Advanced fuselage and wing structure based on innovative Al-Li alloys

Final Report Summary - AFSIAL (Advanced fuselage and wing structure based on innovative Al-Li alloys)

Executive Summary:
The project AFSIAL (Advanced fuselage and wing structure based on innovative aluminium lithium alloy - numerical trade off study and experimental stiffened panel validation) funded by Cleansky was mainly aimed to combine the most suitable materials with the optimised design and the best welding process, in order to obtain panels characterized by required properties and significant weight reduction. In detail aim of project was to develop a metallic solution combining innovative aluminium alloys of the Al- Cu- Li family and advanced assembling technologies such as Laser Beam Welding, investigating also the possibility and potentiality expresses by hybrid welding and an innovative simultaneous double- sided dual beam welding of T joints, trying to demonstrate the feasibility of this material and process solution, bringing it to a TRL of 4.
The project Consortium initially consisted of 5 EU partners with overall coordination of ENEA, Italy. Two
partners from France (Constellium and ESI Group), one from Great Britain (TWI Ltd) two from Italy (RTM s.p.a. and the same ENEA).

After various events, one of the consortium partners, RTM s.p.a. has bankrupt and its planned activities were not completed.

Initial work was focused on two main goals: the first one was to identify the low density aluminium alloys most suitable for each of the aero structure part while the second one was to identify the best welding configuration and the best laser parameter for the development of the welding process and manufacturing of the flat panels with laser (RTM) and hybrid laser (ENEA). In this context it is included the development of split-beam laser welding in relation to low density aluminium alloys identified both from a performance point of view that energy, made by TWI ltd. This particular aim was an additional target than originally proposed by the Consortium, as required by the P.O.

The project AFSIAL also aimed to numerically design and optimize a set of representative metallic aircraft panels. To make this, ESI Group (the Consortium partner who has been performing this activity) has also developed a novel procedure which was primarily in the combination of advanced multi-function optimization criteria in conjunction to highly non-linear structural behaviour, involving limit loads and eventual failure.

The last aim of AFSIAL was to manufacture some representative panels according to all specifications (material, welding parameters, numerically design) and to test them.

Unfortunately, the bankruptcy of RTM s.p.a nullified much of this last target. reducing what was expected to the only attempt of welding wings by ENEA, attempt also failed because of difficulties encountered in the machining of materials provided by Constellium as explained in other part of these reports.

Project Context and Objectives:

The project AFSIAL aims at developing a metallic solution combining innovative aluminium alloys of the Al- Cu- Li family and advanced assembling technologies such as Laser Beam Welding, investigating also the possibility and potentiality expresses by hybrid welding and an innovative simultaneous double- sided dual beam welding of T joints, trying to demonstrate the feasibility of this material and process solution, bringing it to a TRL of 4.

For this purpose Consortium tried to implement four main actions focalized on bottom and crown fuselage and upper and lower wing, representative of the four major parts of the aircraft contributing to the total structure weight:

1) material development; aim is a low density Al-Cu-Li alloys which offer direct weight reduction of about 5%, percentage which may increase up to 20% through adapted design.
2) Design ; aim is to identify optimum design calculating the overall weight of each panel design configuration also performing a detailed calculation of stresses and breaking loads of panels
3) Manufacturing; aim is test three welding technology. Laser beam welding (advantages are very low distortion, the absence of defects and reduced postweld re-work), Hybrid laser welding (it combines the advantages of LBW with arc welding), Split-beam laser welding (advantages are potential reduction of heat inputs used to make the welds, a simplification of the equipment used to manufacture the welds)
4) Testing. Aim is to test the mechanical properties required by their structural function in the aerostructure to validate the material + design + manufacturing solution.

Overall aim of the project is therefore to combine the most suitable materials with the optimised design and the best welding process, in order to obtain panels characterized by required properties and significant weight reduction.
Significant weight reduction.

