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Physics Procedia 12 (2011) 113–122

Physics Procedia

LiM 2011

Laser Beam Welding of Hard to Weld Al Alloys for a Regional Aircraft Fuselage Design – First Results

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Abstract

Light weight design of fuselage structures is a major goal for future aircrafts to reduce structural weight for increased efficiency regarding fuel consumption. One objective is to validate and demonstrate the technology that offer the best opportunities of weight reduction and short production time. It involves the development of laser welding technologies for difficult weldable high strength aluminum alloys, containing Cu and / or Li. Another objective is to identify and evaluate approaches for first welding trials on T-joints of the alloy 2139 which are very promising regarding weld seam quality and achieved mechanical properties.

Keywords: CO_2 laser beam welding; high strength aluminium alloys; Al-Cu-Mg-Ag,;Al-Li; weldability; regional aircraft; static strength

1. Motivation / State of the art

The Clean Sky Joint Technology Initiative (JTI) is a large European research project including six Integrated Technology Demonstrators (ITD), one of it is called “Green Regional Aircraft”[1)], in which the described work is integrated.

Riveting has been the state of the art joining technology for aircraft fuselage since decades[2)]. The necessary overlap joint demands a large amount of material which restricts weight saving requirements. For regional aircrafts which usually fly short distances a low overall weight is very important to allow the use of smaller and less powerful engines to reduce fuel consumption. Furthermore the riveting process is quite intensive in process time[2),3)] regarding the production chain compared to welding speed of LBW (Laser Beam Welding) technologies. From those limitations, two research areas emerge now for regional aircraft fuselages: the transfer form the riveted differential built up to laser welded integral structures and the introduction of high strength materials, figure 1.

For larger metallic aircrafts such as Airbus A318, A 340-600 and A380, laser beam welding (LBW) has already shown advantages to overcome limitations of conventional riveted fuselages[4)]. For small passenger aircrafts, such as ATR 42, the transfer of LBW technology in the fuselage is quite more challenging not just for the weight saving potential but also regarding short production time and cost management. The smaller panel sizes provide shorter weld seam length and the thickness is reduced, but also represents a challenge since it still has to be proved, if it represents an advantage for the structure. Furthermore, panel distortion has to be avoided or monitored by a low

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doi:10.1016/j.phpro.2011.03.015

energy input in order to reach the given production tolerances. Since material suppliers have reconsidered the strength advantages of the proposed material-concepts (Al-Li), developed decades ago, metallurgical research has been conducted to obtain better properties at reasonable material costs. Aluminum-alloys with ultimate tension strength of about 500 MPa and with less welding restrictions are now available. Those alloys would allow lower structural weight and the same or even higher loads on the fuselage compared to conventional weldable materials, such as AlMgSi. The challenges for laser beam welding are to provide appropriate, crack free joints with low porosity, resulting in high mechanical performance of the welded joint. In the initial stage it has to be investigated and evaluated which weld seam properties can be expected from precipitation hardenable aluminum alloys such as 2139 (Al-Cu) in integral structures.

