Wing of the Future Project – Aluminum Wing Options for the Sustainable Aircraft of Tomorrow

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Constellium

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In aircraft wing structure design, two types of concepts predominate today—largely metallic aluminum wing structures used for short-medium range, single-aisle aircraft, such as the Airbus A320 or Boeing B737, and largely composite wing covers used for the latest long-range, twin-aisle aircraft, such as the Airbus A350, Boeing B787, or B777X. The largely composite wing cover structure has recently been expanded to single-aisle aircraft, smaller than the aircraft previously mentioned, such as the A220, which was initially designed by Bombardier under the CSeries brand, as well as the latest Dassault business jet, called the Falcon 10X.

The pressure to reduce environmental impact is now leading aircraft manufacturers to drastically reduce the CO_2 emissions for the whole life cycle of their products. On the one hand, this puts structural weight back at the center of the debate. On the other hand, it brings into focus two recycling considerations—namely, the increasing number of aircraft increases the volumes of pre-consumer scrap that needs to be treated, and end-of-life recycling is more complex with composites than with metallic materials.

Concerning the aircraft use phase, the key levers to achieve the net zero carbon footprint target in 2050 are enhanced technologies, such as hydrogen propulsion, enhanced engine technologies, or structural lightweighting. For example, this could include increased efficiency of operations and infrastructure and growth of sustainable aviation fuel, as summarized by the International Air Transport Association (IATA), as shown in Figure 1. When considering the full life cycle, aluminum airframe structures have an excellent potential to achieve nearly full circularity by recycling the pre-consumer scrap generated in the manufacturing route and the end of the life of the aircraft.

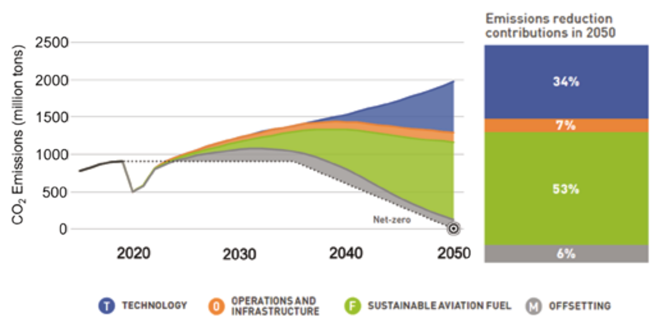


Figure 1. Levers to achieve net zero carbon footprint target in 2050. (Source: IATA.)

Due to the increasing demand for air travel, aircraft manufacturers are counting on higher manufacturing rates for single-aisle aircraft. It will be necessary to develop efficient methods of rapidly manufacturing high-performance airframe structures while remaining in a neutral economic balance compared to the traditional metal structure as the current reference for single-aisle aircraft.

Today, the research and technology focus of airframers is the development of next generation short/mid-range aircraft with a significantly decreased carbon footprint by revisiting the entire airframe architecture. The key drivers in this research are increasing performance and developing cost-efficient manufacturing that is compatible with monthly build rates beyond 80 aircraft. This requires a large range of material offerings to select the best options.

Enhanced materials, such as the lithium-containing Airware® technology, as well as cost reducing and performance increasing assembly technologies, such as friction stir welding (FSW) and bonding, are levers to achieve highly competitive cost-performance balances. These technologies are being investigated in the Wing of the Future Project. The current available materials data and coupon tests, which integrate various materials and assembly configurations, were used to generate the required stress allowables for the trade studies, which are investigating various design concepts within a typical single-aisle aircraft wing panel structure. The state-of-the-art technologies are summarized in this article, before presenting the trade study results, in which weight reductions of more than 20% have been achieved compared to the current flying baselines. New wing designs as high aspect ratio wings have not been considered at this stage.

The objective of the Wing of the Future Project is to confirm the weight and cost reductions of the new wing panel structures discussed in this article. The project also aims to increase the maturity level of the technologies found to be applicable for the continuous enhancement of existing aircraft or the launch of a new airframe configuration. The Wing of the Future Project is currently ongoing, and additional results obtained will be presented at a later date.

