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# Advanced welding technologies used in aerospace industry

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# Abstract

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The purpose of the research is comparison of welding processes for the aerospace industry and identification of optimal welding technologies used in the recent decades. The research was conducted by a critical review of literature, published and e-papers on the value of modern advanced welding technologies for aerospace industry, including their fundamentals and application for aerospace structural components.

This work is mostly an articles-based study that includes the articles in the area of welding investigations in aerospace industries. The articles were identified through multiple formal search methods including electronic searching of main databases (ScienceDirect, Springer and Elsevier), the use of free-texts, index terms, named authors, reference scanning and citation tracking.

Based on the findings and subsequent discussions, it is found that conventional fusion welding technique is no longer competitive to fulfill the demanding standards of aerospace industry, therefore advanced welding technology is the main choice of large global aerospace companies as reliable, sustainable and efficient joining processes, which bring prospects for further development of new light weight aerospace materials and structures.

The information provided in this work can be used as the comprehensive review of current trends in joining of aerospace structures with advanced welding processes and as the basis for further scientific research on the industrial implementation of advanced welding in the aerospace sector.

Keywords: advanced welding technologies, aerospace, applications

# Table of content

## Terminology

| | |
|---|---|
| Al | Aluminium |
| BM | Base material |
| Cu | Copper |
| EB | Electron beam |
| EBW | Electron beam welding |
| EFT-1 | Engineering flight test-1 |
| EM-1 | Exploration Mission 1 |
| FOD | Foreign object damage |
| FSW | Friction stir welding |
| FW | Friction welding |
| GKN | Guest, Keen & Nettlefolds |
| GMAW | Gas metal arc welding |
| GTA | Ground test article |
| GTAW | Gas tungsten arc welding |
| HAZ | Heat affected zone |
| IFW | Inertia friction welding |
| LBW | Laser beam welding |
| Li | Lithium |
| LFW | Linear friction welding |

| | |
|---|---|
| MAG | Metal active gas |
| Mg | Magnesium |
| MIG | Metal inert gas |
| NADCAP | National aerospace and defense contractors accreditation program |
| NASA | National aeronautics and space administration |
| Ni | Nickel |
| NZ | Nugget zone |
| PAW | Plasma arc welding |
| Sc | Scandium |
| SEM | Scanning electron microscope |
| SLS | Space launch system |
| SZ | Stir zone |
| Ti | Titanium |
| TIG | Tungsten inert gas |
| TMAZ | Thermo – mechanically affected zone |
| TWI | The Welding Institute |
| V | Vanadium |
| VPPA | Variable polarity plasma arc welding |
| WCZ | Weld centre zone |

# 1 Introduction

The aerospace industry is broadly defined as an industry network that designs, builds and provides in-service support to aircraft, helicopters, guided missiles, space vehicles, aircraft engines, and related parts. The industry includes small to medium-sized enterprises that design, manufacture or service specific aerospace items for large global companies such as Boeing, Airbus and Lockheed-Martin who design, assemble, sell and provide in-service support to the entire aircraft systems. (1, p. 32.)

The aerospace transportation, as all other transportation sectors, is facing new challenges, targeted on lower environmental impact (aviation industry is responsible for the 2% of annual global emissions (2)), more technological innovation and greater economical efficiency. The demand for the reduction of pollutant emissions and operational costs, and at the same time, for increasing aircraft dispatch reliability and comfort of the passengers, embed more pressure on the development of new design solutions, methods and concepts for air transportation systems. (3.)

More efficient and environmentally friendly transportation systems require increasingly lighter structures. New materials and new production processes are constantly emerging or in continuous development for improving their efficiency in different ways as reducing their environmental impact or reducing the life-cycle costs through structural weight reduction or reducing manufacturing costs. (3.)

The increasing application of innovative materials, such as high strength aluminium alloys, challenges the manufacturing processes of the Aerospace Industry. Despite this challenge, the processes need to comply with high requirements regarding the reproducibility and the quality of the products. For this reason, the adaption of conventional welding technologies to the new materials is considered to be difficult. Therefore, advanced welding technologies have been proposed for the Aerospace industry. (4.)

## 1.1 Weight and cost assessment

The main force for the use of welding in aerospace structures is weight savings, which directly translate into better economics. The faster a vehicle moves, the higher the potential savings by reducing weight (5). Figure 1 illustrates the trend, which correlates the vehicle speed with the transportation cost per kilogram, assuming the fuel cost between one to two euros per 4 liters. This trend has been changed due to the increase of oil costs and increase of the transportation efficiency. Nevertheless, it is expected that this exponential illustrative trend keeps unaltered nowadays. (3, p. 146.)