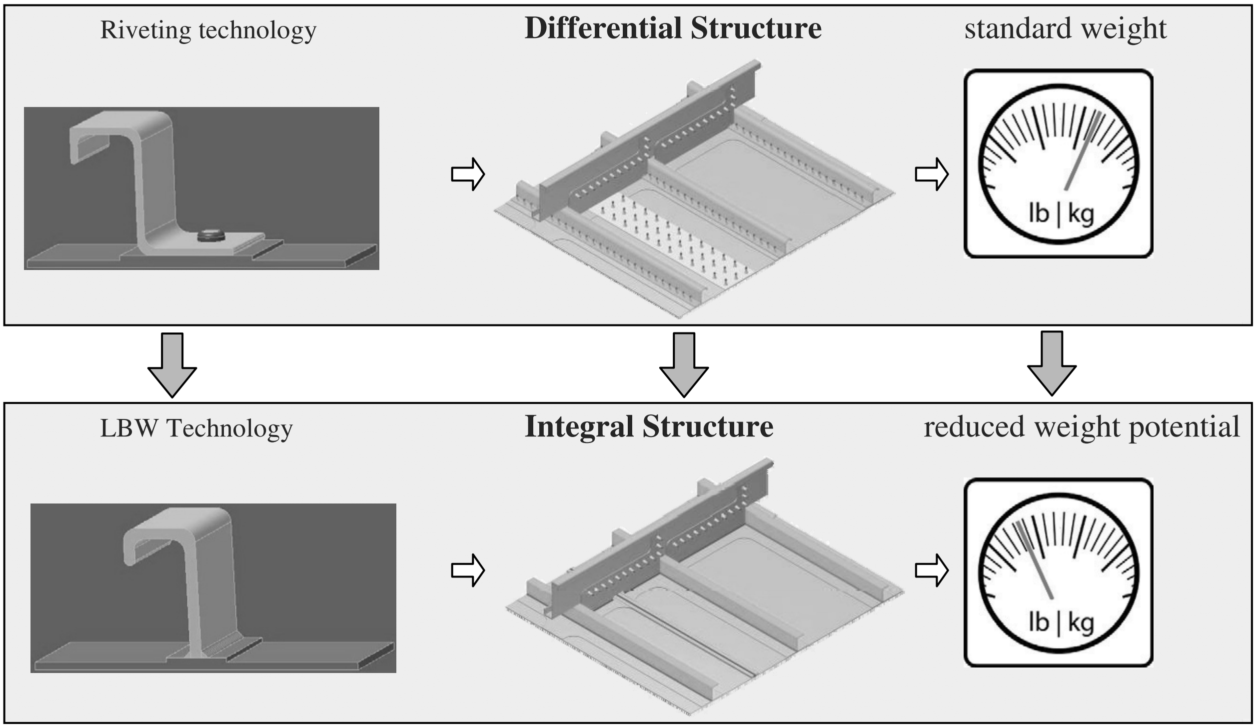


Figure 1: Transfer from a riveted differential to a laser welded integral fuselage structure (schematic)

If the weldability can be shown and mechanical strength can be proven for this alloys, a fuselage-demonstrator has to be welded and compared to a riveted variant. In this article first results of welding trials will be presented including mechanical properties of T-joints, such as T-tension test. In addition to that tests will be performed were the weld seam (T-joint) is loaded under hoop stress or longitudinal stress. After this, the process welding parameters and the test conditions will be used as an initial reference for an enhanced alloy 2198.

2. Materials and Experimental procedure

2.1. Materials

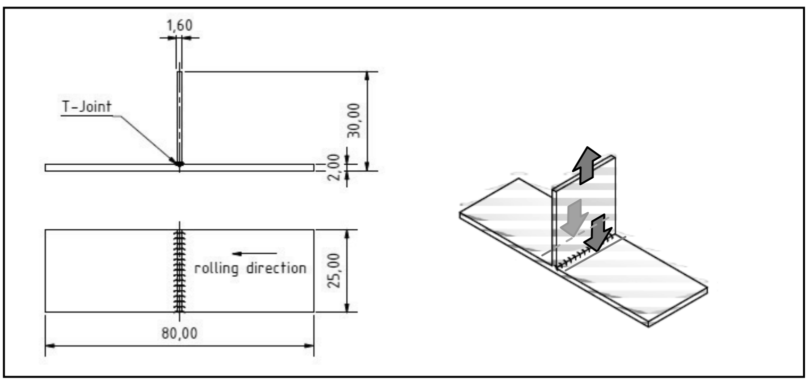
As already mentioned, LBW technology requires weldable aluminum alloys. The first steps for developing an integral structure for fuselage structures were made with the material AlMgSiCu[5)] (grade of 6xxx group) for large passenger aircrafts[2),6),7)]. The already existing 2024 alloy for riveted structures was designed for high strength and good damage tolerance, as well as for corrosion resistance but not for weldability. Recent developments in the metallurgical field offer now weldable Al-alloys of the 2xxx series such as 2139 and 2198. Those alloys are based on the phase system Al-Cu-(Li) and provide high strength and, in case of 2198, reduced density with a high E-modulus[8),9)]. Those age hardenable alloys have to be welded with additional filler wire in order to avoid metallurgical induced hot cracks in the weld seam that occur during the solidification process after welding[10),11)]. A typical alloy used for filler wire is AlSi12. Hot cracking depends also on the weld parameters and the mechanical clamping gradient of the joint caused by the stiffness of the component. A current limitation of the materials with lithium is set by an inhomogeneous sheet surface that occurs after the solution annealing and causes a large pore formation in laser weld seams.

