Considerations regarding aluminum alloys used in the aeronautic/aerospace industry and use of wire arc additive manufacturing WAAM for their industrial applications

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1. Introduction

Aluminum and aluminum alloys are widely used in many applications in various top industrial fields.

From the beginning of the development of aeronautics and aerospace industries (since the 19th century), aluminum alloys began to be used to the manufacturing of flight vehicles components (e.g. airship vehicles), due to their low weight, high mechanical strength and high corrosion resistance.

Aluminum has also been used since the early 20th century to make components for aircraft, for example: engine housing, cylinder block and other components of aircraft engines [1-3].

During the same period, the heat treatment of an aluminum alloy was carried out for the first time, which was a remarkable technical progress at that time, which later led to the massive use of aluminum in aeronautical and aerospace engineering, aluminum alloys becoming the most widely used materials from these top industries.

The classification of aluminum alloys according to the main alloying elements includes eight series of alloys, presented in the tab. 1, for which it is mentioned whether or not they are heat treatable, as well as mechanical strengths [4]. Alloys from the 1xxx, 3xxx and 5xxx series are not heat-treatable. Alloys from the 2xxx, 6xxx and 7xxx series are heat treatable. The 4xxx series of aluminum alloys includes both heat-treatable and non-heat-treatable alloys. For non-heat-treatable alloys, their characteristics and properties depend on the cold processing degree. The different chemical compositions, as well as the different mechanical and metallurgical properties of the aluminum alloy series, determine the different behavior of the alloys in the manufacturing processes as well as in welding.

Table 1. Aluminum alloys classification [4].

Series	Main alloying element	Heat treatable		Rm [MPa]
1xxx	Pure commercial aluminum		No	70-175
2xxx	Copper, heat treatable	Yes		170-520
3xxx	Manganese		No	140-280
4xxx	Silicon	Yes	No	105-350
5xxx	Magnesium		No	140-380
6xxx	Magnesium and silicon	Yes		150-380
7xxx	Zinc, heat treatable	Yes		380-620
8xxx	Other alloying elements	Yes		280-560

The properties and characteristics of aluminum alloys make some of them a suitable choice for the aeronautics and aerospace industries [3, 4], for the following reasons:

- the use of aluminum alloys to make components for the structure of aircraft gives them a much lower weight. With a density of about 1/3 of the steel density, the use of aluminum alloys in construction of aircraft structural elements reduces their total mass and thus allows them to become more efficient in terms of fuel consumption;
- the high mechanical strength of some aluminum alloys allows their use to replace some components and structural elements made of higher density metallic materials, while maintaining the mechanical strength of those metals and at the same time benefiting from a lower weight of the components. Under these conditions, the benefits of using high-strength aluminum alloys contribute to increasing the cost-effectiveness of the manufacturing process;
- the high corrosion resistance of aluminum and aluminum alloys recommends their use to make components for aircrafts which operating or coming into contact with various corrosive environments (e.g. salt water, various chemicals, etc., which during time, may have dangerous effects on the structural integrity of aircrafts).

In aerospace engineering are common aluminum alloys which are used in a number of applications, but also some lesser-known alloys, with possibilities for future use, as materials for the aeronautics and aerospace industries [1, 2].

Over time, the aeronautics and aerospace industries have increasing technical requirements for materials used in these fields. The development of air transport and the need for international long-distance flights has required a great industrial progress, which led to the fabrication of aircraft with high technical performances. The aeronautics industry has had to find solutions for the materials used to make the various aircraft components (e.g. aircraft body, aircraft engine parts, etc.), materials which must have very high durability and resistance to fatigue, which has contributed to the development and use on a large scale of many different types of aluminum alloys [1, 3].

2. Aluminum alloys for use in aeronautics and aerospace industries

The aerospace industry uses quite a lot of aluminum alloys (especially from the 2xxx, 5xxx, 6xxx and 7xxx series) to withstand the low temperature conditions and even below zero degrees, encountered in space. Aluminum alloys used for the manufacturing of structural and interior elements of aircraft and aerospace vehicles have high durability and high resistance to different types of corrosion. These alloys have high stability and are very suitable for use in manufacturing of mechanical components, where the high electrical conductivity of aluminum is important [5].

2.1. Aluminum alloys (2xxx, 5xxx, 6xxx and 7xxx series)

For the manufacturing of different types of components from aircrafts (fuselage structural elements, wings and support structures, etc.) some common aluminum alloys are used (especially in T3, T6 and T7 tempers). Table 2 presents a brief description of the main variants of material tempers, some of them with several subdivisions [6, 7].

Table 2. The main temper variants [6, 7].

Temper and short description	
T1	Cooled from an elevated temperature shaping process and naturally aged to a substantially stable condition
T2	Cooled from an elevated temperature shaping process, cold worked and naturally aged to a substantially stable condition
T3	Solution heat treated, cold worked and naturally aged to a substantially stable condition
T4	Solution heat treated and naturally aged
T5	Cooled from an elevated temperature shaping process and then artificially aged
T6	Solution heat treated and then artificially aged
T7	Solution heat treated and artificially overaged / stabilized to control important properties
T8	Solution heat treated, cold worked and then artificially aged
T9	Solution heat treated, artificially aged and then cold worked
T10	Cooled from an elevated temperature shaping process, cold worked and then artificially aged

Solution heat treatment involves heating the product to a solutionizing temperature, holding at temperature long enough to allow constituents to enter into solid solution and cooling rapidly enough to hold constituents in solution [7].

The 2024 aluminum alloy is probably the most commonly used in aerospace engineering. This alloy, whose main alloying element is copper, was developed after experiments that allowed small cold deformations and a period of natural aging that led to an increase in the yield strenght. When the material is in the annealing state, it has a good formability and machinability. Although it has a relatively low level of corrosion resistance, lower than Al 6061 [30], it can be hot or cold processed until a high finish is obtained. Generally, joining by welding is not recommended for 2024-T3 alloy [2]. If welding is required, arc and consumable electrode welding in an inert gas environment can be applied. Being a high quality alloy, with high tensile strength of approx. 470 MPa, with excellent fatigue resistance, 2024-T3 aluminum alloy is used in the aeronautical industry to make fuselage elements (fuselage skin, fuselage frames / bulkheads), wing tensioning elements, ribs and spars, wing lower panels and stingers, empennage (tail), stiffeners elements for commercial and military aircrafts (e.g. fuselage components of Space Shuttle Orbiter, wings and vertical tails, fuselage panels of Eclipse 500 aircraft) [1,3,5,8,9,10].

The 2014 aluminum alloy (second as use in aeronautics, after 2024 aluminum alloy) is characterized as strong, hard metal, suitable for arc and resistance welding. However, it is used mainly to make elements for the internal structure of the aircraft and less in the external elements of the aircraft body, because it has a low corrosion resistance. [1, 8].

The 2219 aluminum alloy offers maximum resistance to high temperatures. An important application in which this alloy was used is the external fuel tank from the Columbia space shuttle. This alloy has good weldability, good breaking strength and at extreme temperatures, but welds need heat treatment to maintain corrosion resistance [1, 8]. Due to its properties, this alloy is the basis for developing propulsion tanks made of Al-Li alloy (resulting in the Weldalite family of alloys [10]).

The 2224 aluminum alloy is an improved version of the 2024 alloy, which was developed based on the technical requirements for Boeing 757 and 767 aircrafts [11].

It has high breaking strength, having copper as main alloying element, but also a significant content of magnesium and manganese. It has a low content of iron and silicon. It is used to make structural components for Boeing 767 aircraft, components of aerospace structures, aircraft wings, wing lower ribs, etc. [5, 12].

The 5052 aluminum alloy belongs to the category of non-heat-treatable alloys, offers the highest strength of alloys in this class and is very ductile, so it can be formed into different shapes. It is also very resistant to saltwater corrosion in marine environments [1, 3, 5, 8]. This alloy can be easily welded using the most usual techniques, having some of the best welding characteristics. It is used in various commercial and industrial applications, including: tanks and panel components [2, 3].

The 6013 aluminum alloy has high strength, good formability and weldability, very good compression properties, as well as excellent corrosion resistance.

It has a good resistance to stress cracking and is hardenable by aging. It is often marketed in the T4 condition and can be aged to the T6 condition [13]. It is a very important alloy for the fabrication of parts for military and civil aircrafts (e.g. fuselage skin - 6013-T78), respectively for many industrial applications (e.g. ABS braking systems, different types of valves, hydraulic applications, etc.)

The 6061 aluminum alloy is a common lightweight alloy, with high mechanical strength, which is suitable for use to manufacturing of components for light aircrafts. The alloy has a very good weldability, is easy to use, process and handle, has corrosion resistance in the marine environment and in atmospheric conditions, being recommended for manufacturing of fuselages and wings elements [1, 3, 8, 14].

The 6063 aluminum alloy is found in fine detail elements, being used mainly for aesthetic and architectural finishes. This alloy is mainly used for components with complicated extrusions [1, 8].

The 7010 aluminum alloy has zinc as main alloying element, being used in the fabrication of high strength components for the aerospace field (e.g. ribs and spars). It has very high resistance to fatigue and corrosion. In the T76 condition, the material is heat treated and stabilized by artificial over-aging, its degree being chosen so that the corrosion resistance by exfoliation to be maximum [5, 15].