In detail, to achieve these objectives, the AFSIAL project is articulated according to the next objectives:

a) Identify the low density aluminium alloys most suitable for each of the aerostructure part. Produce and supply rolled and extruded products from these alloys, for the development of the welding process and manufacturing of the flat panels.

b) Identify the best welding configuration and the best laser parameter to be used in fuselage and wing panels manufacturing. Solve the welding issues that arise during this technology development phase.

c) Explore the potential of split-beam laser welding in relation to low density aluminium alloys identified both from a performance point of view that energy.

d) Supply design WPs with the main properties required for the modelling of the panels, by testing both base material and welded components. Validate selection of combined material and welding process for fuselage and wing panels.

e) Predesign fuselage and wing panels: identify the panel geometry by parametric variation of skin, frame and stringer thicknesses and of frame and stringer pitch.

f) Design stiffened fuselage and wing panels in detail so that they can be manufactured. Prepare the numerical model for mechanical testing of panels.

g) Manufacture fuselage and wing panels for TRL demonstration and mechanical testing.

h) Validate the material and process solution developed in the project by testing the panels and comparing the results to the model predictions.

i) Final report communicated to CSJU.

Project Results:

A great part of planned WPs have been carried out, but, referring to what reported in the previous paragraph, not all the planned aims have been achieved.

This section shows the obtained results for each WP.

WP1 - Identification of innovative metallic materials aluminium lithium alloys most suitable for fuselage (Constellium)

The activity carried out has identified and selected the material for fuselage and wings chosen in the AIRWARE offer by CONSTELLIUM. These Al-Cu-Li alloys with relatively low lithium content show good behaviour on various fields, depending on the alloy and the required application.

Fuselage: Constellium has identified 2198 T8 alloy which has a good “Fatigue Crack Growth under hope stress than the same 2024 T3 alloy which is the most common solution used for fuselage.

For the stringer the selected material is 2196 T8511. These two alloys (2198 T8 and 2196 T8511) are compatible with LBW technology using some precautions during the welding process. Constellium, based on its own previous experiences, recommends to proceed according to two steps. The first one consists of welded made on an intermediate temper (T84 for 2196 profiles and T3 for 2198 sheets. A second step after welding which consists on a final ageing treatment on final T8 temper.

Wing: The current solution is represented by the 7150 T6 alloy. Constellium has identified the 2195 T84 alloy for the upper wing skin (it shows high strength) and the 2500 T84 alloy for the lower wing skin (it shows a good compromise between tensile yield stress and toughness again associated with a lower density). As recommended by Alenia these two alloys need to be welded with a thickness between 9 and 13 mm instead of usual 2 – 3 mm. and Constellium has declared no experience with this. Also for wing Constellium has indicated an intermediate temper for welding and a post welding heat treatment.

The material needed by welding partners of the Project (ENEA, RTM, TWI) has been delivered by Constellium.
The material needed by welding partners of the Project (ENEA, RTM, TWI) has been delivered by Constellium at the beginning of January 2014 and has been received after the middle of January. This WP has been the first of the whole Project. Its delay (about three months than originally planned in the first version of ANNEX I) has affected the entire project.

WP2 - Development of innovative Laser Beam Welding process most suitable for fuselage and wing application (ENEA, Constellium, RTM, TWI)

WP2 is characterized by three activities lines each of one principally developed by one of welding partners:

1) RTM – This partner has investigated the best welding configuration and the best laser parameter to be used in fuselage panels and for wing applications production closely connected with the used materials;
2) ENEA – This partner has investigated the potential of hybrid laser welding process Nd: YAG-TIG applied to materials provided by Constellium;
3) TWI – This partner has developed split-beam double sided welding conditions applicable to two different fuselage stringer-skin joint configurations. Considering that the three welding partners have operated with different welding approaches and solutions a final output of this WP has been a comparison of the weld qualities, welding speeds, thickness penetration capabilities, heat inputs and estimated overall energy consumptions per unit length of weld made with laser and hybrid laser-arc welds.

As first common step, all three welding partners have dealt the preparation of samples to be welded principally basing on material availability, on preliminary design and its own preparation capabilities.