2.2. Welding equipment for test samples

For the welding trials a CNC-machine with a work area of 10 x 3 x 1 m³ and two integrated CO_2-lasers of 4,5 kW output power were used to meet the requirements of a future application, see figure 2[12)]. The T-joints on this research were obtained by a simultaneously both side welding process. High beam quality and low focus diameter of the laser beam allow laser parameters with low energy input per unit length to ensure low distortion of the samples. Helium was supplied as a process gas for laser beam welding process. To adjust skin and stiffener to each other, a vacuum unit for the skin and a mechanical clamping device for the stringer were used. In the machine, integrated optical sensors allow an accurate focus positioning in the fillet weld of the T-joint, according to the CAD data and to adjust the tolerances of previous manufacturing processes.

Figure 2: Large welding machine for industry-orientated welding and the integrated CO_2-laser [12)]

Before going into large and expensive structural tests after welding a new Al-alloy, tests on small samples were conducted to provide strength values for welded T-joints and optimized welding parameters. The purpose was to obtain specific mechanical properties for different material conditions and load situations. In a next step within the project, the transfer to larger samples or even component test will be performed. However, for the first evaluation step a variation of two load conditions will be investigate on three different sample variants, figure 3.

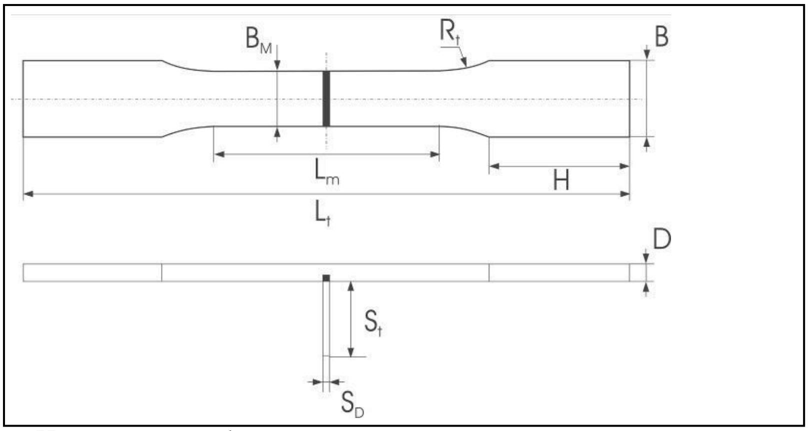


(a)

T-tension sample

Figure 3: (a) Sample to prove T-tension stress of the weld seam

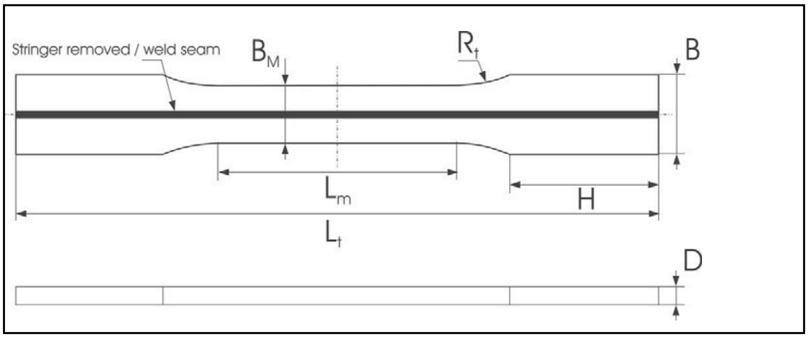
(b)



Hoop-stress sample

parameter	size [mm]
B	20
B_M	12,5
D	2,6
H	47
L_m	50
L_t	200
R_t	100
S_t	12
S_D	1,6

(c)



Longitudinal stress test sample

parameter	size [mm]
B	50
B_M	40
D	2,6
H	88
L_m	120
L_t	340
R_t	50

Figure 3: continued (b) hoop stress sample corresponds to circumferential load in the fuselage; (c) strength test sample with weld seam corresponds to longitudinal load in the fuselage

In difference to the T-tension test in which basically the weld seam strength was evaluated under tension load of the stringer perpendicular to the skin, the hoop stress test is almost equal to a standard tension test but here the cross section of the base material is influenced by a weld seam, see figure 3 b and c. The base material was tested with a comparable sample size without the stringer.