The 7050 aluminum alloy is one of the better choice for aerospace applications, is a heat-treatable alloy with high corrosion resistance and which maintains its resistance in wide sections, being more resistant to breakage (including negative temperatures), to corrosion and more durable than other aluminum alloys (e.g. 7075). It has a high content of zinc and copper as alloying elements, a high ratio between zinc and magnesium, contains zirconium instead of chromium, for a microstructure with fine grains, respectively a low content of iron and silicon. These changes in the alloy composition, together with an aging treatment, lead also to a high fatigue resistance. It is frequently used in the aerospace industry, in the T6 condition to making the external structure of the wings and fuselages, fuselage frames / bulkheads; in the T76 condition for empennage tail, landing gear support parts, as well as the fabrication of various parts especially for military aircrafts [1, 3, 8, 16]. Welding is not recommended due to its reduced properties and characteristics.

The 7055 aluminum alloy is a new alloy in the 7xxx series, developed in 1991, mainly for use in structures that are subjected to compression stresses. It has advantages compared to 7150 aluminum alloy in terms of compressive and tensile strength, while maintaining its breaking and corrosion resistance.

The 7055-T77 alloy is best choice for industrial applications in which compressive strength is extremely important, such as wing upper structures, wing upper skin and wing upper stringers, horizontal stabilizer and keel beams from aircraft or spacecraft structures.

Compared to 7150 (T651 or T7751), 7055-T77 alloy brings a 7-10% increase in compressive strength and yield strength, which allows significant weight savings compared to 7150 alloy [17].

The 7068 aluminum alloy is the strongest aluminum alloy currently available on the commercial market, high corrosion resistance and low weight make it perfect for military aircraft applicqtion that have to withstand difficult conditions and attacks [1, 3, 5, 8].

The 7075 aluminum alloy has a resistance similar to that of steel due to high zinc content, as well as excellent fatigue resistance and at low temperatures [18]. Zinc is the main alloying element in 7075 aluminum alloy. Its strength is similar to that of many types of steels and has good processing properties, which led to the choice of 7075 aluminum alloy as a material for making components and modules from fighter jets (e.g. Mitsubishi A6M Zero, during World War II)). This aluminum alloy is frequently used in the manufacture of components for military and civil aircrafts. In T6 condition is used for fuselage elements (skin, frames / bulkheads, stringers), wings elements (upper skin, lower and upper stringers, lower panels) and empennage (tail). In T73 condition is used for aircraft fuselage ribs, high-stressed structural parts, aircraft fittings, missile components, gears, shafts, safety parts and other components for aircrafts and aerospace vehicles [1, 3, 5, 8, 14]. If joining by welding is required for this alloy, resistance welding is recommended to be used to join parts made of this alloy.

The 7085 aluminum alloy is used in aerospace applications (T7651 – ribs, spars) because it offers a good combination of strength and hardness for parts made of thick or very thick material. This alloy is part of the new generation of high-strength alloys for thick sheets. Compared to the 7010 and 7050 aluminum alloys, this alloy contains more zinc and less copper and magnesium, which gives the combination of the mentioned properties [5, 19].

The 7150 aluminum alloy was developed as a new generation derived from the 7050 aluminum alloy, in the T6 and T77 condition being used in the aeronautical field especially for the fabrication of aircraft wings elements (upper skin, upper ribs), fuselage ribs and spars. It is a heat-treatable alloy, has high mechanical strength and corrosion resistance, in the T77 condition obtaining the best combination of these properties.

Table 3. Chemical composition of the mentioned aluminum alloys.

Al alloy	Chemical composition										References
	Cu	Mg	Mn	Zn	Cr	Fe	Si	Ti	Zr	other	Al	
2024	4.4	1.5	0,6								balance	[31,33]
2014	4.4	0.5	0,6		≤0.1		0.8					[70]
2219	5.8-6.8	0.02	0.2-0.4	0.1		0.3	0.2	0.02-0.1	0.1-0.25			[10]
2224	3.8-4.4	1.2-1.8	0.3-0.9	≤0.25	≤0.1	≤0.15	≤0.12	≤0.15		≤0.15		[70]
5052		2.5			0.25							[31]
6013	0.6-1.1	0.8-1.2	0.2-0.8	≤0.25	≤0.1	≤0.5	0.6-1.0	≤0.1				[70]
6061	0.15-0.04	0.8-1.2			0.04-0.35	≤0.7	0.4-0.8	≤0.15				[31]
6063	≤0.1	0.4-0.9	≤0.1	≤0.1	≤0.1	≤0.35	0.2-0.6	≤0.1				[70]
7010	1.5-2.0	2.1-2.6	0.1	5.7-6.7	0.05	0.15	0.12	0.06	0.1-0.6	0.2		[70]
7050	2.3	2.3		6.2					0.2			[31]
7055	2-2.6	1.8-2.3	≤0.05	7.6-8.4	≤0.04	≤0.15	≤0.1	≤0.06	0.08-0.25	≤0.05		[70]
7068	1.6-2.4	2.2-3		7.3-8.3					0.05-0.15			[31]
7075	1.2-2.0	2.1-2.9	0.30	5.1-6.1	0.18-0.28	0.5	0.4	0.2				[31]
7085	1.3-2.0	1.2-1.8	≤0.04	7.0-8.0	≤0.04	≤0.08	≤0.06	≤0.06	0.08-0.15	≤0.15		[70]
7150	1.2-1.9	2.0-2.9	≤0.2	7.2-8.2	0.1-0.22	≤0.2	≤0.15	≤0.1		≤0.15		[70]
7175	1.6	2.5		5.6	0.23							[70]
7475		2.3		5.7	0.22		1.5					[70]

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The 7150 and 7050 aluminum alloys, used together, lead to the production of quality components for passenger aircraft (e.g. Boeing 777), military transport and fighter aircrafts. [20].

The 7175 aluminum alloy was developed starting from the 7075 aluminum alloy, it is heat treatable and it has high resistance to breakage and corrosion, determined by a low content of iron and silicon. The T73 material condition eliminates the development of corrosion cracks. It is an alloy widely used in the manufacture of components in the aerospace industry (e.g. wing lower panels) [5, 21]

The 7475 aluminum alloy is high resistant to breakage and fatigue and due to its strength, it is sometimes found in structural elements of the bulkheads of larger aircrafts (7475-T6 - fuselage skin, 7475-T73 – wing lower skin, 7475-T76 - fuselage ribs) [1, 4, 8, 14].

Table 3 show the chemical composition of aluminum alloys above mentioned.

2.2. Aluminum-lithium alloys for application in aeronautics and aerospace industries

Al-Li alloys are a category of extremely important alloys that are part of the 2xxx series, widely used in the aeronautics and aerospace industries, for aircraft structures, aerospace structures, launch vehicles, satellites and helicopters [10, 22].

Al-Li alloys have been developed since 1920, with the first generation of Al-Li alloys, which was later improved by adding about 2% Li in order to reduce the weight of the alloys through a lower material density (with 8 -10% lighter and stiffer than the usual ones from the series of aluminum alloys 2xxx and 7xxx respectively), thus obtaining the second generation of Al-Li alloys.The analysis of these alloys found that a lithium content of 2% or more caused several disadvantages (e.g. tendency to have strongly anisotropic mechanical properties, low transverse ductility of the material, decreased breaking strength, etc.) [10].

The development of these alloys has continued intensely since the 1990s, to obtain Al-Li alloys (tab.4) with low lithium content (but with slightly higher densities than the second generation) that have an excellent combination of characteristics and properties necessary for engineering applications, resulting (after 2000) third-generation of Al-Li alloys with multiple applications in aerospace industry [2].

Table 4. Al-Li aluminum alloys (third generation) [2].

Alloy	Li [%]	Cu [%]	Mg [%]	Ag [%]	Mn [%]	Zn [%]	Zr [%]	Density [g/cm^3]	Year
2050	1.00	3.60	0.40	0.40	0.35	≤0.25	0.11	2.70	2004
2055	1.15	3.70	0.40	0.40	0.30	0.50	0.11	2.70	2012
2060	0.75	3.95	0.85	0.25	0.30	0.40	0.11	2.72	2011
2076	1.50	2.35	0.50	0.28	0.33	≤0.30	0.11	2.64	2012
2098	1.05	3.50	0.53	0.43	≤0.35	0.35	0.11	2.70	2000
2099	1.80	2.70	0.30	-	0.03	0.70	0.99	2.63	2003
2195	1.00	4.00	0.40	0.40			0.11	2.71	1995
2196	1.76	2.90	0.50	0.40	≤0.35	≤0.35	0.11	2.63	2000
2198	1.00	3.20	0.50	0.40	≤0.50	≤0.35	0.11	2.69	2005
2199	1.60	2.60	0.20		0.30	0.60	0.09	2.64	2005
2297	1.40	2.80	≤0.25		0.30	≤0.50	0.11	2.65	1997
2397	1.40	2.80	≤0.25		0.30	0.10	0.11	2.65	2002

The density of the third generation Al-Li alloys is 2 - 8% lower than the conventional aluminum alloys from the 2xxx series (2.77 - 2.80 g/cm^3) and from the 7xxx series (2.80 - 2.85 g/cm^3), the density of the material being very important influence factor on the efficiency of the aeronautical / aerospace structures.