TWI activity

As welding trials, TWI has used Z shaped 2196 stringers supplied by Constellium and machined by the same TWI to simple “I” shaped stringers. TWI has carried out several welding trials with 4 different techniques:

a) single sided autogenous welding to develop conditions then applied simultaneously from either side;
b) single sided wire fed welding to identify the wire feed rate;
c) double sided autogenous welding to evaluate the weld profiles produced;
d) double sided wire fed welding introducing wire feed only from one side.

The obtained results may be summarized as follows:

1) for the 1st case the most acceptable weld was produced at 6m/min. Penetration was less consistent at higher speeds, and pinhole defects began to form in the welds at 5m/min.
2) for the 2nd case Trials welded on the 1.2mm/1.7mm/1.2mm stringer/pad/skin combination with wire feed, have pointed to the unacceptable root concavity observed in the single-sided autogenous welds. To improve the situation, it also experienced different conditions of materials cleaning.
3) for the 3rd case TWI has integrated with its own facilities the Optoskand beam splitter, realized by the same TWI to carry out the double-sided welding trials. All the operation began on the 1.2mm/1.7mm/1.2mm stringer/pad/skin combination without wire feed, using the best single-sided autogenous welding conditions identified earlier, in particular:
   - Laser beam powers of 2.23 and 2.33kW using a requested laser power of 5kW;
   - Laser beams (two off) focused on directly opposite points either side of joint line, ie in the same position along the joint length but from opposite sides.
   - Welding speed of 5m/min.

These welding tests have highlighted that

I) the cross-section of one of these welds showed that at least one of the weld caps was slightly concave, that in some cases there were transverse weld metal cracks;
II) were evident cracks and pores associated with the spot tacks used to assist in the fixturing of the joint prior to welding.
prior to welding, suggesting in the same time that transverse weld metal cracking could not be avoided in autogenous welds and that the laser tacking required further development.

4) for the 4th case, always based on the results from similar single sided welding, has been used lower wire feed rates of 0.6 0.8 or 1m/min, with an overall requested beam power of 3.55kW. Lower wire feed rates of 0.8 or 1m/min appeared to reduce the number of hole defects, although they were still present.

At the end of this experimental activity TWI has obtained the next main conclusions:

• Using a 5kW (fibre) laser beam source, either with or without such a device, has proven more than capable for welding 1.2mm thickness stringers, at welding speeds of 5~6m/min, using two 1.3kW beams.
• A NaOH, then HNO3, chemical cleaning route appears beneficial in reducing the porosity content of the laser welds;
• Wire feed addition during laser welding, as opposed to autogenous laser welding, is necessary to improve the weld profile and reduce or eliminate weld concavity;
• Stable welding of thinner stringers, with thicknesses <1.2mm appears difficult with such an approach, given that finding a balance between sufficient heat input to fully fuse the stringer/pad joint, whilst avoiding blow through/hole defects, has proven challenging.

RTM activity
RTM has used for its experimental activity the material AIRWARE 2198 for sheets and AIRWARE 2196 for stringers, supplied by Constellium, choosing initially two different sections: 1.5 mm and 1.0 mm. even if the research was carried only on 1.5 thick sheet which was more representative of the actual case.

After having designed and realized the needed tool RTM has carried out tests using a laser source with the next technical characteristics:

a) Laser source IPG YLS 5000
b) Type Laser in fibra
c) Delivering fiber diameter 0,100 mm

Also based on its own past experiences, RTM has developed and optimized the best welding parameters, identified considering that the speed must be such as to allow a sufficiently fast process, for productivity and little thermal load, that magnification must sufficient because smaller spot are worst for wire melting and the excessive intensity produce a lot of melting bead explosion.

These welding parameters were used to produce small scale mock-up of 500 mm length to check the feasibility of the weld over bigger length.

ENEA activity
ENEA used for the activities planned in this WP the material AIRWARE 2198 for sheets and AIRWARE 2196 for stringers, supplied by Constellium, reducing the thickness of of samples to 1,1-1,2-1.4 and 1.5 mm. The earlier tests were conducted using a single laser source and developing the best welding parameters. Only later tests have been performed with the hybrid system. In this last case the presence of two of two heat sources (LASER + TIG ) has highlighted an excess energy intake to very thin thickness.