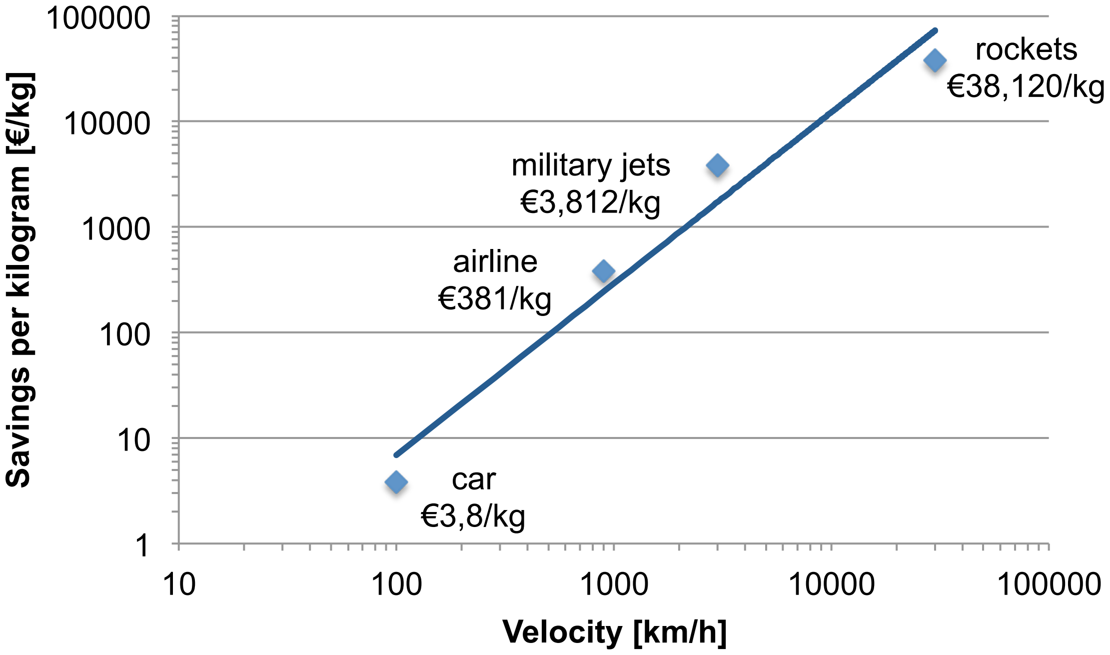
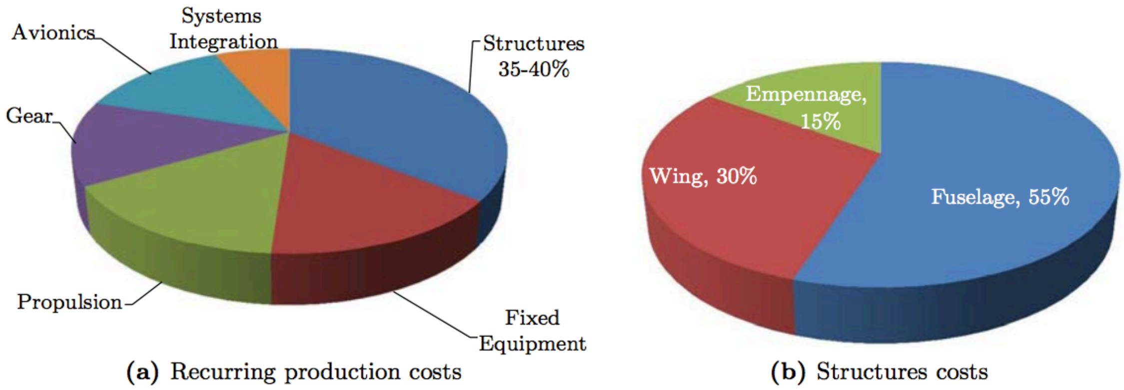


Figure 1. Costs per kilogram vs. transportation speed, illustrative trend (3, p. 14; 5)

Moreover, the analogous trend is applicable for anything that moves (any movable component). In an aircraft, there is often a multiple effect for rapidly moving part within the overall structure. For instance, a kilogram of weight savings on a disk of a turbine engine can be worth the 10 times the same weight saved on the fuselage as a kilogram saved on the engine can save 5 to 10 kilograms on the wing structure. As a consequence, this is the driving force for the manufacturing of bladed disks or “blisks” as shown in Figure 23 and Figure 24. In a conventional turbine stage the blades are mechanically attached to a hub. This attachment involves interlocking parts that add significantly to the total weight of the rotating part. In a blisk, the blades and the hub are a single piece; interlocking mechanism is eliminated with significant weight savings. Linear friction welding and diffusion bonding are key enabling technologies to manufacture blisks. The F119 (the engine used in the F-22 jet fighter) is believed to contain blisks manufactured with these techniques. As additional example, there is the linear welded blisk produces by MTU München for Eurofighter (6). (5; 7, pp. 386-387.)

Furthermore, the overall importance of the manufacturing costs of the aircraft structures is illustrated in Figure 2. Figure 2a shows that the largest slice in the production costs of an aircraft corresponds to the structures, where in turn, the fuselage corresponds to about 55% of the total structure cost. Consequently, optimization in the structural manufacturing processes has a large impact on the final aircraft costs and should be a main concern for the aircraft manufacturers. For instance, a huge amount of manual labor tasks are found in riveting structures due to the complexity involved in the automation of some of the procedures. (3, p. 147.)



**(a)** Recurring production costs

**(b)** Structures costs

Figure 2. Significance of aerospace structures costs (3, p. 147)

## 1.2 Materials

Aerospace materials are defined in this thesis as structural materials that carry the loads exerted on the airframe during flight operations (including taxiing, take-off, cruising and landing). Structural materials are used in safety-critical airframe components such as the wings, fuselage, empennage and landing gear of aircraft; the fuselage, tail boom and rotor blades of helicopters; the airframe and skins and thermal insulation tiles of spacecrafts. Aerospace materials are also defined as jet engine structural materials that carry forces in order to generate thrust to drive the aircraft. (1, p. 1.)

Practically, aerospace materials affect every aspect of the aircraft, including the following:

- purchase cost of new aircraft;
- cost of structural upgrades to existing aircraft;
- design options for the airframe, structural components and engines;
- fuel consumption of the aircraft (light-weighting);
- operational performance of the aircraft (speed, range and payload);
- power and fuel efficiency of the engines;
- service maintenance (inspection/repair) of the airframe and engines;
- safety, reliability and operational life of the airframe and engines;
- disposal and recycling of the aircraft at the end-of-life. (1, p. 1.)

The space industry places extraordinary demands on the properties and performance as these are based on considerations of safety and reliability (8, p. 55). Aerospace materials must be light, stiff, strong, damage tolerant, durable, cost-effective and easy to manufacture. Moreover, aerospace materials must be sustainable. Particularly, that means the production of aerospace materials must have little or no impact on the environment and their application reduces the environmental impact of the aircraft by lowering the fuel burn through the weight reduction. It is estimated that only less than about 100 different types of metal alloys, composites, polymers and ceramics correspond the combination of the abovementioned demands. (1, pp. 4-5; 7; 9.)