Also, the third generation of Al-Li alloys brings improvements compared to the aluminum alloys of 2xxx and 7xxx series, in terms of specific rigidity and specific buckling resistance of the material. Thus, the specific stiffness of the third generation Al-Li alloys is 28.9-31.2 GPa/(g/cm^3) being on average with ~13% higher than the aluminum alloys of the 2xxx series and with ~ 15% (on average) higher than those in the 7xxx series.

At the same time, the specific buckling resistance of the third generation Al-Li alloys is ~1.58-1.65(GPa)$^{1/3}$/(g/cm^3), with ~8% higher than 2xxx aluminum alloys, respectively with ~9.5% higher than 7xxx aluminum alloys [10].

Specific rigidity and specific buckling resistance are important parameters in the design and manufacture of components in the aeronautical and aerospace fields. Specific rigidity is especially important for elements such as lower surfaces of the wings, frames, ribs; specific buckling strength being important for fuselages and wing upper surfaces of aircrafts, respectively for aerospace vehicles [10].

The reduction of the material density, simultaneously with the increase of the specific rigidity and of the specific buckling resistance, constitutes important elements for reduction of the components weight, with effect on their efficiency increase.

The structural elements of aircraft / aerospace vehicles are subject to complex and multidirectional stresses, which lead to the idea that the isotropic mechanical properties of the materials used are very important. This is one of the main reasons that led to the need to develop the third generation of Al-Li alloys.

The use of these high-performance (third-generation) Al-Li alloys in aerospace applications offers the opportunity to save significant amounts of materials, as well as the possibility of developing and using new unconventional joining processes of them.

The development of third-generation Al-Li alloys is ongoing, most of these alloys being developed since year 2000. Some of Al-Li alloys from the 3rd generation have been used to manufacturing of various elements for aerospace structures, including civil and military aircrafts, respectively spacecraft and launch vehicles [10]:

- The 2050 aluminum alloy is a third generation Al-Li alloy used (in the T84 condition, with medium strength) to make important structural elements, such as elements of internal structure of aircraft wings, elements of reinforcement of the lower wings (Airbus A380), components of the internal structure of the aircraft, ribs, spars, wing lower skin, elements of the wings and forged fuselage (in the T852 condition), etc. It is also used to make parts at the bottom (most loaded part) of vehicles for the space transportation of equipments for space and scientific space missions.

The 2050-T84 alloy (in the form of sheets) can be used as a replacement for the 7050-T7451 aluminum alloy in the manufacture of spars, ribs and other elements of internal structures.

The 2050 alloy in the T852 condition (forged) can replace the 7175-T7531 and 7050-T7452 aluminum alloys to fabrication of accessories for aircraft wings or fuselage;

- The 2055 aluminum alloy has a medium / high strength, it can be used (in the T8E83 condition) to make ribs, floor beams, seat rails, upper wing ribs. In the T8X condition and in the form of sheet, it can replace 7055 (T7751 and T7951) alloys, as well as 7150-T7751 and 7255-T7951 alloys when making skin elements for the upper wings of aircrafts. In extruded form, alloy 2055-T8E83 can replace alloys 7055 (T7751 and T79511), 7075 (T73511 and T79511), 7150 – T6511 and 7175-T79511 to fabrication of the above-mentioned elements;

- The 2060 aluminum alloy is resistant to damage and can be used on fuselage elements (in the T8E30 condition), wing lower skin (T8E86), forged wings / fuselage (T8E50). In the form of sheets / sheets, it can replace (in the T8E30 condition) 2024-T3 and 2524-T3 alloys when making fuselage elements, pressure cabin cover, and in the T8E86 condition it can replace 2024-T351, 2324-T39, 2624 -T351, 2624-T39 alloys when making elements from lower wings. As a forged material, the 2060 aluminum alloy (T8E50) has a high resistance and can replace the 7175-T7351 and 7050-T7452 aluminum alloys when making wing / fuselage accessories;

- The 2076 aluminum alloy, extruded, in the T8511 condition, is resistant to damage and can be used to make tensioners and wings lower skin, fuselage elements and pressure cabins. It can replace the 2024 (T3511 and T4312), 2026-3511 and 6110-T6511 aluminum alloys when making the mentioned components;

- The 2098 aluminum alloy has medium strength, and in the form of sheets / sheets (in the T82P condition) can be used to make fuselage panels from F16 aircraft, and can be a replacement for the 2024-T62 aluminum alloy. It can also be used to make elements of internal structure from aircrafts;

- The 2099 aluminum alloy in the form of sheets has a medium strength, being used to make internal structure elements from the fuselage and ribs (in the T86 condition), being able to replace the 7050-T7451 and 7x75-T7xxx aluminum alloys. As an extruded material, in the T81 condition it has a high strength and has the same uses as those mentioned to the 2076 –T8511 aluminum alloy. In the T83 condition, as an extruded material, it has a medium / high strength and can be used similarly to 2055-T8E83 aluminum alloy, especially for floor beams, seat rails, frames, lower wings, panels and fuselage elements (e.g. on the Airbus A380), being able to replace the same 7xxx series aluminum alloys;

- The 2195 aluminum alloy was developed in 1992. In the form of sheets (in the T82 condition) it has a high resistance and can be used to make elements from the wings upper skin. It can replace 7150-T7751, 7055 (T7751 and T7951), respectively 7255-T7951 aluminum alloys. It is also used for constructive elements from the external tank of the Space Shuttle Super Lightweight (first launched in 1998); to make (by welding) large panels from cryogenic tanks, as well as dome shape elements from fuel tanks for aerospace vehicles;

- The 2196 aluminum alloy is used in the manufacture of fuselage elements, pressure cabins, frames, ribs, upper wings elements, floor beams and seat rails (as extruded material, in the T8511 condition). It can replace 7055 (T7751 and T79511), 7075 (T73511 and T79511), 7150 – T6511 and 7175-T79511 aluminum alloys when making the elements mentioned above;

- The 2198 aluminum alloy has good specific rigidity and compressive strength, it can be used to make (by FSW welding) the tanks and fuselage elements from the SpaceX Falcon 9 launcher. In the form of sheets (T8 condition) it is resistant to damage and has a medium strength, being able to replace the 2024-T3 and 2524-T3 aluminum alloys to make fuselage elements and pressure cabins;

- The 2199 aluminum alloy in the form of sheets is resistant to damage and can be used (in the T86 condition) to make elements from the lower wings, and in the T8E74 condition to pressure cabins, fuselage elements and panels, as well as for lower wings. Can be used as a replacement for 2024-T3 and 2524-T3 aluminum alloys;

- The 2297 aluminum alloy is used to manufacturing of bulkheads (Lockheed Martin F-16) and other components of military aircraft, as well as for various panels for space shuttles, due to its high elastic modulus and low density;

- The 2397 aluminum alloy is used to make fuselage bulkheads (Lockheed Martin F-16) and other parts of military aircraft. This material is a medium strength alloy which could replace the 2124-T851 aluminum alloy in some applications.

Compared to classical / conventional aluminum alloys, Al-Li alloys are materials that are improved in terms of characteristics and properties, low density, strength and rigidity (elastic modulus) helping to reduce the weight of the components made. They are recommended for use in the aerospace industry due to their properties, which are corresponding to the technical performance requirements and loads/stresses to which various structural elements of aircraft and aerospace vehicles are subjected. The corrosion resistance of Al-Li alloys (especially in the form of sheets / plates) is very important, the use of these alloys instead of conventional alloys 2xxx and 7xxx may eliminate the need to apply coatings (low strength) to prevent corrosion, layers that add extra weight to the components made.

In addition, by using 3rd generation of Al-Li alloys, greater weight savings are possible (taking into account higher stiffness and specific strength), more efficient structural concepts can be applied and unconventional joining processes can be used (e.g. eg laser beam welding, friction stir welding) and superplastic forming [10].

Laser beam welding can be performed automatically, with high welding speeds. During the welding process, a small amount of heat is developed and very small welding seams are obtained. It can be applied to the fabrication of fuselage panels made of 6xxx aluminum alloys (since year 2001 it has been applied for components of A318, A340 and A380 aircrafts).

Research is currently being carried out (within the European aeronautical research program “Clean Sky”) on the application of laser beam welding to third generation Al-Li alloys (e.g. 2196 and 2198), for the production of fuselage panels from Al-Li alloys [10].

Friction stir welding is a process that can be applied to make welded joints with simple geometries (especially butt joints), the positioning and fixing of the joining components being done with special clamping systems. FSW welding has multiple aerospace applications [10], such as:

- large panels from Al-Li 2195 alloy cryogenic tanks (from Lockheed Martin);
- fully stiffened panels (case study for innovative structural concepts);
- longitudinal joints for 2024 aluminum fuselage panels (Eclipse 500 aircraft);
- making various components for aircrafts (e.g. Airbus and Embraer);

- jointing of Al-Li alloy components of the Orion Crew module (including a 11.3 m long circumferential weld to join two specific elements of it);
- fuselage elements from Al-Li 2198 (SpaceX Falcon 9 space launch system);
- the manufacture of elements (dome type) of 2195 Al-Li alloy of the fuel tank, respectively the joining of component parts of the main tank (conventional aluminum alloy) of the Ariane 5 rocket launcher.