Aluminum-Lithium Alloys for Enhanced Wing Covers

Constellium has significant experience in the development of aluminum-lithium alloys, particularly since the launch of its Airware technology, in which the best chemistry in the Al-Cu-Mg-Li phase diagram has been found to achieve the required property balances.[1]

The so-called "sweet spot" for a well-balanced composition optimizes the hardening precipitation in Airware alloys. It is dominated by T1 hardening precipitation with a plate shape located on the {111} crystallographic planes, while the δ′ precipitation has a spherical shape homogeneously distributed in the aluminum matrix.[2] Figure 2 shows two examples of Airware microstructures on nanometric scale observed by a transmission electron microscope (TEM).

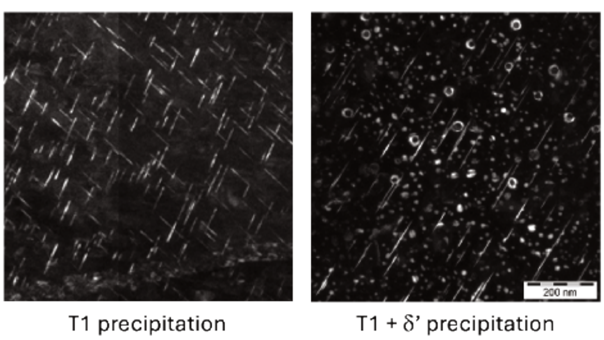


Figure 2. Illustration of the Airware hardening precipitation, showing examples of T1 and mixed T1 hardening precipitation and δ' precipitation.

In Figure 3a, the major trends for the upper and lower wing skin products are shown in the simplified Al-Cu-Li diagram.[3] Compared to the current well-established alloys, such as Airware 2050 or Airware 2198, the high damage tolerant AW236 wing skin and the high strength AW226 alloys are positioned with lower copper and lithium contents. AW236 has a lower copper and slightly higher lithium content compared to AW226. The lower copper content in AW236 leads to a higher toughness, while slightly increased lithium content in AW226 raises the stiffness and decreases the density of the alloy.

Concerning AW226, a roughly 1% lithium content leads to a 5% density reduction and a 5% increase of the elastic modulus compared to typical 7xxx alloy references. The high solute content is still well positioned compared to the solubility limit, so that a significant strength increase can be obtained.

Figure 3b summarizes the stiffness and density of the Airware alloys, both those that are flying (e.g. 2050) and in development (e.g. AW226 and AW236) compared to comparable products from the conventional 2xxx and 7xxx families.

Complementary to the physical properties, other key properties need to be considered to increase the design allowables required by the airframers to achieve the relevant weight reductions. The spider diagrams shown in Figure 4 and Figure 5 summarize the increase of the major properties of AW226 and AW236 compared to the current flying baselines.

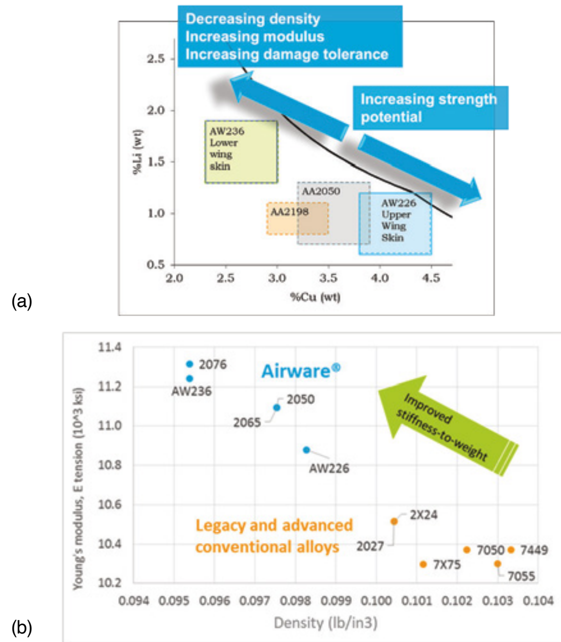


Figure 3. Metallurgical principles to optimize the property balance in wing skin products (a) and a comparison of stiffness and density of Airware alloys compared to conventional materials (b).