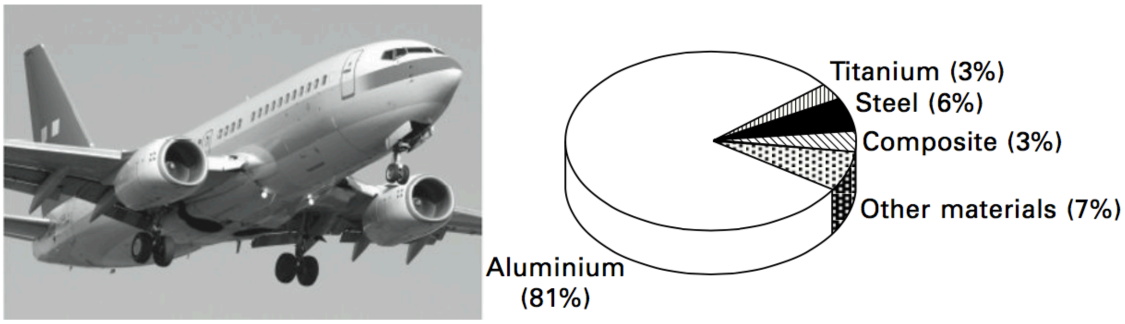
The main groups of materials used in aerospace structures are aluminium alloys, titanium alloys, steels and composites. In addition to these materials, nickel-based alloys are important structural materials for jet engines. These materials are the main focus of this thesis. Other materials have specific applications for certain types of aircraft, but are not mainstream materials used in large quantities. Examples include magnesium alloys, fibre–metal laminates, metal matrix composites, ceramics for heat insulation tiles for rockets and spacecraft, and radar absorbing materials for stealth military aircraft. (1, pp. 4-5; 9.)

Rarely a single material is able to provide all the properties needed by an aircraft structure and engine. Consequently, the combinations of materials are used to achieve the best balance between cost, performance and safety. Table 1 gives an approximate grading of the common aerospace materials for several key factors and properties for aerospace structures. From Table 1, it could be noticed there are significant differences between the performance properties and cost of materials. For instance, aluminium and steel are the least expensive, composites are the lightest, steels have the highest stiffness and strength meanwhile nickel alloys have the best mechanical properties at high temperature. As a result, aircraft are constructed using a combination of materials, which could cover the specific demands of the aerospace structure or component. (1, pp. 5-6; 9.)

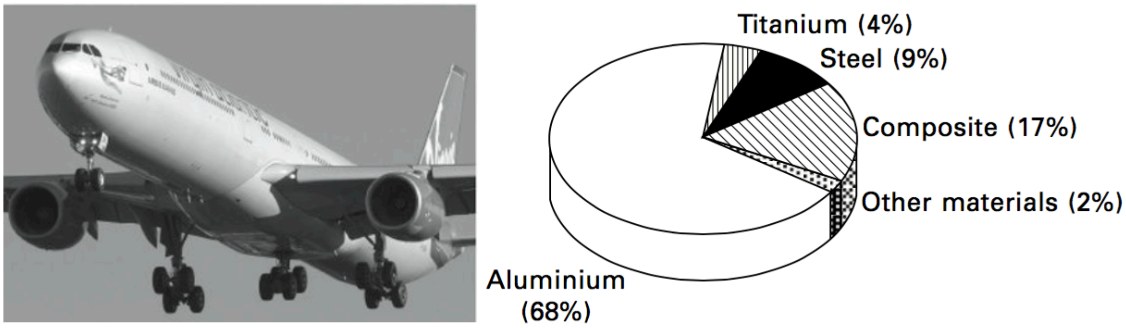
Figure 3 and Figure 4 show the types and amounts of structural materials in various types of modern civil and military aircraft. A common feature of the different aircraft shows the use of the same materials: aluminium, titanium, steel and composites. Although the weight percentages of these materials differ between aircraft types, the same four materials are common to the different aircraft and their combined weight is usually more than 80–90% of the structural mass. The small percentage of ‘other materials’ that are used may include magnesium, plastics, ceramics or some other material. (1, pp. 7-8; 9.)

Table 1. Grading of aerospace materials on key design factors and their application (1, p. 6; 9; 10)

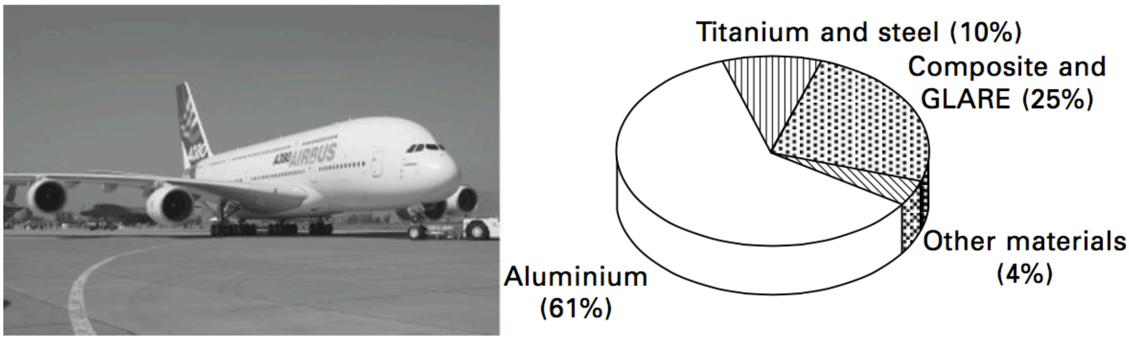
| Property | Aluiminium | Titanium | Magnesium | High-stregnth steel | Nickel superalloy | Carbon fibre composite |
|---|---|---|---|---|---|---|
| Cost | Cheap | Expensive | Medium | Medium | Expensive | Expensive |
| Weight (density) | Light | Medium | Very light | Heavy | Heavy | Very light |
| Stifness (elastic modulus) | Low/medium | Medium | Low | Very high | Medium | High |
| Strength (yield stress) | Medium | Medium/high | Low | Very high | Medium | High |
| Fracture toughness | Medium | High | Low/medium | Low/medium | Medium | Low |
| Fatigue | Low/medium | High | Low | Medium/high | Medium | High |
| Corrosion resistance | Medium | High | Low | Low/medium | High | Very high |
| High-temperature creep strength | Low | Medium | Low | High | Very high | Low |
| Ease of recycling | High | Medium | Medium | High | Medium | Very low |
| Application | - Wing skins;<br>- airframe structures;<br>- fuselage stringers and frames;<br>- floor beams;<br>- seat rails;<br>- missile casing;<br>- empennage. | - Aeroengine fan and compressor discs, blades, vanes, and nacelles;<br>- nozzle assemblies in the exhaust section<br>- heavily loaded military airframes and landing gear parts<br>- propellant tanks and other pressure vessels for space vehicles. | - Gearboxes, gearbox housings and transmission housing of helicopters;<br>- landing gear wheels;<br>- door frames. | - High-strength and load density airframe components;<br>- landing gear;<br>- wing box components;<br>- rocket motor casings;<br>- heat exchangers. | - High-pressure turbine blades, discs, shafts;<br>- combustion chamber, afterburners, thrust reversers;<br>- oxygen storage tanks for spacecraft. | - Wings, fuselage;<br>- empennage and control surfaces (rudder, elevators, ailerons)<br>- aeroengine inlet fan blades |