For this reason ENEA would have to determinate again welding parameters but, based on its own experience, technician decided to use the laser parameters and an electrode TIG smaller from diameter of 1.6 mm, this allowing the use of lower current TIG. Tests were satisfactory with tickness of 1.3 mm, 2.8 mm and 4 mm. macrographs did not reveal the presence of excessive porosity even if there was excessive cooling of the welding. This circumstance has therefore suggested the need for a heating system of the cord or a post weld heat treatment after welding.

WP3 - Ranking of most interesting materials and relative process solutions ( ENEA, Constellium, ESI)
This WP includes analysis activities related to the results of the previous WPs, in order to identify the most
This WP includes analysis activities related to the results of the previous WPs, in order to identify the most suitable solutions for fuselage and wing panels in terms of material and LBW process. In detail, CONSTELLIUM characterised materials supplied in WP1 to welding partners, with respect to the tensile and compression properties, fatigue crack growth rate (FCGR) and R-curve. ESI, based on the extensive information received from CONSTELLIUM regarding tension laboratory data, carried out calibration activities on the following materials, as a preliminary numerical step:
I) Aluminum AA2195-T82 (Wing Upper Panel skin and stringers);
II) Aluminum AA2050-T84 (Wing Lower Panel skin and stringers);
III) Aluminum AA2198-T8 (Fuselage Upper and Lower Panel skin);
IV) Aluminum AA2196-T8511 (Fuselage Upper and Lower Panel stringers).

ENEA, starting from suggestion of Constellium regarding the deformations induced by excessive power source (laser + tig), has developed a new equipment able to correctly place the samples to be welded under the T-joint configuration maintaining the perfect perpendicularity stringer/plate during welding. Main objective of ENEA activity in this WP has been the development of new welding parameters, closely connected to the use of a TIG source and to thickness of 5 mm and 7 mm. Considering the number of input variables required by a hybrid welding system, a methodology DOE was used to identify which ones are most important and which ones that most affect the response of the whole system. All the the parameters determined during the previous WP2 was considered as "screening" able to highlight those few variables that really matter. The deliverable shows the best welding parameters for the two alloys studied. To test the new hybrid welding parameters, two gases - Agon (Ar) and Helium (He) - have been used so that the lack of penetration of TIG noticed with the argon gas has overcome by using helium gas achieving considerable results. In detail a greater penetration, a better bead appearance, decrease of inclusions and an increase of filling material. Furthermore during the welding phases was verified the necessity for TIG - LASER group of a zigzag movement; it was observed that the T- joint welding of the different aluminium alloys does not allow a linear trajectory welding but requires small undulating movements in respect of the connecting line between the stringer and the plate, respectively, of ± 0.2mm. Only in this way the TIG arc is able to spread out uniformly on the surfaces to be welded. On the most significant samples were carried out RX and metallographic investigation to verify the quality of hybrid welding.

WP4 - LBW Flat large stiffened panels (fuselage and wing) preliminary design (ESI) and WP5 - LBW Flat large stiffened panels (fuselage and wing) design (ESI)
The activity of ESI Group in the project AFSIAL consisted of numerically designing and optimizing a set of representative metallic aircraft panels. In this respect two fuselage curved panels were designed (a crown panel and a bottom panel) together with two wing curved panels (an upper panel and a lower panel respectively). The design of the curved fuselage and wing panels, that was aimed to obtain the minimum possible weight, was performed taking into consideration loads and boundary conditions (simply supported) identified clearly by our aero partner ALENIA. After their design, the curved fuselage and wing panels were geometrically linearized obtaining their equivalent flat shape and resulting to the corresponding flat panels. This was done through only a geometrical process linearization: the flat panel had the same thicknesses and stringer pitches coming from the architecture of the designed curved panel (frozen).