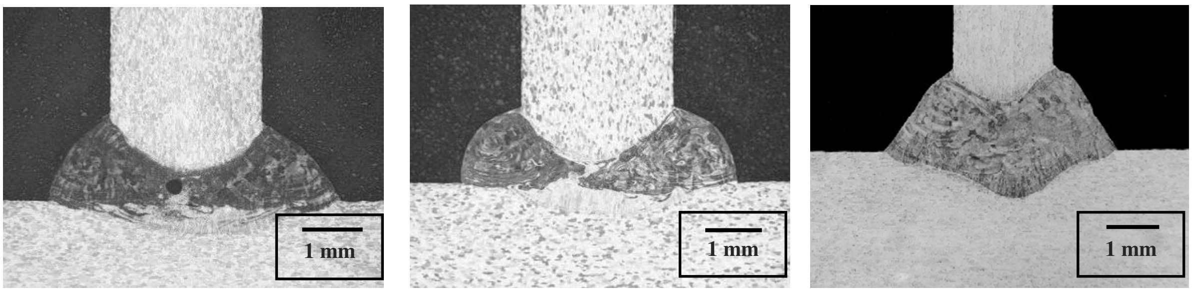
3. Results and Discussion

3.1. Welding tests and T-tension strength

The first welding trials were performed with skin-material of 2,6 mm thickness. Also the stiffener elements were made out of the skin sheets in the shape of strips, both of the alloy 2139. To prevent hot cracks during welding, which are typical for low Si-containing alloys, a high amount of AlSi12 filler wire was used. For the first two welding trials the parameter sets are shown in table 1 (parameter A and B). Both conditions provided full penetrated weld seams and a convex shape caused by the high amount of filler wire, figure 4. Within the loop of parameter variation, the T-tension strength was determined for each parameter set. For condition A and B the obtained T-strength lay at a reasonable value of about 300 MPa. To increase the load capability of the T-joint an improved edge preparation of the stringer was used, the hot crack appearance was reduced and the pore formation was minimized. Additional a preparation of the stiffener was needed to obtain a more common geometrical stiffener skin proportion, the stringer was chemical milled down to 1,6 mm. And finally the weld seam parameters were optimized for the new material thicknesses. The laser parameter C were used, table 1.

Table 1. Different variants for welding parameters and corresponding T-strength on 2139 samples

laser beam welding parameters	parameter set A	parameter set B	parameter set C
wire feed rate [m/min]	7,0	9,0	5,0
energy input per unit length [J/cm]	320	280	280
optical focal length [mm]	150	150	150
T-strength as welded [MPa]	ca. 300	ca. 305	ca. 368
T-strength PWHT [MPa]			ca. 441



LBW parameter, variant A	LBW parameter, variant B	LBW parameter, variant C
width: approx. 5 mm	width: approx. 4,75 mm	width: approx. 3,96 mm
depth: approx. 0,6 mm	depth: approx. 0,6 mm	depth: approx. 0,81 mm
cross section approx.: 6,1 mm²	cross section approx.: 5,5 mm²	cross section approx.: 5,01 mm²

Figure 4: Cross sections of the main parameter set that were tested during welding trails

The result of all those improvements show, that finally a T-tension strength up to 368 MPa is possible under the same heat treatment conditions. If the samples were additionally precipitation aged T-strength values up to 441 MPa can be achieved for that particular material.

Micrographs of all three welded variants were prepared, see figure 4. For the further discussion the sample of the parameter set C will be used. The weld seam itself shows a good symmetry, full penetration and enough weld seam depth into the skin, 0,84 mm, see figure 4 (right). Scattered pores cannot be completely avoided but do not influence the weld seam strength dramatically, if the amount is low enough. Macro cracks were not found within the reviewed cross sections and by using the optical microscope. The hardness measurement indicated the strength mismatch of those aluminium alloys, see figure 5.