Titanium (3%)
Steel (6%)
Composite (3%)
Other materials (7%)
Aluminium (81%)

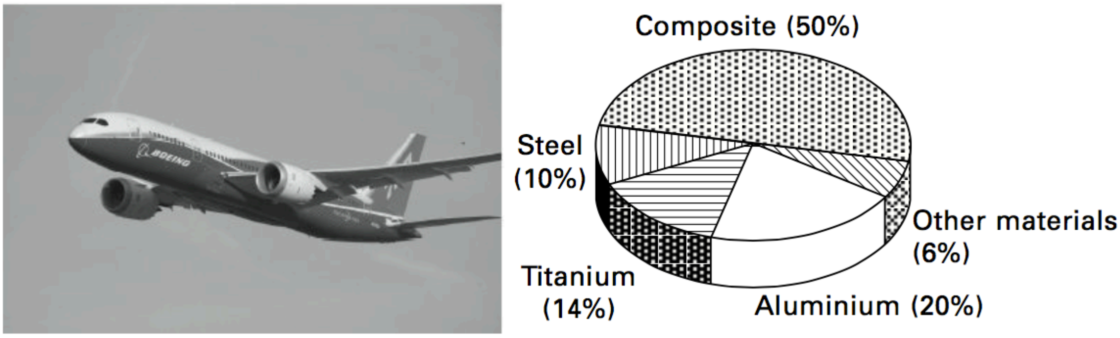
(a)


Titanium (4%)
Steel (9%)
Composite (17%)
Other materials (2%)
Aluminium (68%)

(b)


Titanium and steel (10%)
Composite and GLARE (25%)
Other materials (4%)
Aluminium (61%)

(c)


Composite (50%)
Steel (10%)
Other materials (6%)
Titanium (14%)
Aluminium (20%)

(d)

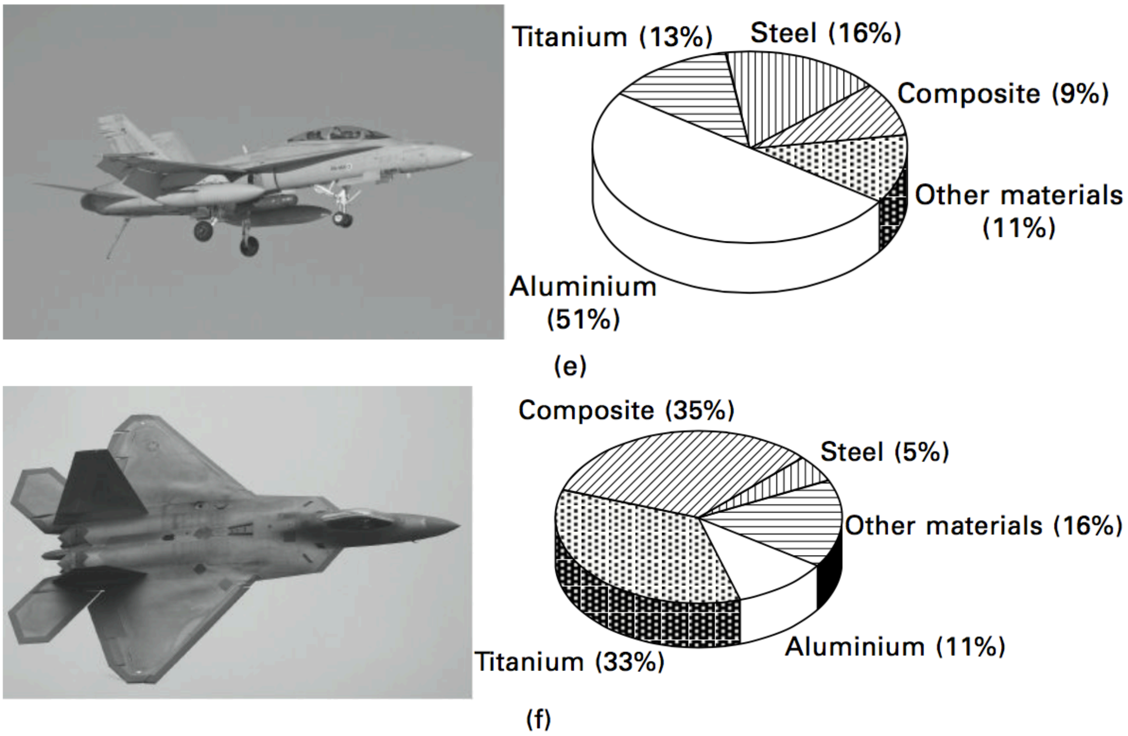


Figure 3. Structural materials and their weight percentage used in the airframes of civilian and military aircraft. (a) Boeing 737, (b) Airbus 340-330, (c) Airbus A380, (d) Boeing 787, (e) F-18 Hornet (C/D), (f) F-22 Raptor (1, pp. 7-8)