The application of the FSW welding process to the development of components of the SpaceX Falcon 9 space launch system and Ariane 5 rocket launchers are major innovations in manufacturing processes, being representative examples of current efforts to implement FSW in the development of components for aerospace vehicles, in order to replace the use of conventional welding.

Superplastic molding: processing can be applied to Al-Li aluminum alloys, as well as other types of aluminum alloys, to obtain superplastic properties. This process was used only in the case of "niche" applications for making sheet metal components with complex geometries [10].

The use of the above processes for applications (made of aluminum alloys) in the aeronautics and aerospace industries, makes important contributions:

- the mechanical fastenings (with rivets and screws) of the structural elements of aircraft and aerospace vehicles are eliminated, thus contributing to the reduction of the weight, the number of their component parts, as well as the reduction of costs. As a result, the corrosion resistance can be increased by reducing the number of fixing holes, gasps and cracks in materials;
- processes can have a high degree of automation with fewer manufacturing steps.

Although these beneficial aspects could also be achievable, for reasons of increased safety regarding the occurrence of defects or breakdowns, frame structures that are fully realized by welding (on commercial transport aircraft) are not accepted.

Case studies on innovative concepts for the use of Al-Li alloys (third generation) to the construction of aircraft structures have seen improvements since the design phase in order to achieve a high tolerance to damage and significant weight savings.

A comparative analysis between a conventional aluminum alloy (2524-T3) and Al-Li alloys (2099 and 2199), used to make fuselage and lower wing panels, showed that the Al-Li alloy panels are approx. 5% lighter than those made of conventional aluminum alloy 2524, also those made of Al-Li alloys bring an improvement of about 25% in strength to complex stresses [10].

2.3. Selection of materials and applications of Al-Li alloys in the aeronautics and aerospace industries

Considering the particular constructive complexity of different types of aircrafts and aerospace vehicles, the choice of material categories and quantities needed to make the various structural components is very important.

The selection of structural material categories for aircraft and aerospace vehicles must take into account:

- type of flight vehicles (e.g. aircrafts, helicopters or aerospace vehicles);
- the structural elements or components in which these materials are used;
- the specific properties of the analyzed materials (including their advantages and disadvantages).

Third-generation Al-Li alloys compete with conventional aluminum alloys, carbon fiber composites and metal fiber laminates for aerospace applications, especially in the construction of elements in transport aircraft structures.

Although the use of these innovative materials is booming in terms of the structural weight of flight vehicles (e.g. transport aircraft), aluminum alloys still account for about 60% of this. On the other hand, there are also transport aircraft (e.g. Boeing 787 Dreamliner), where the degree of use of aluminum alloys changes, being used approx. 50% composite materials and only 20% aluminum alloys [10].

In the case of military aircraft made at a high technical and technological level, in terms of the materials used to make them, the emphasis is increasingly on composite materials and, to a lesser extent, on titanium alloys and aluminum and steel, respectively.

There are well-known industrial companies (e.g. British Aerospace, Alenia Eurofighter, DASA, Lockheed Martin, CASA) that use 35-40% composites and most of which are used for aircraft external skin elements and substructure elements.

In the case of helicopters and light aircrafts, where it is extremely important to keep the weight as low as possible, even 80-90% composite materials can be used in the manufacture of these flight vehicles. [10].

Hybrid structures made mostly of various composite materials, Kevlar, but also of metal materials (e.g. metal frames made of aluminum alloys) could be future solutions for new types of helicopters or other flight vehicles.

When making structural components with complex geometry and which are highly loaded (e.g. cabin frame) it is still recommended to use aluminum alloys [10].

Figure 1 shows a hybrid structure of a helicopter (of the current generation) on which there are highlighted structural elements that are suitable to be made of conventional aluminum alloys or Al-Li alloys (A – skinning and stringer elements, B - skinning and extrusions, C – main cabin frame forging, D - different sheet components and extrusions), observing other elements that can be made of carbon, Kevlar, Nomex or composite materials.

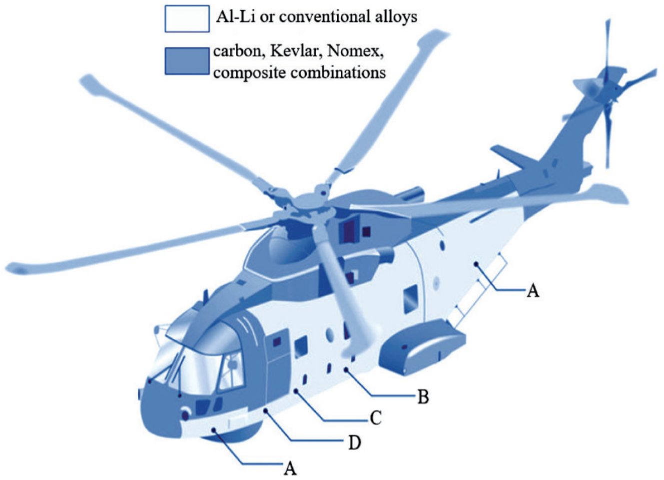


Figure 1. Hybrid metal/composite airframe of helicopter [10].

Another example of a hybrid structure is shown in fig. 2, for an aircraft, important areas where metallic materials (e.g. aluminum alloys) are used, as well as CFRP (Carbon Fiber Reinforced Polymer) composite materials, and GLARE (GLAss REinforced aluminum laminates) being highlighted.

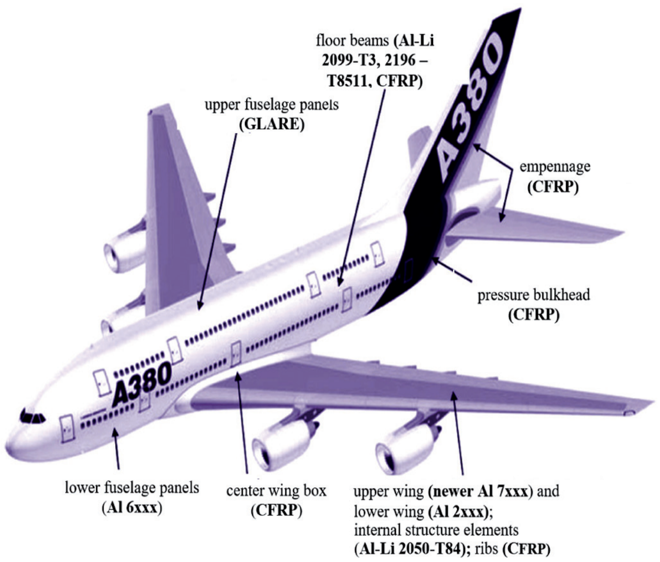


Figure 2. Hybrid metal/composite airframe of aircraft [10].

Considering the development of Al-Li alloys (third generation) in the last ten years, several of them have been accepted/approved for use in the manufacture of components for commercial transport aircraft. The data presented in Chapter 2.2 on Al-Li alloys, as well as in fig. 3 show that Al-Li alloys can successfully replace conventional aluminum alloys in different applications. Al-Li alloys are developed in a wide range of alloys with different material conditions (temper), which allows to obtain optimized properties of materials and also the possibility to select the materials which best corresponds to a specific application.

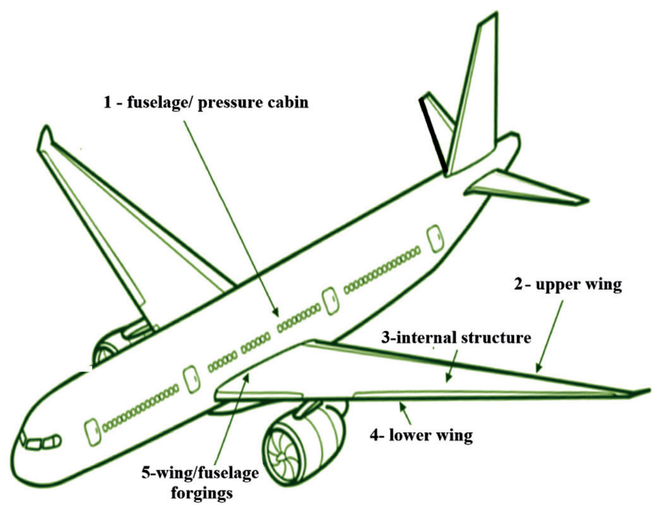


Figure 3. Aircraft structure elements – use of Al-Li alloys [10].

Zones 1-5 of fig. 3 represent major elements of aircraft structure where Al-Li alloys can be used. Table 5 shows the types of Al-Li alloys used to make various elements of the aircraft structure in correlation with the areas shown in fig. 3.

Table 5. Al-Li alloys used to aircraft structure elements [10].