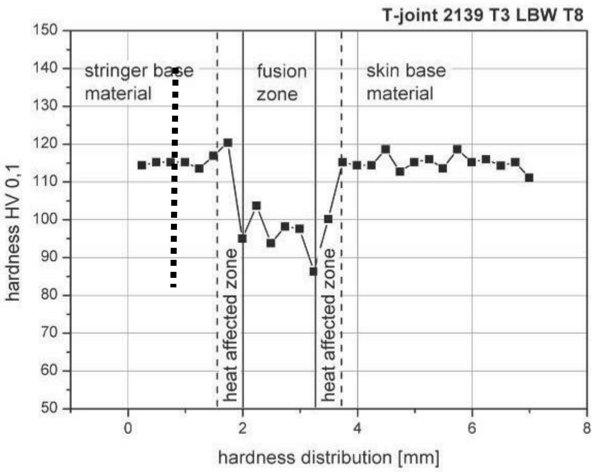
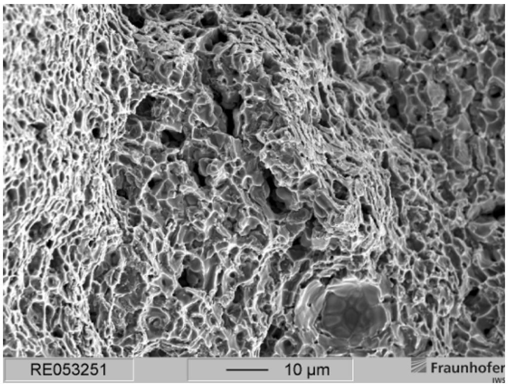


Figure 5: Hardness perpendicular to the skin, parallel to the stringer: welding condition T3 base material was welded and finally post welded heat treated

Additionally fracture surfaces were analysed by scanning electron microscopy, to get information on hot cracks existence and fracture behaviour. It was observed that for all reviewed samples a ductile fracture surface appears. A closer look into the structure shows very sporadic appearance of micro hot cracks. In figure 6 two pictures of the fracture surface are shown. A quantitative comparison of a sample with a low T-tension test value (332 MPa T3LBWT8) and a sample with a high T-tension test value (446 MPa T3 LBW T8) were made. A trend of a slightly higher amount of hot cracks can be observed for the sample with the lower value. It cannot be evaluated at this stage, if that is the only explanation of the differences in the T-tension strength, because there are some other factors that may have an effect on T-strength, such as pores, flank angle of the weld seam, homogeneity of the fusion area at the particular sample section to name of a few.



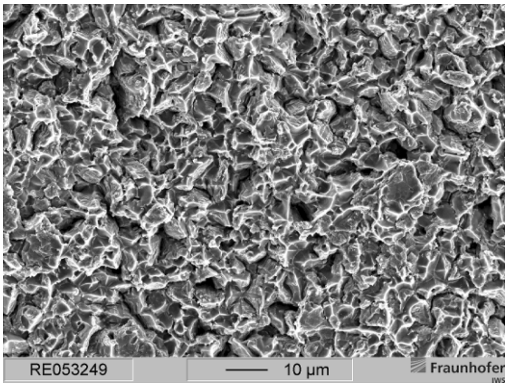


Figure 6: SEM fractographs for samples of the same heat treatment condition but with significant difference in T-tension strength (ductile fracture surface, left picture: T3 LBW T8 / 332 MPa, indicates a slightly higher amount of hot cracks than the T3 LBW T8 condition with 446 MPa, right picture)

3.2. Hoop stress test

The load distribution into the stringer and the skin for the T-tension test is very specific and does not occur in a real fuselage, the test has to be seen more as a quality control of the weld seam quality and less as a structural test. A clear contrast represents the hoop stress sample, which is loaded in the same manner as the skin is in a pressurized fuselage. Under that condition the weld seam will influence the performance of the base material under tension stress. According to the metallographic cross sections, figure 4, the base material profile is influenced by the fusion zone with a discontinuous depth pattern of maximal 0,84 mm and over a width of around 5 mm. Additionally the heat affected zone covers an area of 0,5 to 1 mm around the fusion zone. The results of the tension tests for each condition are shown in figure 7 where the tensile stress test values (left diagram) and the stress-strain curves (right diagram) are given. Abbreviation of “T3 LBW” means base material was welded in T3 condition, “T3 LBW T8” means after welding in T3 a additional heat treatment for 16 hours at 175 °C was followed. In the column diagram the welded condition has to be compared to the accordant base material. The specific strength values in the diagrams show, that the yield strength of both welding conditions (T3 LBW and T3 LBW T8) is slightly higher than that of the base material, while the ultimate strength of the welded sample is lower. In the T8 condition the specific strength values of the welded sample and the base material are in the same range.