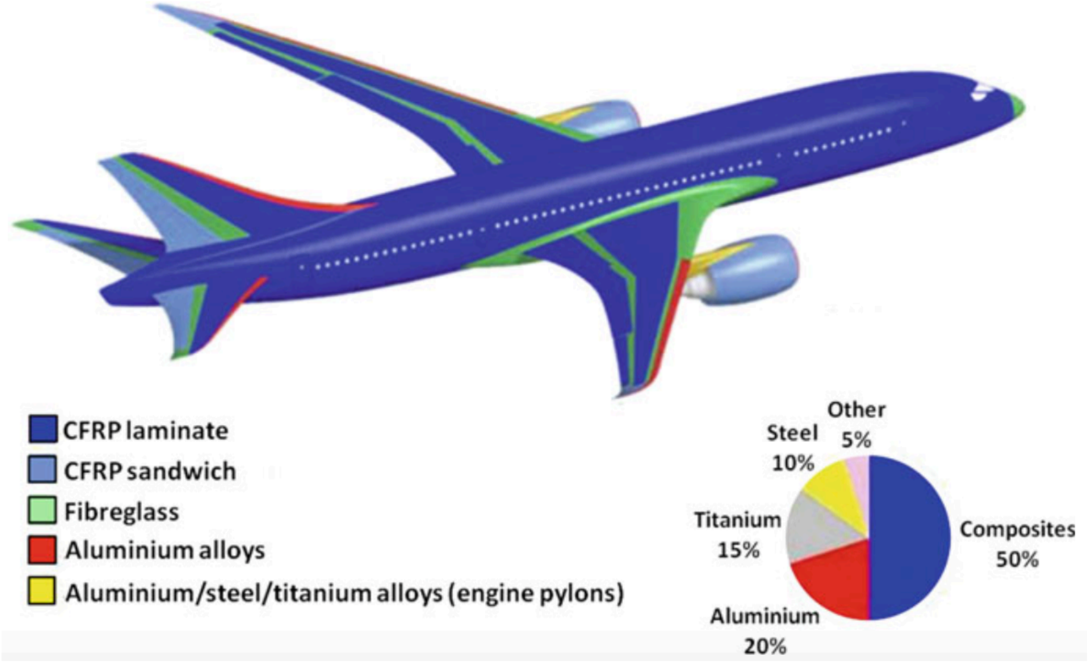


Figure 4. Airframe materials distributions and percentages for the Boeing 787 (9, p. 310)

Furthermore, Figure 5 illustrates the aerospace materials used in the main components of a modern jet engine General Electric CF6, which is normally used in the Boeing 787 where superalloys cover over 50% of the total weight. (1, p. 253; 9, pp. 199-201.)

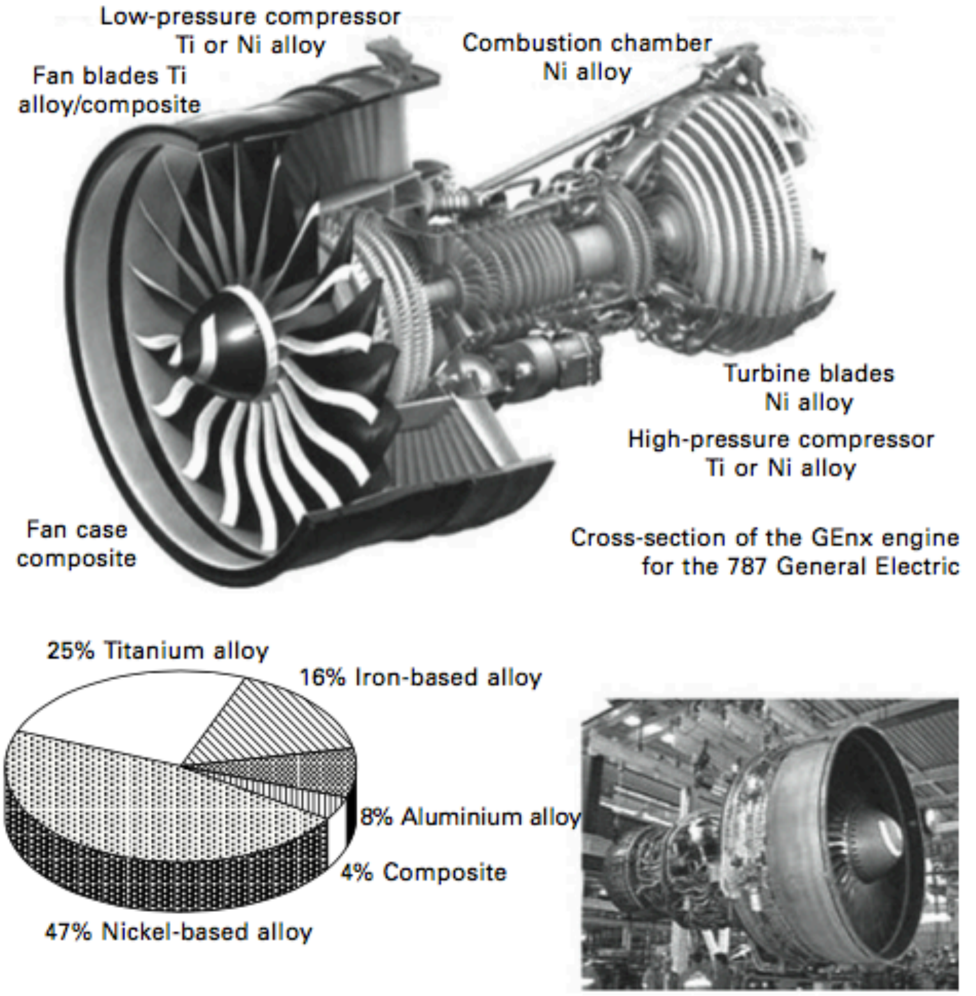


Figure 5. Material distribution in the aircraft turbine engine General Electric (CF6) (1, p. 253)

Although the application of composites has been increasing dramatically recently, reaching 50 and 53 % of the structure mass for B787 and A350, respectively, light metals, such as aluminium and titanium, still account for over 30 % of the structure mass (11). Thus, a study of technologies and manufacturing processes, which focuses on these light metals still has great potential.

### 1.2.1 Aluminium

Aluminium alloys have been the main airframe materials since they started replacing wood in the late 1920s (1, p. 8). The attractiveness of aluminium is that it is a relatively low cost, lightweight metal that can be heat treated to fairly high-strength levels. Moreover, aluminium presents good stiffness, strength and fracture toughness. Disadvantages of aluminium alloys include a low modulus of elasticity, rather low elevated-temperature capability (130 °C), and in high-strength alloys the susceptibility to corrosion and fatigue. (1, pp. 8-9; 9, p. 30.)

Various types of aluminium alloys with different compositions are used according to the specific structural applications in aircraft (1, p. 9). The most common are high strength 2XXX, 7XXX and 6XXX aluminium alloys that have wide application due to high strength, toughness and excellent strength-to-weight ratio (7, p. 132).