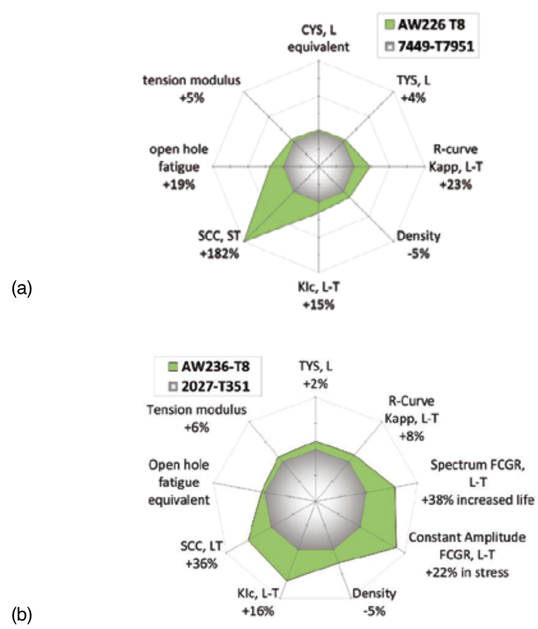
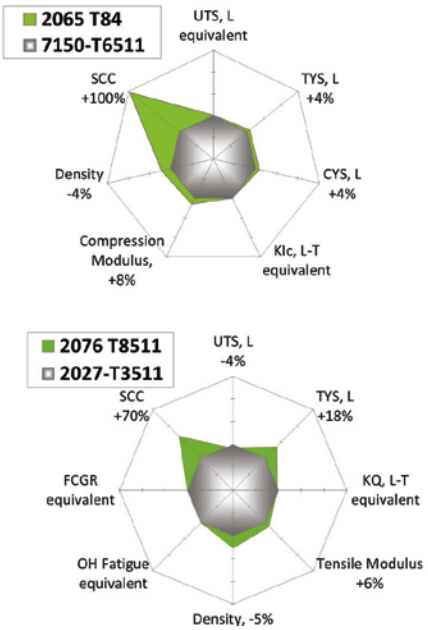


Figure 4. Key properties of AW226 upper wing skin alloy compared to a high strength conventional alloy 7449 T7951 (a), and AW236 lower wing skin alloy compared to a high toughness conventional alloy 2027 T351 (b).



(a)

(b)

Figure 5. Key properties of 2065 T84 upper wing stringer alloy compared to a high strength conventional alloy 7150 T6511 (a), and 2076 T8511 lower wing stringer alloy compared to a high toughness conventional alloy 2027 T3511 (b).

The upper wing skin product AW226 provides a significant toughness increase, including a 15% increase for the plane strain rate and more than 20% for the plane stress toughness, while maintaining strength. Particularly for single-aisle aircraft used for short haul routes, an enhancement in fatigue performance is required even for the upper wing panels. The endurance fatigue is improved by 15% and the variable amplitude fatigue loading, or so-called "spectrum fatigue," has a doubled lifetime tested on high load transfer assembled specimens (Figure 6). A high strength Airware alloy with a chemistry very close to AW226 was compared to a high strength 7xxx alloy, which is close to the 7449 T79 baseline. In a high load transfer specimen type, the spectrum load of a typical single-aisle aircraft was applied and repeated multiple times. As a result, a 100% increase in lifetime could be measured for the Airware product.

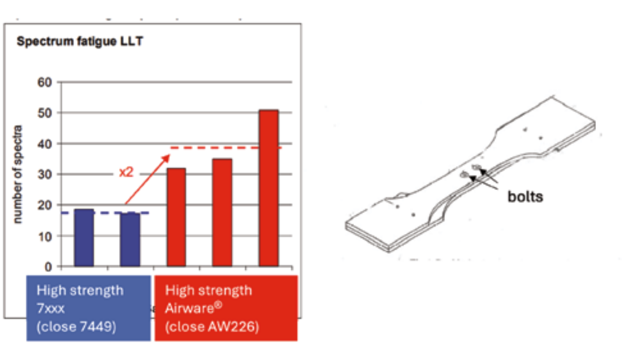


Figure 6. Typical spectrum fatigue in commercial aircraft components.