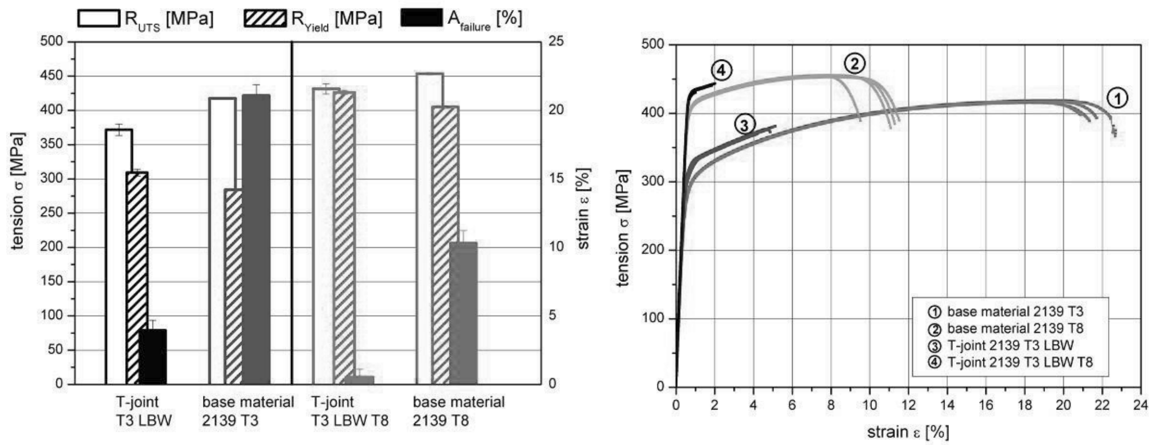


Figure 7: Tension values for each condition in the hoop test (left), stress strain curves for the base materials and the T-joints (right)

In difference to the strength, the strain values of the tested sample are more effected by the existence of the weld seam. While the base material shows quite a high plastic performance, the elongation in the welded conditions is a lot reduced, see left diagram. Even if the amount of weld seam in the cross section is less than 35 % the influence to the base material is quite strong. In the T8 condition there is almost no elongation of the sample left. Consequently is the plastic deformation of the base material strongly affected by a very small amount of fusion zone in the cross section. The challenge is now to optimize heat treatment conditions or to improve the plastic deformation of the sample. Possible strategies could be:

- no post welded heat treatment to use the remaining strain that was measured in the T3 LBW condition
- analysis of different socket geometries in the weld seam area to reduce the load and protect the weld seam.

3.3. Longitudinal stress test

In the longitudinal stress test the weld seam orientation is parallel to the load direction, what would represent the tension stress in the upper fuselage of the aircraft. The percentage of the fusion zone in the cross section is now reduced down to 4 %. The stiffener was removed from the skin by machining to avoid an effect of that additional cross section to the test. The sample is shown in figure 3, two conditions were tested:

- welding in T3 condition without any post welded heat treatment
- welding in T3 condition with additional heat treatment: 16h at 175°C (T3 LBW T8).

The base material results were taken from the previous test, according to the sample size (b) in figure 3. In figure 8 the results of the static test are presented. Although the yield and the ultimate strength are almost not affected by the presence of the weld seam, its presence does affect the fracture strain significantly. Independent of the heat treatment condition, 4% weld seam in the cross section reduces the fracture strain about 50 % from that of the base material. That leads to the need of a socket if the fracture strain is required under the given load direction.

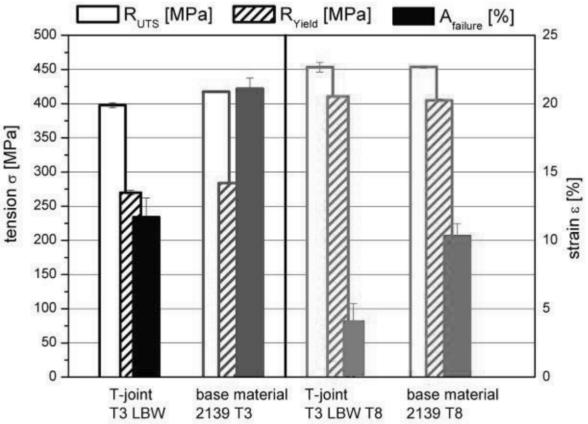


Figure 8: Tension values for each condition of longitudinal stress test

The effect of the weld seam on the fracture strain is similar for both, hoop and longitudinal stress test. Therefore the weld seam works comparable to a geometrical notch which would cause higher strength values especially seen in the hoop stress test. The weld seam caused strain constrain through the sample cross section, consequently the highest strain constrain is expected for the hoop stress sample. First the remaining stringer across the load direction inhibits a necking of the sample and the weld seam leads to a strain constrain across to the sample thickness. Additional heat treatment reduces the remaining strain in case of the hoop stress test even more than it is the case for the as welded condition. It has to be further investigated which condition is optimum for the use in a fuselage especially under consideration of fatigue and damage tolerance.