High-strength aluminium alloy is the most used material for the fuselage, wing and supporting structures of many commercial airliners and military aircraft. The competition between the use of aluminium and composite is intense, although aluminium will remain an important aerospace structural material. (1, p. 8.)

Aluminium-lithium (Al-Li) alloys are examples of currently successful materials (for instance, the alloys AA2195, AA2198 and AA2014). Lithium is less dense than the aluminium (0.53 g/cm$^3$ compared to 2.7 g/cm$^3$), which results in the reduced density of the alloy and improved the mechanical properties. However, as the material costs are high, the economic benefit for airframes is low. (12, p. 244.)

Al-Li alloys are already applied for space applications for weight reduction. Beginning in the later 1990s, these Al-Li alloys have been applied in different aerospace structures such as the Space Shuttle external tanks, where the Al-Li alloys AA 2219-T87 (8, p. 231) and AA2195-T8 was used in order to reduce the total weight and enable the shuttle to carry out more payload (9, p. 53; 12, p. 244). Presently, in Orion module, liquid oxygen and hydrogen tanks of SLS (Space Launch System) aluminium-lithium alloys AA2195 are applied (8, pp. 187-188; 13).

### 1.2.2 Titanium

Titanium alloys are used in both airframe structures and jet engine components because of their moderate weight, high structural properties (e.g. stiffness, strength, toughness, fatigue), excellent corrosion and oxidation resistance, superior creep resistance up to about 600 °C and good damage tolerant properties. The structural properties of titanium are better than aluminium, although it is also more expensive and heavier. Various types of titanium alloys with different compositions are used, although the most common is Ti–6Al–4V, which is used in both aircraft structures and engines. (1, p. 9; 7, p. 10, 130; 9, pp. 121-122.)

Titanium is generally used in the most heavily loaded structures that must occupy minimum space, such as the landing gear and wing–fuselage connections. The structural weight of titanium in most commercial airliners is typically under 10%, with slightly higher amounts used in modern aircraft such as the Boeing 787 and Airbus A350. The use of titanium is greater in fighter aircraft owing to their need for higher strength materials than airliners. Titanium alloys account for 25–30% of the weight of modern jet engines, and are used in components required to operate to 400–500 °C. Engine components made of titanium include fan blades, low-pressure compressor parts, and plug and nozzle assemblies in the exhaust section. (1, p. 9.)

### 1.2.3 Steel

Steel is the most commonly used metal in structural engineering, however its use as a structural material in aircraft is small (under 5–10% by weight). The steels used in aircraft are alloyed and heat-treated for very high strength, and are about three times stronger than aluminium and twice as strong as titanium. Steels also have high elastic modulus (three times stiffer than aluminium) together with good fatigue resistance and fracture toughness. This combination of properties makes steel as a material of choice for safety-critical structural components that require very high strength and where space is limited, such as the landing gear and wing box components. However, steels are not used in large quantities for several reasons, with the most important being its high density, nearly three times as dense as aluminium and over 50% denser than titanium. Other problems include the susceptibility of some grades of high- strength steel to corrosion and embrittlement that causes cracking. (1, p. 10.)

### 1.2.4 Nickel-based superalloys

Nickel superalloys have excellent heat resistant properties and retain their stiffness, strength, toughness and dimensional stability at temperatures much higher than the other aerospace structural materials. Moreover superalloys have good resistance against corrosion and oxidation when used at high temperatures of 800–1000 °C. Therefore, Ni-based superalloys are an exceptional class of structural materials for high temperature applications, particularly in the challenging environment of the turbine sections of aircraft engines where the temperatures are 900–1300 °C. Superalloys are used in engine components such as the high-pressure turbine blades, discs, combustion chamber, afterburners and thrust reversers. A problem with superalloys is their high density of 8–9 g/cm$^3$, which is about twice as dense as titanium and three times denser than aluminium. (1, p. 10, 251-253; 9, pp. 199-201, 215-216.)

## 2 Welding of Aerospace structural components

Welding includes the joining process for metals and plastics where both the work pieces to be joined with the usage of filler materials. A common method for welding metals is fusion welding, where the heat source is used to bring the parts to partial melting temperature. (12, p. 34.)

One of the most commonly used heat sources in fusion welding is an electric arc created by an electrical discharge between an electrode and the work pieces used to join the weld region generating enough heat to melt the material under the arc. The solidification of the melted material forms the weld. (12, p. 34.)

A consumable or a non-consumable electrode can be used in arc welding process. In the first case, the molten metal from the electrode and the molten base metal mix together, solidifying to form a joint upon cooling. In order to protect the molten material from contamination or the surrounding atmosphere a flux or shielding gas are used. In the second case, the joint is constituted by the base metal that melts and solidifies. (12, p. 34.)

High temperatures generated by the welding process alters the microstructure in the welded areas creating a fusion zone associated with the molten metal, and a heat affected zone (known as HAZ), which undergoes metallurgical transformations. This can change the mechanical behavior of the material. In aluminium alloys, the transformation of microstructure is most common for aerospace industry. These metallurgical transformations can lead to softening of the material in the HAZ, cracking and porosity. The process of fusion and solidification also generates residual stresses that can lead to distortion. These are important in aluminium welding due to the high thermal conductivity of this material and linear expansion coefficient which leads to large fusion and heat affected zones. For these reasons, the welding process requires optimization (heat input, metal composition and cooling rate) aiming at minimizing microstructural changes and residual stresses in welded joints. (12, p. 34.)

Examples of conventional, fusion welding processes that can be used for joining aluminium alloys, typically applied in fuel and oxidizer tanks in rockets are TIG /GTAW (Tungsten Inert Gas/Gas Tungsten Arc Welding) and MIG/MAG/GMAW (Metal Inert Gas/Metal Active Gas/Gas Metal Arc Welding). Meanwhile, thick sections of aluminium joints are welded with plasma arc welding (PAW). (10, pp. 65-66.)

Titanium is a highly reactive metal. Hence inert gas welding processes such as gas tungsten arc welding TIG are used for welding sheets, while thick section welding is done by PAW. (10, p. 69.)

Ultrahigh-strength steels such as carbon-free maraging steels and medium carbon low-alloy steels are employed for rocket motor casings, landing gears, etc. These are mainly welded by inert gas welding processes such as TIG. (7.)