Concerning the lower skin, the major property requirements are fatigue and damage tolerance. Even though the incumbent 2027 T351 is already a very highly damage tolerant product, Airware AW236 is able to entirely overperform 2027 for all key properties (Figure 4b). For plane stress and plane strain toughness an increase of 8% and 16%, respectively, can be observed. Fatigue crack propagation with constant and variable amplitude are key requirements for lower wing skin applications, and major improvements of more than 20% and 35%, respectively, can be obtained. As for the upper wing skin, the density and Young's modulus are improved by more than 5% and 6%, respectively.

The step change in the stress corrosion resistance is valid for the upper as well as for the lower skin. With a threshold stress increase of more than 35% for the lower wing skin and an increase of more than 180% for the upper skin, the inspection intervals (time between inspections) could potentially be increased, largely thanks to the corrosion behavior.

The excellent corrosion behavior of Airware alloys can also be confirmed for the upper and lower wing stringers (Figure 5). Underlining the development of an enhanced metal wing box is the ability to double the stress levels with the high strength Airware 2065 alloys and achieve a 70% stress level increase with the lower wing skin with high damage tolerant Airware 2076 alloys. Complementary to the intrinsic improvements of the density and Young's modulus, the strength increases with these Airware alloys used in the upper and lower stringers compared to the respective reference alloys are noteworthy.

Overall, the Airware package for the upper and the lower wing covers already allows for significant performance increases, thanks to the improved properties compared to the current baselines. Combining these enhancements with smart assembly technologies will allow manufacturers to go even further in improving the performance of a future metallic wing box.

Friction Stir Welding

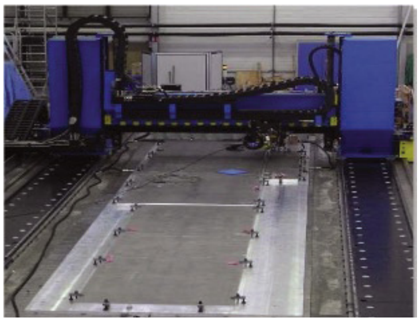
The FSW process is well adapted to long weld lines and has a high degree of flexibility to achieve well balanced properties and reduce buy-to-fly ratios. Figure 7 shows examples of medium-thick gauge plates of around 1 inch in thickness welded in spanwise and chordwise orientations. For the Wing of the Future applications, the spanwise joint shown in Figure 7a is of interest.

In the Wing of the Future Project, the application of the FSW technology has two main objectives. On one hand, it is used to replace a longitudinal bolted joint and on the other hand the reduction of the buy-to-fly ratio. The switch from a bolted to a welded assembly leads to a monolithic structure rather than the current built-up structure. The smart placement of the longitudinal joint and the introduction of the integral structure concept removes the need for material reinforcements required in the riveted structure. In addition, the welding process can be highly automated. All three of these aspects result in a significant cost reduction.

Figure 8 summarizes the principles of the FSW process. A rotating welding tool based on a shoulder and a pin is introduced in the metal in between the two plates to be welded. Once the tool is at the right temperature, the welding operation starts and the tool advances to the end of the parts to be joined. At a precise position defined at the end of the weld, the tool is retracted, and the part can be unclamped.

In the thermo-mechanically affected zone, there are three areas—the nugget, the heat affected zone, and the base metal. The static properties in the joint are in general lower than in the base metal, so that the quality of the joint can be described by the joint efficiency factor. The Airware materials have an excellent weldability and, if the material is in the intermediate T351 temper, then the post-weld heat treatment will increase the static properties. Table I shows an example of welding Airware 2050 in either T3 and T8 temper. In the case of the T3 welding with a post-weld heat treatment, the static properties increase by nearly 10%.