3.4. Transfer to lithium containing alloy 2198

First welding trials of the alloy 2198 show that there is a significant problem with pore formation in the weld seam. Independent of the laser parameters, there was no improvement to reduce the amount of pores in the fusion zone. By changing the skin material (6xxx) it could be seen, that the used stringer material is responsible for the pore issue, figure 9 (left). A test with skin material an a stringer, 2198 where the original surface was removed by chemical milling showed significant lower porosity in the fusion zone, figure 9 (right).

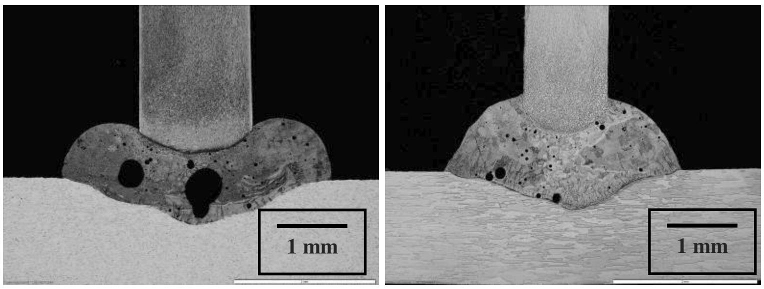


Figure 9: Micrograph of welding different materials, 2198 Stringer and 6xxx skin (left), 2198 Stringer with removed surface layer and 2198 skin (right)

From the metallurgical point of view there should not be a major problem regarding weldability of 2198 besides the low evaporation temperature of Lithium. However, it was found that by removing the surface layer of the stringer the weldability could be increased. Supported by that experience T-tension tests are in process and a small demonstrator was welded, figure 10. With a size of 430 x 650 mm² the demonstrator and three stringers and as well two clips it could be shown that weldability of 2198 is possible even with very thin skin (1,6 mm) and stringer (1,2 mm) thicknesses. Distortion is really low due to the low energy input. The technology is now available to be transferred to larger panel sizes.

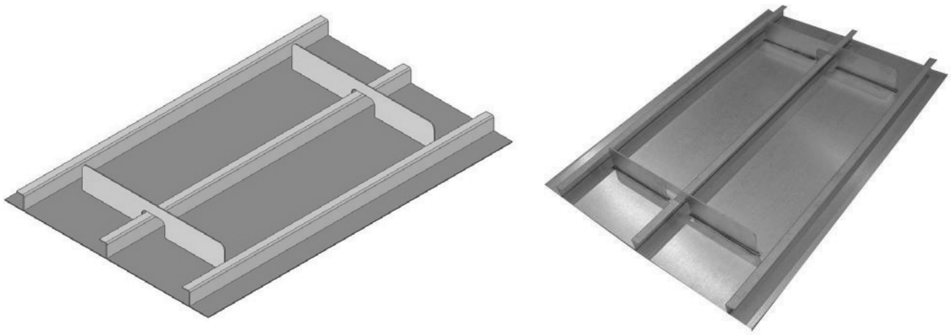


Figure 10: Demonstrator for integral fuselage welded of high strength alloy 2198, CAD sketch (left), laser welded demonstrator with three stringer and two clips, 430 x 650 mm² (right)

4. Conclusion

The first results of the project show a good weldability of the used alloy 2139 and as well quite good mechanical properties compared to the base material. There is a potential of high strength materials for thin walled structures regarding weight reduction in the use of integral structures. The limitation of fracture strain in welded structures has to be considered for new light weight fuselage design. The advantages for manufacturing and the experience for laser beam welding that were obtained, were transferred to the aluminum-alloy 2198, which should provide even higher mechanical properties than 2139. A small demonstrator of the alloy 2198 was welded to prove weldability for stringer and for clips.

Acknowledgements

This research has been conducted within the Clean Sky Joint Technology Initiative (JTI) in the frame of the European research project “Clean Sky Joint Technology Initiative”. IWS and the involved partners are grateful for the financial support.

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