Welding is a joining alternative mainly applied in metallic structures, however it can also be used to join ceramic and thermoplastic polymer components. This process is widely applied in many different sectors due to the high joint efficiency without substantial weight penalty. This joining process is easily fully automated and in most of applications is an inexpensive process when compared with the fastened applications. An important drawback is the disassembly of these joints, since it cannot be done without the destruction of the weld. (3, p. 49; 12, p. 225.)

The application of welding in aerospace structures is an attractive option, since it allows joints with less stress concentration points and might be applied efficiently without overlapping the two joining parts (with a butt-joint configuration) reducing the joint weight. This weight reduction can have a small impact in the production costs, however, a huge impact in the life cycle costs. (3, pp. 49-50; 12, p. 225.)

## 2.1 Advanced welding technologies in Aerospace Industry

The application of welding process has been limited due to two major reasons: high susceptibility of cracks in welded joints compromising the structural integrity and the low weldability with conventional fusion welding processes of the aluminium alloys (mainly 2XXX and 7XXX series (12, p. 225)) increasingly employed in the airframes, (3, pp. 30-33) fuel tanks of launch vehicle, space shuttles and space ships (14). Therefore, more expensive, advanced welding technologies as Friction Welding (FW), Laser Beam Welding (LBW) and Electron Beam Welding (EBW) were proposed, as the processes of choice for welding of aerospace structures with high reliability and high efficiency production, as shown in Figure 6 and Figure 7. (5.)

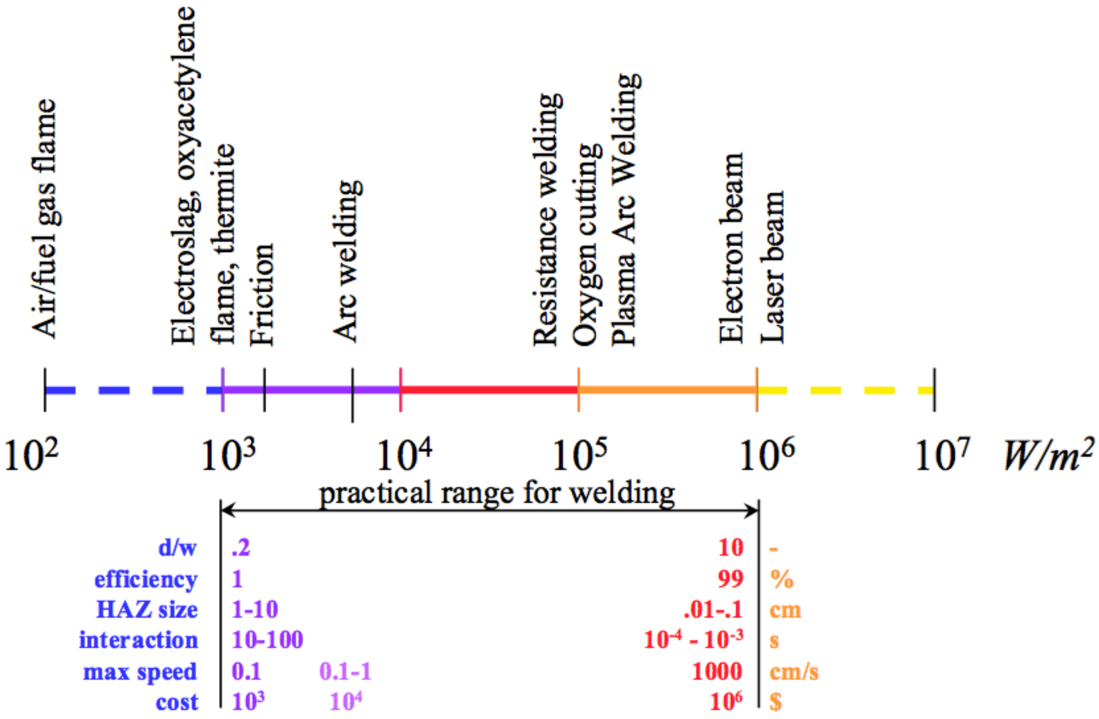


Figure 6. Welding processes ranked according to heat source intensity (5)

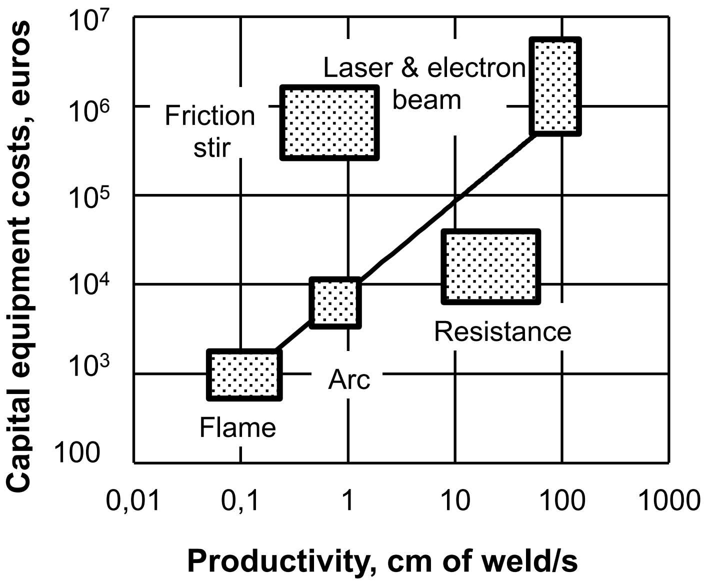
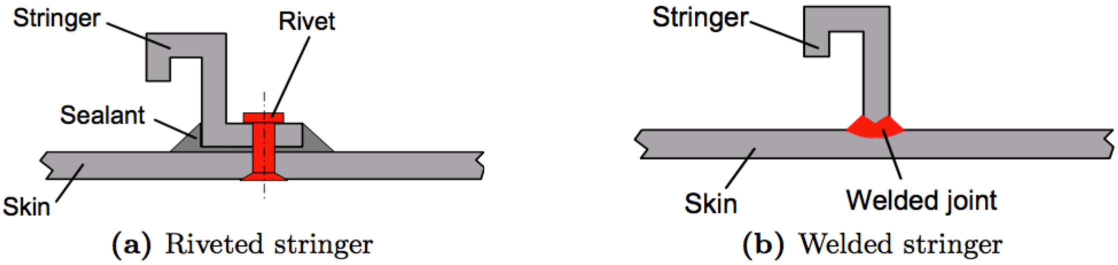


Figure 7. Illustrative capital cost of welding equipment as a function of productivity (5)

These advanced welding processes can now deal with the low weldability of the hardened precipitated aluminium alloys, although the low crack arrest remains and resists the massive adoption of these joining processes (3, pp. 49-50; 12, p.