Numerical models and simulation (with the right test boundary conditions) of the flat panel was necessary to foresee panel test capability and for numerical-experimental correlation. The procedure followed was to use the ESI Group proprietary explicit dynamic code (VPS) and the associated optimization code PAM OPT with a novel technique in order to identify the threshold of
associated optimization code PAM-OPT with a novel technique in order to identify the threshold of plastification and/or buckling for each corresponding case, without having to refer to the traditional “eigenvalue” (buckling) type of analysis that the industry uses with classical FE codes like NASTRAN or ABAQUS.

The novel procedure developed by ESI Group was primarily in the combination of advanced multi-function optimization criteria in conjunction to highly non-linear structural behaviour, involving limit loads and eventual failure.

An innovative procedure in calibrating the material properties within the bounds of the advanced ESI-Wilkins-Kamoulakos rupture model was improved and validated and this allowed ESI Group to model in a predictive way the elastoplastic to rupture behavior of the materials in question.

The fuselage and wing panels were then modelled with their original geometric and material attributes and were tested under operation, limit and ultimate conditions in tension and compression. It was numerically shown that their original design was wholly inappropriate.

Then PAM-OPT was used to optimize the panels in order to meet the Limit Load and Ultimate Load certification constraints and minimizing the panel mass.

The major problem was how to automatically detect during the optimization procedure the onset of panel buckling and eventual global buckling. The major achievement of ESI in the AFSIAL project was the definition and validation of such a complex automated optimization procedure with negligible human intervention / judgment.

In this way the panels were optimized with respect to the panel skin thicknesses, the Z stringer connection thicknesses and sizes, the stringer height and width and the stringer thicknesses, under the suitable combination of constraints involving maximum displacements and max plastic strains and minimum mass as objective function.

In this way new designs of the panels were suggested with considerable mass savings (between 16% and 30% and sometimes even 50%).

The designs were tested and fine-tuned for robustness through stochastic analysis and they were proposed to the consortium.

Based on the ESI recommendations, new modified panels were suggested by the partners from which their linearized version (flat panels) were to be manufactured and tested both numerically and physically. ESI tested numerically the new panels to rupture to reveal their limits and mode of failure. This was indispensable for the eventual mechanical testing of these panels in the laboratory as their predicted behaviour could assist the design of a suitable experimental setup and associated methodology.

WP6 - Flat large stiffened panels manufacturing (ENEA-RTM)

This activity had to be carried out by and ENEA to manufacture both fuselage (RTM) and wing (ENEA)

RTM has not carried out activity due to bankruptcy

Regarding ENEA, preliminarily the material to be welded was prepared by removing the excess material by machining and by reducing the initial thickness of about half. The milling work was carried out in ENEA laboratories with mechanical equipment not automated, creating some samples smaller than those required by the project as agreed with the Topic Manager.

The first welded samples sent to Constellium has highlighted some difficulties due to the tendency of aluminium plates to deform due to the extremely high specific power supplied during welding. Constellium analyzed these samples and highlighted:

a) the failure to meet the acceptance criteria of the welding. The excessive heating of aluminum, due to the presence of two energy sources, has caused the deformation of material and this has determined an alteration of the height between the surface to be welded, the laser focus and the distance between the
alteration of the height between the surface to be welded, the laser focus and the distance between the GTAW electrode. In this way it was not possible to respect the relative distances determined in all preliminary investigations. The highlighted problem was not easily solved since it would have required the presence of an adaptive system capable of correcting the relative distance GTAW / LASER and the surface of the sample in real time. Moreover, it would take a follower joint.
b) High value of the surface roughness due to surface treatment. The plates had originally a thickness twice that final: machining has removed much of the required amount from the side opposite that of welding reducing a few tenths of a millimeter was eliminated from the welding side. This procedure was followed on preliminary samples and because welding had provided good results, was performed the same work also on demonstrators.
To overcome the problems highlighted by Constellium relative to deformation and surface treatment, ENEA has asked in july 2014 a company specialized in mechanical processing to realize 3 sheets with 9 stringers with larger dimension than those produced previously and with roughness characteristics as required by the specifications of Constellium.
In addition, to further contain the deformations and further improve the cooling of the welded surfaces was developed and realized in ENEA a new system of clamping able to compensate for the deformations of plates and to cool the rear surface of the same plates by flushing cold air.
New Welding has been planned according to a new way suggested by Topic Manager; considering that was not strictly required the tandem welding of sources, it has been decided to perform a step of continuous welding with the laser only and subsequently a hybrid welding.
Machining operations carried out on the panels caused serious problem of reflection of the laser itself, this causing the failure of the welding of aluminum alloy. The same problem was found on all the metal sheets and all stringers. Failure of the spot welding made the welding operations extremely complicated.
After a careful evaluation of this particular situation, ENEA Technician thought that the reflection of laser might be attributed to the surface of the aluminum alloy machined with a low roughness, as required by the project. Comparing the test carried out on the league inAl2198-T3 with the one made on the league Al 2050 (worked almost like a mirror) it was possible to observe a significant difference. So the problem might be due to the mechanical machining required.
Regarding to the problem of the lack of welding by the only laser source is reasonable to think it was closely connected to the high reflectivity of worked aluminum; in fact many of the not worked metal sheets had a good welding. Regarding the hybrid welding, it always provided a good weldability on the not worked and/or with little mechanical processing metal sheets, or with a not excessive removal of material.
To better understand the reasons of this problem ENEA’s researchers have performed several tests on samples of the same alloy of the final metal sheets as well as a metallographic analysis. This hypothesis was related both to the heat treatment and to the crystalline structure of the alloy. Being necessary to reduce the thickness of the original metal sheet from about 10 mm to 4 mm, with the same removal action from both surfaces of the sheet, the immediate consequence was that was removed the surface heat treatment which improved the mechanical characteristics but also improved the material weldability. Furthermore, from the metallographic analysis it was observed that the structure in the periphery was clearly different from the central part; this difference was produced in the phase of rolling of the sample. Another hypothesis was linked to the segregation of hydrogen in the aluminum matrix. Thanks to the heat treatment, the problem of segregation of hydrogen was certainly avoided in the first surface layers but it was not guaranteed in depth.
It was therefore necessary, carry out another material the mechanical machining required but also thermal treatments in order to have adequate metal sheets for welding. This was not possible.
WP7 - Experimental validation (Constellium)

Activities have not been implemented due to lack of demonstrators welded (fuselage and wings) as previously explained.

Potential Impact:
The intentions of AFSIAL partners were mainly those of achieving more efficient, safer and environmentally friendly air transport technology, closely connected to energy efficiency targets in aerospace sector. In order to obtain this targets, activities of weight reduction of the fuselage and wing structures and development of a cost effective assembling technology adapted to the low density Al-Cu-Li materials family were implemented.

In other words, AFSIAL partners plan was to combine advanced materials (aluminium solutions) and technologies reducing the manufacturing time and the aircraft structure weight.

Using of Laser Beam Welding, possibility and potentiality expresses by hybrid welding and an innovative simultaneous double-sided dual beam welding, applied to new alloys and to regional aircraft structures were and surely are some of the strong points of the project especially considering the good position of metallic technology compared to Carbon Fiber Reinforced Plastics which requires very high investments with limited weight benefits.

These technology would have certainly helped to strengthen the technological competitive advantage of the European industry in aircraft design and fabrication.

Unfortunately, only some of the objectives have been achieved because of the economic problems of one of the partners.

Certainly beam splitting device has demonstrated its potential: it has been integrated successfully in to an existing (fibre) laser system for simultaneous, high speed, double-sided welding of stringers to skins. It may be an interesting development for aerospace industry.

In this context, also the hybrid welding could represent an aspect of particular interest but have been identified limitations in welding of the material considered that need further investigation.

The same interest is for numerically designing and optimizing of representative metallic aircraft panels developed by ESI Group which has improved and validated An innovative procedure in calibrating the material properties within the bounds of the advanced ESI-Wilkins-Kamoulakos rupture model allowing to the same ESI Group to model in a predictive way the elastoplastic to rupture behavior of the materials in question.

List of Websites:
No public website address has been developed.

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