Zone	Element of structure	Al-Li alloys used
1. Fuselage/ pressure cabin	skins	2198-T8, 2199-T8E74, 2060-T8E30
	stringers	2099-T83, 2055-T8E83, 2196-T8511
	frames	2099-T83, 2099-T81
	floor beam, seat rails	2099-T83, 2196-T8511, 2055-T8E83
	internal structures	2098-T82P, 2099-T86, 2050-T84
2. Upper wing	covers	2055-T8X, 2195-T82
	stringers	2099-T83, 2055-T8E831
3. Internal structure	spars, ribs	2050-T84
4. Lower wing	covers	2199-T86, 2060-T8E86, 2050-T84
	stringers	2099-T81, 2099-T83, 2076-T8511
5. Wing/ fuselage forgins	various elements	2050-T852, 2060 T8E50

Regarding to Al-Li alloys (3rd generation) in the case of smaller aircraft or helicopters, respectively in the production of components for high-performance military aircrafts, the possibility of using them under the conditions in that aluminum alloy manufacturers will develop such materials at competitive prices that will allow a greater use of them.

For the construction of components in the structure of spacecraft (especially cryogenic fuel tanks and pressure vessels) and satellite structures, the selection of aluminum alloys must take into account: their resistance to stress (static, dynamic, thermal, etc.) to which they are subjected during the space launch process and during space operations, properties that allow operation at cryogenic temperatures, a very good / excellent workability of the material, reliability, as well as costs (of material and manufacturing) at medium level. For example, some types of aluminum alloys used for such applications are: 7075 and 2219 (components of the structure of the Apollo module); 2024, 2124 and 2219 (components from the fuselage, wings, vertical tail - Space Shuttle Orbiter); respectively 2xxx and 7xxx alloys for making components for satellites.

Regarding the use of Al-Li alloys for applications in space programs, the information is quite limited. These relate to the use of Al-Li alloys (2050, 2195, 2198, 2219 and 2295) in vehicle systems for launching and transporting equipment for space and scientific missions [10].

The technical and technological optimization of the components is a continuous activity that aims to increase their performance, since the selection phase of the materials from which they will be made. One such example was the replacement of the 2195 aluminum alloy (used for a fuel tank), with the 2219 aluminum alloy (with lower density, higher strength and rigidity), which led to a reduction by approx. 10% of the weight of the tank [10].

By choosing different categories of materials in order to optimize the flight verhicles in terms of technical performance, their hybrid structures are finally obtained by using conventional aluminum alloys (series 2xxx, 6xxx and 7xxx), Al alloys -Li (from the 3rd generation), but also of components made of composite materials, as well as other materials.

It can be estimated that in the future more and more such hybrid structures will be used (in terms of materials used), in which the share of these materials will vary depending on the type and size of flight vehicle.

3. Use of WAAM on aluminum alloys in the aeronautics and aerospace industries

The welding of aluminum alloys is difficult to achieve by conventional processes, due to the many aspects of material characteristics: high shrinkage on solidification (compared to ferrous metallic materials), cracking on solidification, formation of pore at welding, high coefficient of thermal expansion, oxidation of the material surface, etc.

The occurrence of cracking on solidification is an impediment that creates major problems when welding aluminum, this being closely correlated with the chemical composition of the alloy, respectively with the amount of eutectic that is present in the solidification phase of the material.

Aluminum alloys with a high tendency to crack on solidification are of the type Al-Cu, Al-Si, Al-Mg, Al-Li and Al-Mg-Si, but also the alloys 2024 and 7075 have a high sensitivity to it [23]. At welding of aluminum alloys, the occurence of porosity and cracking on solidification, causes a decrease in the mechanical properties of the joints, which leads to the limitation of the application of conventional welding processes. Porosity is a major problem of aluminum alloys, as they have a higher susceptibility to this defect compared to all other structural metallic materials [24].

In recent years, additive manufacturing has completely changed the methods and manufacturing processes, by the possibility to create three-dimensional components with complex geometries, which can be difficult or impossible to achieve through conventional manufacturing processes.

Additive manufacturing also offers the possibility of reducing the parts manufacturing costs, as well as reducing material waste and manufacturing times [25], being developed and used for production and repair of high performance components for aeronautic and aerospace industries (e.g. commercial/ military aircrafts, space vehicles, etc.) [26, 27].

Wire Arc Additive Manufacturing (WAAM) is a 3D printing process for metallic materials, with an extraordinarily high potential for widespread application in several industrial fields [28, 29].

WAAM uses an arc welding process to perform 3D printing of metal parts. The construction of a part or component by the WAAM process is done by depositing with electric arc of successive layers of material that come from melting of a metal wire, using an electric arc as a heat source.

WAAM allows a great flexibility on how to build parts, as well as obtaining various and complex geometries of the parts made [22, 28, 30].

Also, by using WAAM, some structures with complex 3D geometries, which are difficult to made or which exceed the manufacturing possibilities by using conventional methods and processes, can be designed and made [27].

Research has been conducted on the application of WAAM to a diverse range of materials, demonstrating its potential for large-scale industrial implementation [26].

By using WAAM, deposited materials with certain microstructures, features and properties can be obtained, that are essential for domains where high performance parts and long service life are required, e.g. components for the aeronautics and aerospace industries, operating in complex working environments with varying temperatures and environmental conditions [27].

AM additive manufacturing can also help reduce spare parts stocks. For example airlines companies may have spare parts in stock that may remain unused or become obsolete. A lot of parts, as well as spare parts, can be manufactured by using 3D printing when is necessary, thus eliminate the need for storage or remote transport of them.

The advantages of using WAAM can be summarized as follows: the possibility to make large complex parts by 3D printing [27, 28]; the possibility of use in a wide range of materials [27, 28, 31, 32]; reduced time of making parts by 3D printing [4, 28]; flexibility in making complex parts [4,28], lower costs for process and materials [4, 22, 28-30, 33, 34]; obtaining high quality parts [28], is suitable for repair operations [28, 35].

The limitations of the use of WAAM refer to: the appearance and accumulation of residual stresses and deformations in the material deposited by WAAM [28]; the need for controlled use of shielding gases (for some types of materials) [28]; the qualitative appearance of the deposited surface (requires further finishing) [28], the appearance of environmental influencing factors (temperature and humidity) [1], as well as the lack of standards to ensure the efficient viability of products and components produced by additive manufacturing [1].

WAAM is very topical, research for application to aluminum alloys being of great interest to major universities and research centers.

For example, researches conductted by Cranfield University on the application of WAAM to aluminum alloys has led to the development of some functional components (such as aluminum alloy ribs and cones) and it has been found that the WAAM process could be used in the large scale production of aluminum parts. However, the implementation of WAAM is currently limited by the occurrence, and in this case, of the porosity and low mechanical properties obtained [24].

The porosity and high cracking sensitivity of aluminum alloys when applied WAAM process are closely related to the alloying elements [23] and can occur in both heat-treatable and non-heat-treatable aluminum alloys.

The composition of the wires which are used in WAAM also affects the porosity, so a slight difference in the alloying elements of wires used in WAAM deposition of aluminum alloys can contribute to modification of the material characteristics and solubility of hydrogen, impacting the microstructure and characteristics of the deposited metal [4].

The quality of the WAAM deposited material depends very much on the quality of the wires used. Research using different batches of the same type of wire has shown that there are differences in WAAM material under identical process conditions. A rough surface of the wire, with external and internal defects, with variations in diameter from one batch to another, causes an unstable arc that leads to obtaining layers of material uneven and of lower quality than in the case of wires with a smooth and glossy surface which leadiong to a stable arc and more uniform layers of WAAM deposited metal [4].

Several variants to apply WAAM have been recently developed for optimization of the microstructure and mechanical properties of parts built using WAAM [29]. Some current research and studies recommend a number of methods and techniques for obtaining good results when applying WAAM, such as inter-pass rolling, side rolling, substrate preheating, including non-destructive testing in the process to identify and remedy porosity and defects that may occur [25].

In the case of applying WAAM to aluminum alloys, as in the case of other materials, it is useful to apply inter-layers rolling in order to improve the microstructure by finishing the granulation, reducing residual stresses and deformations that may occur, removing defects, pores, etc.

In order to obtain improved mechanical characteristics (ultimate tensile strength and elongation at break), post-WAAM heat treatments or a combination between inter-layers rolling and post-WAAM heat treatment can be applied [29], obtaining higher mechanical properties (ultimate tensile strength and elongation at break) with the increased of the applied load.

Regarding to the elimination of high porosity and crack sensitivity when applying WAAM (a problem that is highly debated also in the case of aluminum alloys welding), worldwide researches on the use of new WAAM deposition processes / techniques on aluminum alloys, showed that by using the CMT process (which introduces a reduced amount of heat into the process) with its application variants (especially advanced pulsed CMT, CMT-PADV), a lower amount of heat is introduced into the process and together with the application of inter-layers rolling and heat treatments, finished microstructures can be obtained, thus improving the tensile strength and elongation at break for the WAAM deposited metal [23, 24].

3.1. Application of WAAM to Al-Cu-Sn alloys

Al-Cu-Sn alloys are used in the aerospace industry due to their excellent mechanical properties, tin being introduced into these alloys in order to contribute to the finishing of grains to the application of processing processes (e.g. WAAM).

Additive manufacturing WAAM, through its advantages, offers opportunities for the manufacturing of structural components from Al-Cu alloys.

