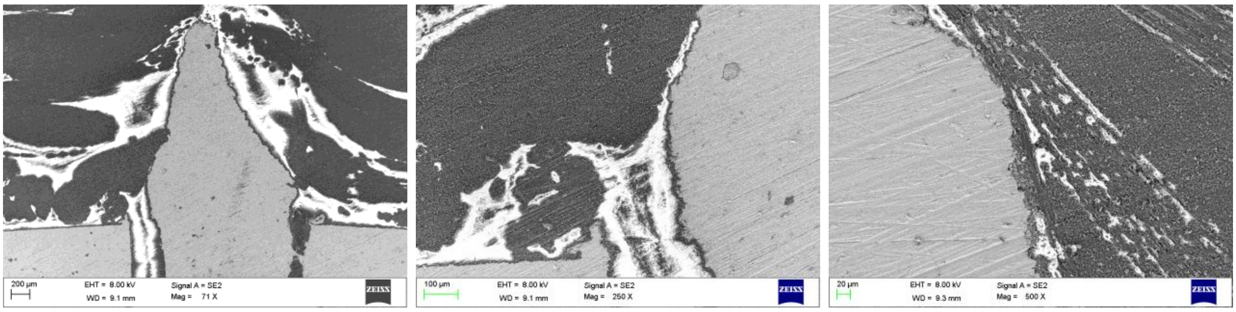
Defective zone localized at the base of pin (see Figure 3.6, a) is the air microscopic bubble formed in consequence of insufficient molding as well as shape of pin. The twisted shape makes it an obstacle for moving the resin and caused a local inhibition, resulting in non-impregnated areas. Another reason 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 (Figure 3.6, b & c), 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, only some 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 Figures 3.6, b, c).

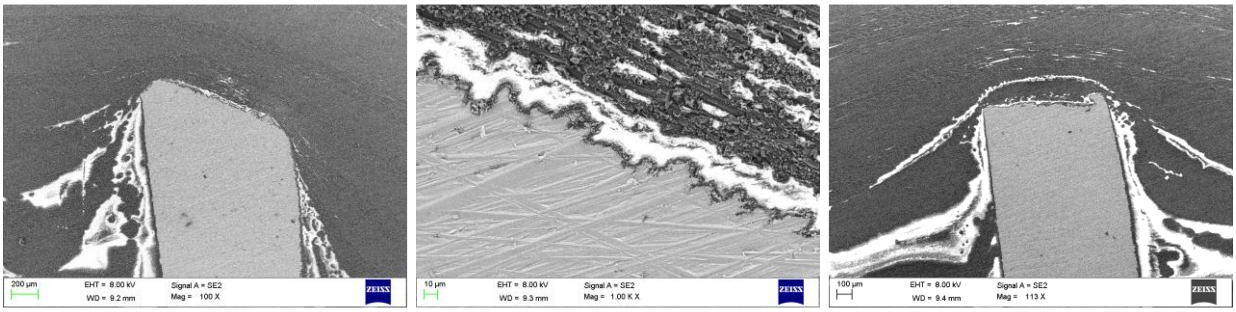
Inspection with SEM studies also demonstrates the presence of air cavities at the base of pins, as well as local damage of pin-CFRP interface at the tip of pin (Figures 3.7, a). In SEM analysis, it is clearly visible interlayer which represents the surface treatment of metal inserts by special adhesive for increasing of metal-to-CFRP adhesion (Figures 3.7, b).



(a)



(b)



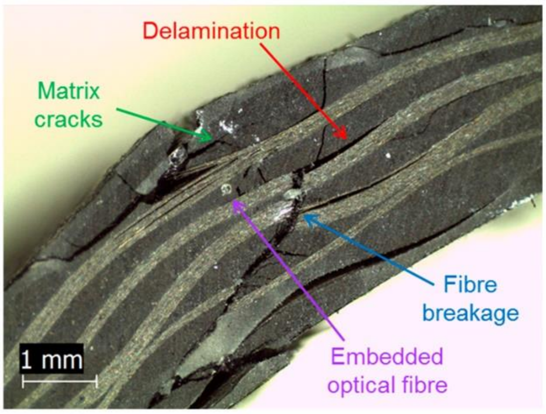
(c)

Figure 3.7: SEM microphotographs of pins’ cross-sections

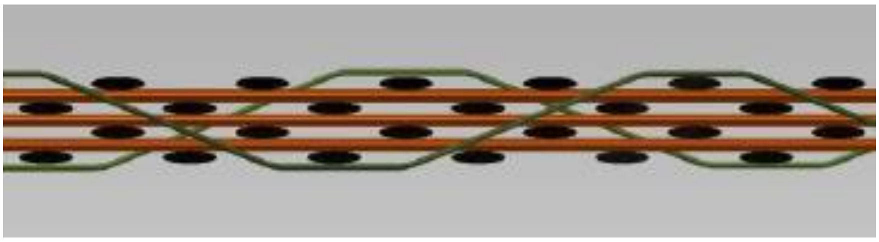
Section of pin (type 2) shows the absence of micro-cracks between the metal and composite. The pin is in tight contact with fibres, which should positively affect the electrical conductivity of the joint with such shape of pin. This effect can be explained by the sharp tip of pin and non-twisted configuration. 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.

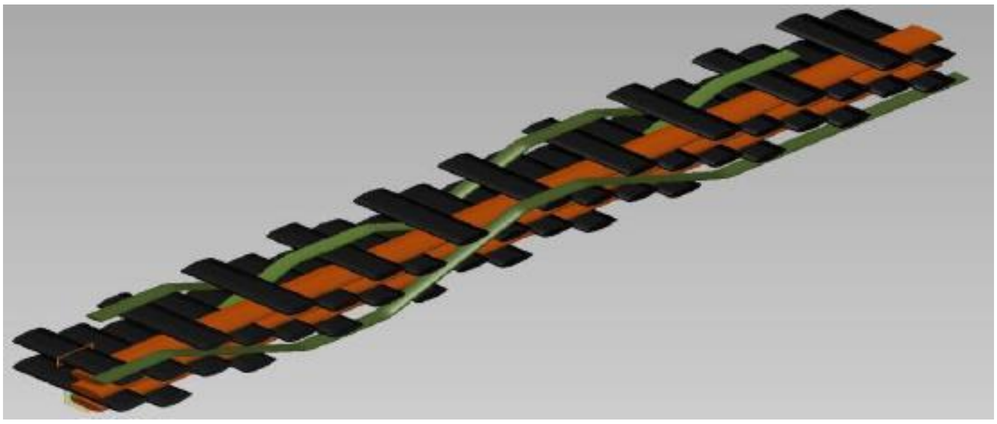
Other Publications:

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)

4. Progress with respect to WP3 performance indicators

Work Package (High-Level Objective)	Performance indicators	Amount achieved by project midpoint (M18)	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	3 1 4 2	> 8 1 > 8 > 5