(a)



(b)

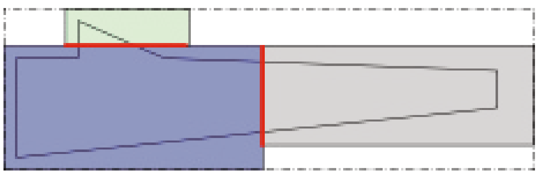


Figure 7. Examples of long welds in wing skin panel type configurations: a spanwise joint on an Airware alloy (a) and a spanwise and chordwise joint in a high strength 7xxx alloy (b).

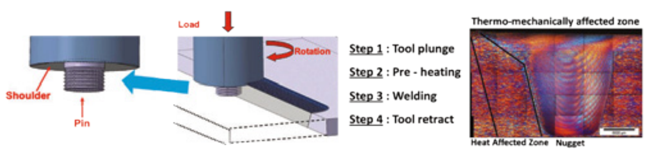


Figure 8. Principles of the FSW process and its microstructure obtained in the welded joint.

Alloy		2050	
Welding Route		Welding in T3 with post-weld heat treatment to T8	Welding in T8
Ultimate Tensile Strength (UTS)	Base Metal	540 MPa (78.4 ksi)	
	FS Weld	432 Mpa (62.7 ksi)	387 Mpa (56.2 ksi)
	Joint Efficiency	**80%**	72%

Table I. The joint efficiency factor for two different FSW welds: T3 temper with post-weld heat treatment and T8 temper.

Although a knock-down factor is observed in the thermo-mechanically affected zone, the impact on the assembled structure can be neglected. As shown in Figure 9, two monolithic panels machined with blade stringers were welded together with the welded joint in the middle of the center bay of a four-stringer panel.[4] Airware 2050 was welded in the T3 temper and a post-weld heat treatment to T8 was applied. A compressive load flow up to 1,750 kN/mm was applied until failure of the panel. No difference between an unwelded reference and the welded panel could be observed.

In addition to studying the static properties, Constellium did a lot of work in the past on characterizing the damage tolerance properties in the welded joint.[5] Open hole

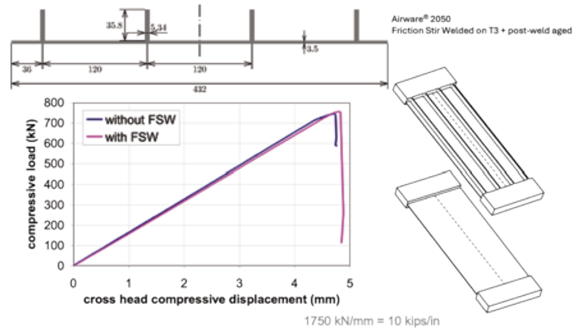


Figure 9. Performance of a FSW panel in compression.

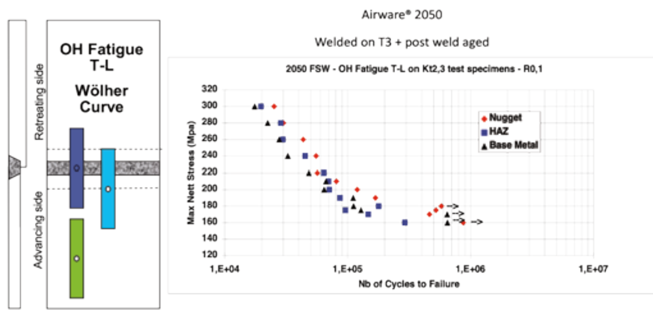


Figure 10. Characterization of a FSW joint for Airware 2050 material, showing an example of open hole fatigue properties across the weld line. Properties in the weld nugget and heat affected zone are shown in comparison to the base material.

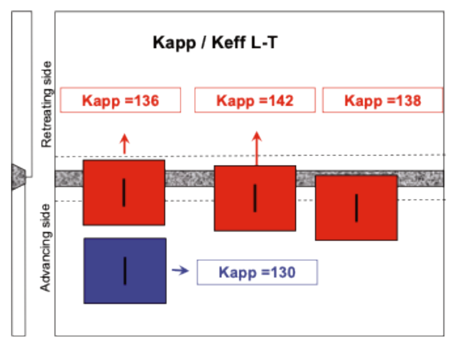


Figure 11. Characterization of a FSW joint for Airware 2050 material, showing an example of plane stress toughness properties across the weld line. Properties in the weld nugget and heat affected zone are shown in comparison to the base material, using CCT specimens W406, B6.35, and L940 (results in MPa√m).

fatigue and the plane stress toughness (K_{app}) are shown in Figures 10 and 11. In the weld nugget and the heat affected zone, specimens were taken perpendicular to the welded joint and compared with the baseline material. In all cases, an increase of the fatigue or toughness properties can be observed, which positively impacts the design allowables discussed hereafter.