Research on the application of WAAM to these alloys has focused on several directions: analysis of the effect of the amount of heat introduced into the process on the microstructure and mechanical properties of the material deposited by using WAAM, analysis of the effect of CMT process on porosity of Al-Cu alloy deposited in a wall shape by using WAAM, tracking the effect of applying the inter-layers rolling.

The results of these researches show that as the amount of heat increases, the thickness of the deposited layer increases, that the deposited material has excellent microstructure and properties, WAAM having a great potential for industrial applications [36].

When using a larger amount of heat introduced into the process, the microstructure has columnar crystals, while a smaller amount of heat introduced into the process leads to a structure with fine equiaxial grains.

Research on making parts by WAAM deposition using Al-Cu-Sn alloy wire, on a 2219 aluminum alloy support, showed that the number and size of pores increases with the amount of heat introduced into the process, as well as the size of the grains. By applying heat treatments, these deficiencies can be eliminated [36].

Research on the simultaneous use of two Al-Cu-Sn alloy wires for WAAM deposition [37] has shown that in this case the amount of heat introduced into the process is 50% lower than when using a single wire at the same speed.

Also, in the case of using two wires the quality of the deposited material is improved, the porosity is much lower, the microstructure is more uniform with fine grains, the process being more efficient [37].

3.2. Application of WAAM to Al-Cu-Mg alloys

Studies performed on the application of WAAM on Al-Cu-Mg alloys have shown that a great influence on the mechanical characteristics obtained, has the chemical composition of materials. In general, the mechanical strength of the material by using WAAM deposition alone, cannot meet the highly requirements imposed by the aerospace industry. Due to the significant increase in dislocation density and granulation finishing, the tensile strength and yield strength can be increased by applying inter-layers rolling. The strength of WAAM heat-treated aluminum alloys can be considerably increased by applying post-welding heat treatments (e.g. in the case of 2319 aluminum alloy, WAAM deposited by advanced pulsed CMT) to achieve a higher mechanical strength compared to forged material [38].

Aluminum alloys, especially high-strength ones, are prone to WAAM defects. Susceptibility to cracking and low evaporation temperature of some alloying elements contribute to cracking to solidification and pore formation, which reduces the mechanical resistance. The 2024 high-strength and heat-treatable aluminum alloy is widely used in aerospace and military applications, but is not available as wires for use at WAAM. The development of high-strength aluminum wires for WAAM is complex as it requires the preparation of a significant number of chemical compositions for them, given that the Cu / Mg ratio has a great influence on the microstructure, cracking and mechanical properties of Al-Cu-Mg alloys [38].

Research on the application of WAAM to Al-Cu-Mg alloys using pulsed MIG / MAG with two wires (in tandem), aimed at controlling the speed of the wire, to obtain a series of materials deposited with different chemical compositions. The impact of the chemical composition, of the amount of heat introduced and of the microstructure on the cracking tendency was studied, in order to determine a range of chemical compositions in which the cracking susceptibility of Al-Cu-Mg alloys to be minimal. Thus, for the Al-Cu3.6-Mg 2.2 alloy, Al-Cu-Mg1.8 alloy and Al-Cu4.4-Mg1.5 alloy, increases in mechanical strength and yield strength were obtained when applying WAAM in tandem with two wires, respectively by applying heat treatment. In order to solve these issues, special wires should be developed, and through their use in WAAM process, the chemical composition, microstructure and mechanical properties of the deposited material, could be controlled [38].

For example, research has been conducted on WAAM deposition for Al-Cu4.3-Mg1.5 alloy, using 1.2mm diameter wire, on a 2024-T351 aluminum substrate (prepared in advance by washing, drying, mechanical cleaning and degreasing). Material deposition was performed by advanced pulsed CMT, under certain process conditions (with preheating of the first layer, respectively with constant values for: wire speed /

deposition speed, cooling time between layers, shielding gas flow, distance between the wire tip and deposited material). The results of the research showed that under these conditions it is possible to obtain a microstructure with equiaxial grains, a significant increase in hardness (>50%) after applying a post-WAAM heat treatment, as well as significant increases of the mechanical strength (> 60%) and of the yields strengtht (> 115%) [38].

3.3. Application of WAAM to Al-Li alloys

As mentioned in Chapter 2, Al–Li alloys are structural materials of great interest in the aeronautics and aerospace industries, due to their high mechanical strength and low weight (10% ~ 15% lighter and 15% ~ 20% more rigid than other materials), thus being among the most competitive light alloys. However, there are only a few applications of Al-Li alloys in the WAAM additive manufacturing process [39].

The manufacturing (without loss) of complex parts for the aeronautical and aerospace industries is a very important and highly topical research subject. To identify the feasibility of Al-Li alloys for the WAAM process, some research have been done on the use of 2050 aluminum alloy wires to make straight wall parts, using a WAAM system based on variable polarity TIG welding. The influence of post-WAAM heat treatment on the microstructure and properties of the deposited material, hardness and tensile strength, was investigated. The research results showed that the microstructures of 2050 aluminum deposited were different, depending on the location of the layers: fine-grained equiaxial grains in the upper layers and large columnar grains located in the lower layers. After the application of a post-WAAM heat treatment, the mechanical properties were significantly improved [39]. The topic of applying WAAM to Al-Li alloys still requires important research, being an open topic, of great relevance and interest.

3.4. Application of WAAM to Al-Mg alloys

The group of aluminum-magnesium alloys is characterized by medium to high strength, corrosion resistance, good weldability and good fatigue properties. These are alloys used in the manufacture of components for the aeronautic and aerospace industries, being easy to be cold processed and can be easily assembled by welding if they have a magnesium content of more than 3% [40]. Considering that the melting point of the aluminum alloy is low (approx. 660^{0}C), the material being quite fluid, in these conditions it is easy to obtain inter-layers overheating during the WAAM deposition process, resulting in a material deposited with low shape accuracy, coarse structure, low properties and porosity. A study [41] on the inter-layers temperatures shows their influence on the quality of deposited material and the fact that at high inter-layers temperatures, the porosity of the deposited material increases. Other studies [42, 43] performed for WAAM deposition of Al-Mg alloys using advanced CMT have shown that reducing the inter-layers temperature contributes to improve the mechanical properties of the deposited material.

Research on the application of WAAM (using the CMT process) on the solubility of hydrogen, respectively on the formation and distribution of pores in Al-Mg alloys, showed that a reduced level of porosities can be obtained in the deposited material. Also, the investigation of the influence of pure argon and pure nitrogen as shielding gases, showed beneficial effects on the geometric and technical properties of Al-Mg alloys deposited by using WAAM [40].

Another study on the application of WAAM to Al-Mg alloys haz analyzed the effect of magnesium content on the microstructure and properties of the deposited material [44]. The results showed that with the increase of the magnesium content of the wires that are used, the degree of oxidation of the surface increased, appearing a wavy form of the deposited layer (for wires with a content of 8% Mg). At a content> 6% Mg, the rate of loss by burning of Mg increased significantly, at> 7% Mg appearing hot cracking in the deposited material. As the Mg content increases, there is an increase in phase precipitation that leads to larger grains dimensions. The study showed that at a content of 6% Mg of the wire used in WAAM, good mechanical properties of the deposited material were obtained (mechanical strength, yield strength and elongation at break) [44].

One direction to be approached in the future is to conduct research regarding the influence of other alloying elements from Al-Mg alloys on the deposited material, in order to obtain chemical compositions of Al-Mg alloys, suitable for WAAM use. The aim is to promote the application of WAAM for the production of Al-Mg alloy components for aeronautics and other priority areas [44].

3.5. Application of WAAM to AlSiMg alloys

AlSiMg alloys are used in the aeronautics and automotive industries due to their good casting capacity, low cracking tendency (when casting), high thermal conductivity, high corrosion resistance and good mechanical properties [45].

These alloys are suitable to make structural components through WAAM using CMT, with possibilities of implementation in industrial applications. Research on the application of WAAM to AlSiMg alloys (using wire with a diameter of 1.6 mm and a deposition rate of 1.6 kg/h), have analyzed the influence of the amount of heat on the material formability, microstructure and mechanical properties of the deposited material. The deposits were made on a support material (substrate) made of 6061-O aluminum alloy [46], respectively 4043 aluminum alloy [47]. In order to carry out the WAAM process in good conditions, it is important to prepare the substrate before deposition (removal of grease and oxide layer). The non-uniform structure obtained (mixture of coarse grains and fine grains, columnar and equiaxial grains) was improved by applying a heat treatment (e.g. to bring the material in the T6 condition), improvements in breaking strength and yield strength being observed. The results showed that WAAM can be applied to AlSiMg alloys, in good conditions by using CMT, the use of large diameter wires (1.6mm) contributing to the efficient formation of the deposited material, fact which facilitates the use of WAAM in engineering applications [46, 47] .

Studies and research on the possibilities of applying WAAM have been performed also for other aluminum alloys: e.g. 2319, 5083, 5087 [4, 23, 24], AlMgMn alloys [48], AlMgSc [23, 49, 50], 4047 and 5356 alloys [41, 51]. The results of these studies and research show that the application of WAAM by using advanced pulsed CMT, together with the inter-layers rolling, the use of argon or argon and helium (as appropriate) as a shielding gas at a constant flow rate, the application of post-WAAM heat treatments, are factors that contribute decisively to achieving satisfactory results.

4. Examples of WAAM applications for Al alloys, in the aeronautics and aerospace industries

The aeronautics and aerospace industries are among the most innovative, continuously developing and implementing the latest technologies and advanced manufacturing processes to substantially increase the quality of products in terms of efficiency and maximum operational safety.

Additive manufacturing is becoming increasingly usable in these top industrial fields, in the manufacturing of complex structural elements, with variable geometries, of aircrafts and aerospace vehicles. In the future it is estimated that a large number of aircrafts will have 3D printed elements in their structure [52].

The possibilities of using additive manufacturing in the aeronautical industry to make panels for aircraft fuselages were demonstrated by STELIA Aerospace (Toulouse, France), in fig. 4 being presented the architecture of an aluminum fuselage produced, at demonstrative level, by applying the WAAM process, with stiffening elements made directly on the surface [53, 54].

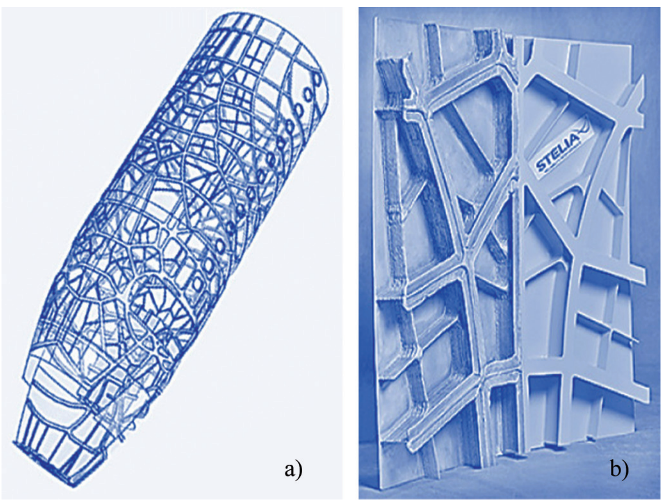


Figure 4. Aircraft fuselage architecture (a) and detail (b); demonstratively made by using WAAM [53, 55].

The stiffening elements have a new design, which resulted from topological optimization studies of the fuselage, carried out by STELIA Aerospace and CT Ingénierie during several years [59]. This new method of making structural elements of the aircraft fuselage should be widely implemented and, on the long term, eliminate the current stiffening elements, which are attached to the fuselage panels with fixing screws or by welding [56].

STELIA Aerospace is a specialized company in designs and manufactures on a large scale, through current advanced techniques, of fuselage sections for all types of Airbus aircrafts, as well as fuselage elements (fig. 5) and specific subassemblies for Airbus, complete equipped wings for ATR, central fuselages which is completely equipped for Bombardier's Global 7000, as well as complex aerostructure parts (made of metal and composite materials) for top companies (e.g. Boeing, Embraer and Northrop-Grumman, Dassault, Bell Helicopter, Bombardier, Guimball, Lockheed Martin, Airbus Helicopter, Leonardo, ATR [53, 57, 58]. Referring only to the year 2019, STELIA delivered more than 4,500 sections of aircraft fuselages [57].

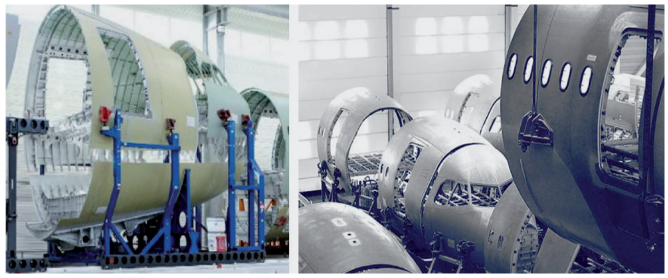


Figure 5. Fuselage sections- STELIA Aerospace [57, 58].

By making the demonstrative fuselage (fig, 4) a new approach was opened, with innovative designs of very large dimensions structural parts derived from new calculation methods (topological optimization).

The development of more innovative technologies with a direct impact on the aeronautics and aerospace industries, as well as the integration of parts functions, the reduction of the environmental impact, the reduction of the weight of components, the use of high-performance materials and lower manufacturing costs [53, 55, 56] .

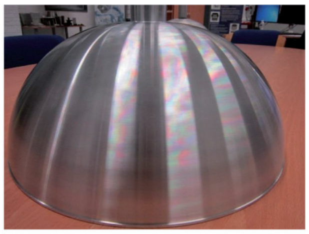
There are currently research groups (e.g. Constellium, Stelia Aerospace and CT Engineering) working in partnership for 3D printing of aircraft fuselages), focusing on optimizations of design processes and additive manufacturing technologies, in order to innovate, streamline aerospace components and structures at the lowest possible cost.

Current limitations regarding on the large-scale application of WAAM in the aeronautics and aerospace industries are related to the size of parts that can be made, costs and efficiency. Development of constructive solutions for fuselages, through additive manufacturing methods, would reduce the number of operations required to produce the component parts of the fuselage, the costs and duration of manufacture of the fuselage, etc. Thus, highly complex components could be obtained for the aeronautics / aerospace field, which are difficult or impossible to achieve using traditional manufacturing processes [60, 61].

Another important example of application that uses the WAAM additive fabrication to aluminum alloys (fig. 6) is a 6m long spar, made at Cranfield University, using a welding robot, with which components of length up to 10m, made of 2024, 2319, 4043 and 5087 aluminum alloys can be built using WAAM [34, 62, 63].

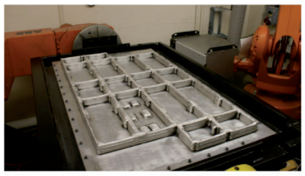
Figure 6. Spar made of aluminum alloy for the aerospace industry, using robotized WAAM [34].

Other examples of parts made of WAAM from aluminum alloys for the aerospace industry are presented in fig.7.

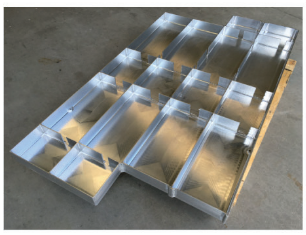

a

b

a). fuel tank dome - Lockheed Martin UK [4]
b). conical shape part (0,8m height) - Lockheed Martin [64, 65]


c

d

c). aluminum aircraft wing rib (2,5m x 1,5 m dimensions), for Bombardier [64]
d). panel type aluminum part 1,2m x 0,8m (satellite breadboards), Cranfield University, Thales Alenia Space [66]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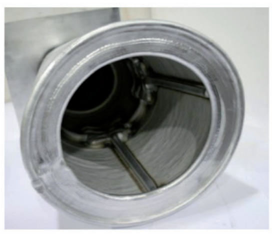
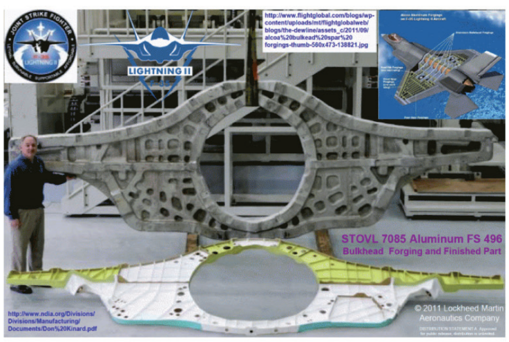

f

e). aluminum stiffened frame, Cranfield University [67]
f). aluminum structure Cranfield University [67]



g

g). aluminum wall type part, application – military aircraft, Lockheed Martin [67]

Figure 7. Examples of applications - made by WAAM to Al alloys.

The construction of the aluminum wall type part (made of 7085 aluminum alloy) used in military aircraft (fig. 7g), by conventional processing procedures, would mean 14 months for forging and another 4 months for processing, resulting in a very large loss of material, approx. 90%. The aim is to make this piece by WAAM, with a much shorter production time and without material loss [66, 67].

4. Conclusions and further development

4.1. Conclusions

WAAM is an interdisciplinary technology with a great potential for development and application in various industrial fields [25].

Manufacturing of parts with complex geometries by using WAAM is very topical in the scientific, academic and industry, because WAAM has a significant potential to reduce costs and manufacturing time for complex components, having medium or large dimensions, used in various engineering applications [29].

WAAM has many advantages in the aeronautics and aerospace industries [1, 4, 22, 27-35, 68]:

- Possibility to make large complex parts by 3D printing;
- Possibility of use in a wide range of materials;
- Short time to make parts by 3D printing;
- Flexibility in making complex parts;
- Obtaining high quality parts;
- Lower process and material costs. By using additive manufacturing processes for the production of components in the aerospace industry, can be obtained benefits that could reach: a 50% reduction in parts costs; reduction of scrap to approx. 10%; reduction of time to market by 64%; reducing by 40-60% of the components weight, with effect on the material savings and low fuel consumption.
- Suitable for repair operations
- 3D printing simplifies aviation supply chains, with more efficient and lighter parts being produced through additive manufacturing.

With these advantages, the market of components for the aeronautics and aerospace industries, made by 3D printing, is expected to exceed $ 4 billion by 2023 [1].