For future wing design, FSW has great levers to improve the cost-performance ratio of future design concepts. Concerning the wing skin material, the cost improvement solutions go hand in hand with performance improvements. FSW enables the use of thinner gauge material, which both improves the buy-to-fly ratio and is advantageous from a metallurgical point of view. The thinner product has better intrinsic properties linked to both faster quench and a sharper crystallographic texture, which is particularly beneficial for wing plate, as it is mainly loaded in the length direction.

Including potential future automation of the welding process and even further tailoring of wing panels by welding dissimilar tempers or alloys shows great potential for future wings (Figure 12).

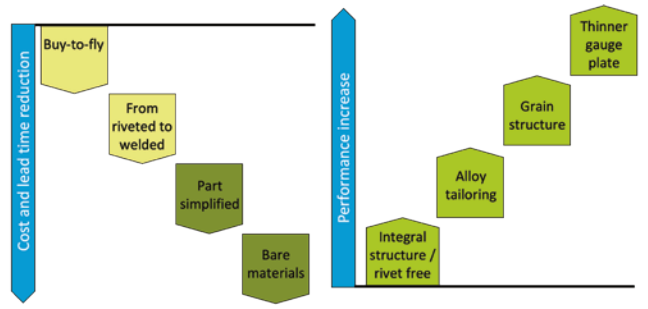


Figure 12. Summary of cost and performance enablers using the FSW technology.

Bonding Technology

Complementing the FSW butt-joint, the bonding technology for the skin-stringer assembly allows for significant performance increases compared to the riveted baselines. Preliminary compression tests on three-stringer panels were done to support the determination of stress allowables for bonded joints. Two stringer geometries were tested, including typical J-shape stringers, which are the current reference, and top-hat stringers (Figure 13).

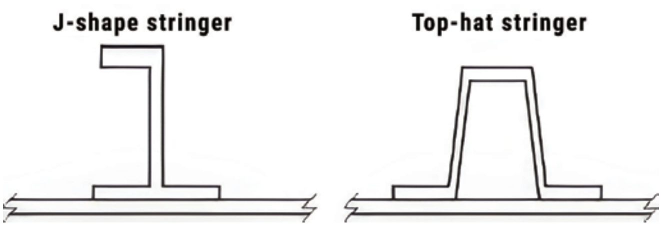


Figure 13. Illustration of the J-shape and top-hat geometry for upper wing stringer geometries.

The stringers were assembled to a 500(LT) x 1000(L) mm^2 size panel for the bonded and riveted configurations. Both stringer geometries were tested in the bonded and riveted assemblies. Figure 14 summarizes the results obtained. The switch from riveted to a bonded assembly increases the load to failure by roughly 15%. The entire panel section, including the top hat stringers, was reduced by 15% compared to the reference J-stringer panel. Nevertheless, a further 3–5% increase of the load flow can be observed when using top hat stringers instead of J-stringers, adding a supplemental performance increase of more than 15%.[6]

For the lower wing skin applications, bonding is expected to increase the residual strength behavior of the panels. These demonstrations will be part of the Wing of the Future Project at a future date.

Trade Studies

The availability of these enhanced technologies—such as the lithium-containing Airware alloys and panel-to-panel longitudinal assembly using FSW and the skin-stringer bonding—opens a wide range of opportunities to improve the cost-performance balance for single-aisle aircraft. Trade studies introducing the step-by-step development of these technologies enable the researchers to determine the trade-offs for various cases (Figure 15).

Today's single-aisle reference aircraft use high damage tolerance 2xxx alloys for the lower and high strength 7xxx alloys for the upper wing panels. The switch to FSW wing panels and bonded stringers without changing the materials already leads to a two digit cost and weight savings, thanks to the bonded design concept, as well as reducing the manufacturing cost and the decrease of the buy-to-fly ratios.

(a)

(b)

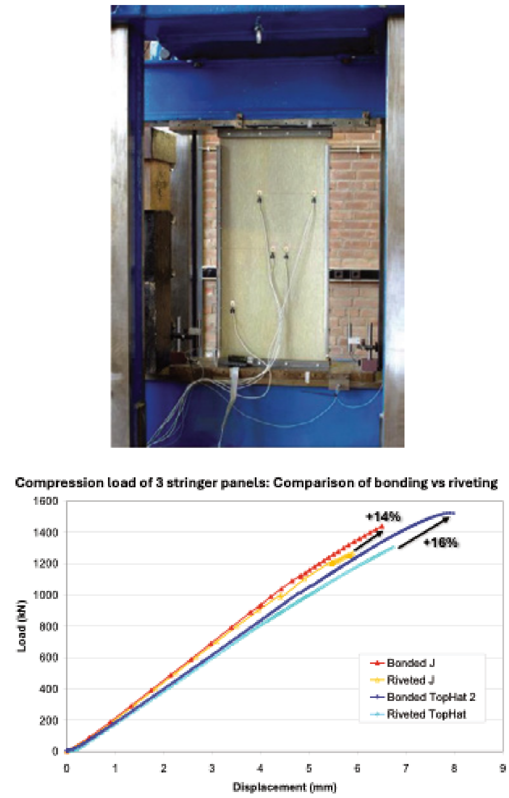


Figure 14. Panel set-up in the compression device (a) and the results obtained in maximum load for the bonded and riveted panels with J- and top-hat stringer geometries (b).

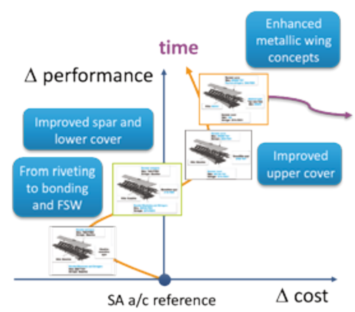


Figure 15. Trade study summary for the enhanced technologies applicable on single-aisle aircraft.

By adding an enhanced spar design to allow the introduction of an improved lower wing skin alloy, the wing box behavior improves even further. The main enablers of the performance increase are the introduction of the lower wing skin alloy AW236 and the enhancement of the crack propagation behavior—either with a constant (+22%) or a variable amplitude (+38%).

The trend to further increase (even double) the performance of the design of the wing box, as well as to make the aluminum alloys competitive with other material options, can be continued by material changes of the stringer materials and the upper wing skin. Lightweighting the wing box can be achieved with the introduction of 2076 alloy lower wing stringers with 5% lower density, nearly 20% higher strength, and 5% higher stiffness; very high strength 2065 alloy upper wing stringers, with 4% higher strength, 6% increased stiffness, and 5% improved density; and an AW226 alloy upper wing with a high strength and toughness balance.

The increase in cost is mainly linked to the material choices, because the manufacturing process is more costly than standard alloys. Nevertheless, the cost remains very competitive to other material choices. Moreover, the technologies considered maintain the excellent levels of the robustness and the high build rate capability of current metal technologies.

To continue to decrease the weight of the outer wing box, the lower wing skin needs to be continually improved. Lower maturity concepts are considered, such as a further improved AW236 alloy for a monolithic lower wing skin or the nearly complete elimination of the fatigue crack propagation by applying fiber metal laminate concepts.

Additionally, it is anticipated that use of Airware combined with FSW and bonding technology will allow for increased inspection intervals. Indeed, the improved corrosion and fatigue of aluminum-lithium alloys and the reduced number of holes in the structure thanks to these technologies will optimize the metallic wing behavior in regards to durability.