Additive manufacturing gives to aircrafts and aerospace vehicles manufacturers, the opportunity to have a more efficient supply chain by producing complex highly customized parts using 3D printing for more efficient and lightweight materials. In order to obtain all advantages of the additive manufacturing, it is necessary that the design and production processes to be significantly revised or modified to allow the use of innovative and faster production processes, to obtain high quality components and to open new directions for innovation in these fields [1, 27].

Materials used in top industrial fields, e.g. titanium, aluminum and steels, including stainless steel, are important topics for WAAM application research, with positive results proving the viability of this technique to produce large customized metallic parts according to the requirements of applications in various fields (aerospace industry, military defense industry, automotive industry, etc.) [29].

Several variants of WAAM application have recently been developed to optimize the microstructure and mechanical properties of parts built using WAAM [5]. Some current research and studies recommend a number of methods and techniques for achieving good results in WAAM application, such as inter-pass and side rolling, substrate preheating, including non-destructive testing in the process to identify and remedy the porosities and defects that may occur [25].

Porosity removal, a highly debated issue in aluminum welding, has been addressed and can be solved at WAAM by applying inter-layers roling and CMT-PADV technique [23].

After analyzing the results obtained in research on the application of WAAM to aluminum alloys, it can be concluded that:

- the accuracy of WAAM deposition and the properties of the deposited material depend on the characteristics of the base material;

- the interval in which the solidification of the metal deposited by WAAM takes place and its behavior during the deposition process has an influence on the surface corrugation. The results of some research indicate that a large solidification interval is more suitable for a uniform material deposition.

- another control factor of the resulting surface corrugation is given by the uniform transfer of the drops during the welding process. A long arc with pulsed energy causes greater dynamic forces during the transition of the droplets, thus affecting the accuracy of the deposition.

- the material properties are uniform distributed on the geometry of the part (deposited material) when the inter-layers temperature is kept constant [51].

- the formation of material deposited layer by WAAM depends on the type of welding process used and the temperature of the molten metal droplets [4].

4.2. WAAM development perspectives

Regarding the future in terms of materials to be used in the modern aeronautic / aerospace industry, high-performance aluminum alloys (from characteristics and properties point of view), along with titanium alloys and composite materials are materials that are used or will be widely used in the construction of structures and components for aircrafts and aerospace vehicles [8, 18].

Experts from industry have positive expectations for the future use of aluminum alloys in the aeronautic and aerospace industries, estimating that the market of aluminum alloys will double in the next ten years, so that these industries should be interested on increase of use recycled alloys in the fabrications processes for meet high demand of aluminum alloys. There is also an impulse for innovation regarding the materials used, as well as in the devising and design of the structural elements of aircraft and aerospace vehicles [8].

For example, the use of newly developed Al-Li alloys to make components and structural elements in the aeronautic and aerospace industries could reduce the weight of components and improve their performance, as they are advanced materials with low density, excellent fatigue properties and cryogenic resistance [1].

Through the increased involvement of several research entities from different countries in the development of the aerospace industry, as well as with significant investments, it will be possible in the future to increase the degree of innovation to obtaining better performing aluminum alloys [8]. It is also necessary in the future to extend researches on the influence of alloying elements in aluminum alloys (presented in Chapter 2) on the deposited material, in order to obtain information that lead to the development of high-performance alloys with chemical compositions suitable for manufacturing of components by using WAAM, for the aeronautical field and other priority indutries [44].

WAAM can be an economical option for the future, given the growing demand for aluminum products, mainly from high-strength alloys for the aerospace, defense, automotive, etc. industries. CMT, GMAW variants have been used and studied as suitable techniques for applying WAAM to aluminum alloys [23].

It remains an open research topic the commercial viability of the WAAM process, which is limited by the fact that the lack of reproducibility in arc stability, porosities, problems regarding microstructure and mechanical properties of the deposited material, have been reported [4]. A number of factors influencing the porosity were also identified, including the working environment, the wire properties, the chemical composition and the batch from which the wire comes, respectively the process parameters.

Research shows that in the future, the mechanical strength of components made by WAAM processes could be increased by applying treatments to cold processing and artificial aging. Although the strength characteristics of aluminum alloys deposited by WAAM will certainly be improved after heat treatment, a very important problem to be solved is to control the deformations that occur. Applying a inter-layer rolling process, residual stress peaks in a part made by using WAAM can be significantly reduced, resulting reduction or even eliminate deformations, improvement of mechanical characteristics, finishing of granulation and hardness increasing [24].

The behavior of the molten metal pool and the solidification characteristics of WAAM deposited metals (for heat-treatable and non-heat-treatable aluminum alloys) can be an important field of study, for thin and thick structures from a metallurgical point of view [23].

The deformations that occur and the uneven shrinkage resulting from the unusual solidification behavior, as well as the residual stresses resulting in the metal structure deposited by WAAM, show a current lack of knowledge in this regard. It will be interesting to research and understand the stress pattern in open and closed contour structures with different thicknesses. Maintaining the preheating temperature and the inter-layers temperature, as well as the relationship between them and the heat accumulation in the material, how to ocur residual stresses and improvemen of mechanical properties, are important areas of study [23].

Non-weldable aluminum alloys have proven good capability for WAAM application, but metallurgical inspection is required to analyze the solidification mode of the deposited material. This may lead to the need to redefine the concept of weldability or to create a new concept, called "WAAMability" of alloys [23].

One aspect insufficient explored refers to the possibility of using WAAM for repair applications. This could considerably reduce the costs associated with the need to completely renew a certain structural part, because using WAAM is possible to carry out localized repairs [29].

Another key issue that is not yet established is related to the certification of WAAM parts. This step is very important to further expand the range of applications of this technology and to address more demanding structural applications, where the associated benefits of WAAM may be of particular interest. Simultaneously with the need some of certification procedures for parts manufactured by using WAAM, there is a need to further development of efficient and integrated systems for non-destructive testing, which must be able to detect the formation of defects during the parts production processes.

The need to develop these in situ monitoring methods is that, with such an approach, any defect generated in the WAAM deposited metal could be repaired immediately after forming and not just at the end of the part construction process. Applying part control only at the end of the process can lead to significant material waste and longer production times, because the place where the defect is placed may be more difficult to access, making it more difficult the effective removal of the defect [29].

Some applications that use parts produced by WAAM are already on the market and the industry is expected to play a critical role in expanding applications for these parts. This fact cumulated with development of certification procedures and efficient methods of non-destructive testing on the production line, can determine as WAAM to become one of the most widely used additive manufacturing technologies in the near future [29].

WAAM is expected to be extended to new materials in the future, and further research should include, together with the improvement and optimization of parameters, monitoring, process control, optimized part design and heat treatments, which will lead to a better understanding and implementation of this technology [25].

WAAM could become a replacement for conventional production methods, such as casting and forging, for some applications. Current issues still limit the industrial use and market approval of WAAM, but various researches are underway to reduce and eliminate them, so that WAAM can compete with traditional manufacturing methods [25].

A good selection of materials for the wires used, as well as a proper design of the WAAM process and technological parameters depending on the type of application, can make it possible to optimize the materials for WAAM and the processes for obtaining multimaterial components. If the realization of components by WAAM is immediately followed by post-WAAM processing, it becomes possible to create geometric shapes of high complexity that are very difficult to achieve by other processes [69].

Highly topical topics, extremely important for further research and development, also target the wires used for the WAAM technique:

An important topic is the investigation of changes in the composition of current standard aluminum wires or even the production of new aluminum alloy wires. For example, there are elements that increase strength and if added to aluminum wires, they will react with the alloy helping to increase the strength of the deposited material (e.g. addition of magnesium to an aluminum-copper alloy) [24];

Consequently, it is intended to develop new aluminum wires with advanced compositions to be used in the WAAM process to obtain high strength parts [24];

Also, in order to improve the quality of the wires and reduce the porosity at WAAM of the aluminum alloys, in order to avoid the differences in the diameter of the wires, it will be possible to make improvements by modifying the wire fabrication process, by using diamond molds, identification and application of new methods for cleaning wires before use [4];

It is necessary to be modified, updated and completed the specifications for welding wires used in WAAM, as they must be restrictive, including in terms of tolerances as accurate as possible for the diameter of the wires, but also for the quality of the surface finish of the wire [4];

Researches are needed on the analysis of the arc stability and the evolution from the thermal point of view of the part made by WAAM, using high-speed thermographic cameras as well as measurements of voltage and current fluctuations during the WAAM process [4];

Determination of an appropriate technique for the analysis of the hydrogen content inside and on the wire surface, as well as the analysis of this effect on the porosity [4];

It is necessary to investigate the influence of wire microstructure on porosity and arc stability, as well as to develop clear specifications for wires used in WAAM processes [4].

Additive manufacturing offers producers in the aeronautic and aerospace industry, the military defense industry, etc., opportunity to have a more efficient supply chain by producing of highly customized specific parts, 3D printed, from lightweight and efficient materials. In order to benefits of all advantages of additive manufacturing, design and manufacturing processes need to be fundamentally changed to enable faster production processes that lead to obtain high quality components on a large scale, and finally, to support the future of innovation in field of fabrication of high-performance components for air flight and space vehicles, vehicles for military defense industry, etc. [1, 27].

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