The Wing of the Future Project is increasing the maturity of the discussed technologies through the well-known test pyramid (Figure 16). With this method, compression and tensile loaded panels are designed and tested up to sub-component level to validate the performance axis of the discussed trade study. Manufacturing demonstrators up to large sub-component level are being developed, including some full-size features, to increase the confidence on the recurring cost data to continuously monitor the competitiveness of metallic solutions.

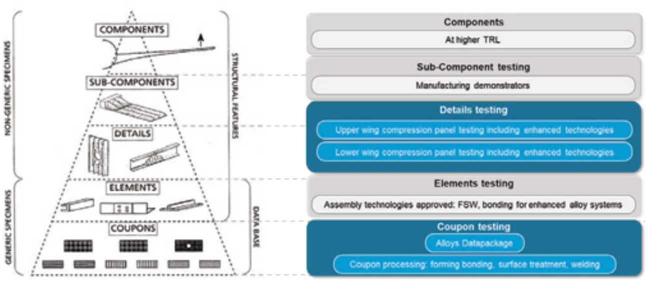


Figure 16. Test pyramid to be used as working protocol for increasing technology maturity within the Wing of the Future Project.

Aerospace Structures with Low Carbon Footprint

In addition to the engineering work, all concepts studied in the project were analyzed in regards to life cycle considerations focusing on the airframe structure. As summarized in Figure 17, metallic solutions have the potential to be fully circular without any loss of performance. New supply chain concepts need to be considered to guarantee good alloy segregation and ensure the scrap has value and provides the highest benefit. The objective is the optimization of the buy-to-fly ratio and a circular manufacturing concept to allow for the introduction of high-performance alloys with a high level of competitiveness, while minimizing the introduction of primary metal.

Depending on the primary metal source, the carbon footprint can vary significantly. But even primary metal production with the lowest CO_2 emissions is still eight times higher compared to the emissions generated by the energy required to recycle the scrap (Figure 18). All scenarios of the trade studies discussed will receive a life cycle analysis to quantitively evaluate the CO_2 footprint with the aim of having even better enhanced options compared to the current baseline.

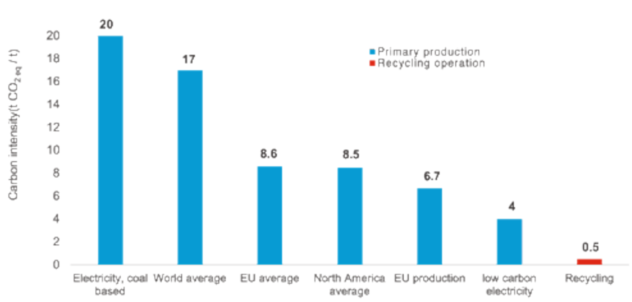


Figure 17. Recycling loop for aluminum structural parts.

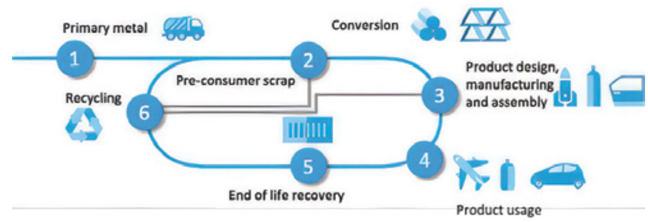


Figure 18. Carbon intensity of aluminum, based on primary production versus recycling.

Conclusion

Since the launch of the enhanced engine options for the single aircraft families, a significant decrease in fuel consumption has been achieved even if the core of the airframe structure has not significantly changed. The Wing of the Future Project is investigating enhanced structural technologies while remaining close to the conventional architecture (for example, excluding concepts changing the aspect ratio of the wing). Even without consideration of aeroelastic aspects, significant improvements of the outer wing box are presented and will be demonstrated following the test pyramid procedure to increase the technical readiness levels.

Trade studies have been demonstrating the high potential of improved cost-performance scenarios to maintain the competitiveness of aluminum options for new single aisle architectures, as well as to continue improving their competitiveness for the current flying aircraft. The trade studies and the key technologies presented will now be translated into hardware testing within the Wing of the Future Project to confirm the cost-performance targets within advanced supply chain scenarios, while further aligning with a circular airframe structural design in order to continuously decrease the carbon footprint.

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