225). Nevertheless, owing to FW, LBW and EBW the application of the welding process has been growing to join metallic structures.

Electron Beam Welding has been adopted to join titanium parts in military aircraft, as in Lockheed Martin F-22 (15), where GKN Aerospace used EBW to join the different parts of the aft boom reducing the use of fasteners by approximately 75 percent. Laser beam Welding has been used by Airbus to join the fuselage stringers to the skin in the A318, A340 and A380 eliminating thousands of fasteners, as shown in Figure 8. These two welding processes are based on high concentrated energy beams which originate small heat affected zones and the distortion (3, p. 50). Friction stir welding has been adopted in producing Delta IV, Atlas V, and Falcon IX rockets as well as the Orion Crew Exploration Vehicle, Ares I and Space Launch System (SLS) (2).



(a) Riveted stringer

(b) Welded stringer

Figure 8. Riveted and welded stringer (3, p. 93)

Other welding processes had been adopted by aeronautical manufacturers as the GTAW, PAW or Variable Polarity Plasma Arc Welding (VPPA) and diffusion welding, but just for specific applications (3, p. 50). Nonetheless, the main focus of this thesis is the most applicable advanced welding processes, therefore processes' fundamentals and the current trends in application of these technologies will be briefly described in the following chapters.

## 2.2 Friction welding

Friction welding based on the frictional heat, which develops due to the relative movement between two components, while being under pressure. These joining processes are also called as solid state welding, due to the fact that generated frictional heat enable to form a permanent joint without melting the interface material. Therefore they differ from fusion welding, which is based on the formation of a molten pool of the material. (16.)

The need for high-quality joints, combined with the inherent difficulty in welding most aerospace materials, has induced the use of solid-state with friction-based welding techniques within the past decade in the aerospace industry (7, p. 25).

Variety of ferrous and non-ferrous alloys can be friction welded. The submelting temperatures and short welding time of FW make it possible to join materials with different thermal and mechanical properties. In some cases friction welding is the only option for some combinations of materials, as the joining by other techniques leads to formation of brittle phases, reducing the mechanical properties of the joint. (17, pp. 1-2.)

Depending on the type of the processes involved friction welding can be classified as:

- Friction Stir Welding
- Linear Friction Welding
- Inertia Friction Welding

### 2.2.1 Friction stir welding

#### Process

Friction Stir Welding is a solid phase process, which operates below the melting point of the workpiece material (18). FSW was invented in 1991 by The Welding Institute (TWI) in the UK (14).

Friction stir welding is based on a non-consumable rotating tool that does not soften during the operation. Figure 9 illustrates that the tool is pressed on the interface of the components to be welded together, softens both of the components around the interface and mixes the softened material to provide bonding. (17, p. 2.)

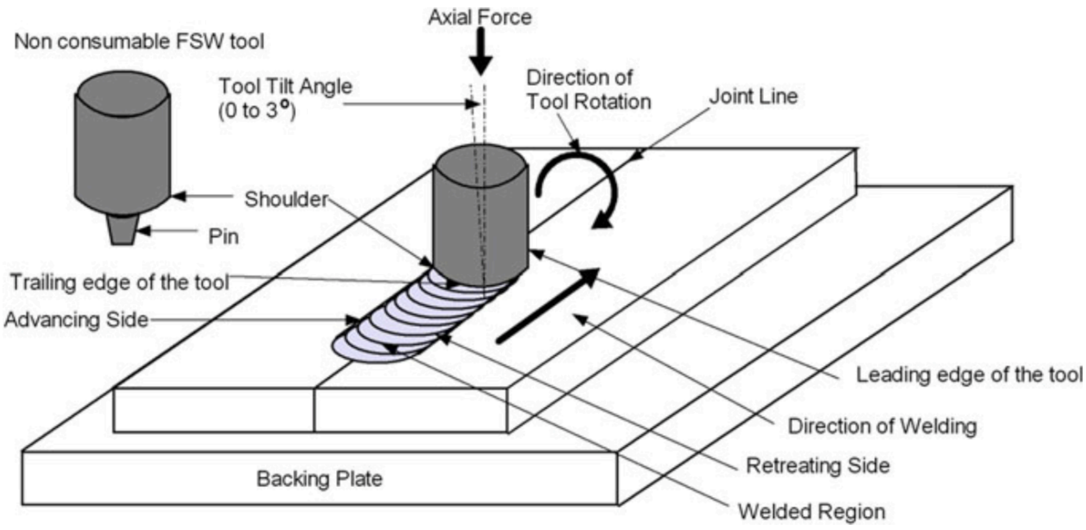


Figure 9**.** Schematic illustration of FSW (19, p. 164)

Figure 10, Figure 11 and Figure 12 illustrate that the resulting welded region could be divided into distinct zones as follows:

A. Nugget Zone or Stir Zone (NZ or SZ).
B. Thermo-Mechanically Affected Zone (TMAZ).
C. Heat Affected Zone (HAZ).
D. Unaffected Base Material (BM). (19, p. 168.)

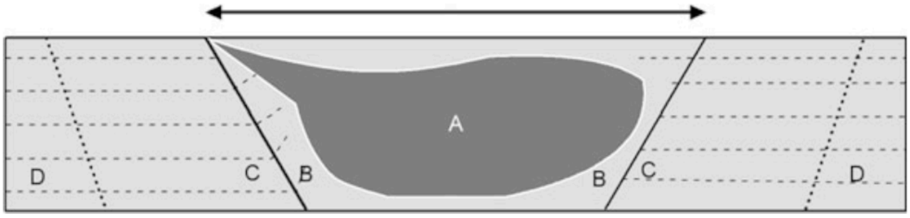


Figure 10. Generalized butt joint profile (19, p. 168)

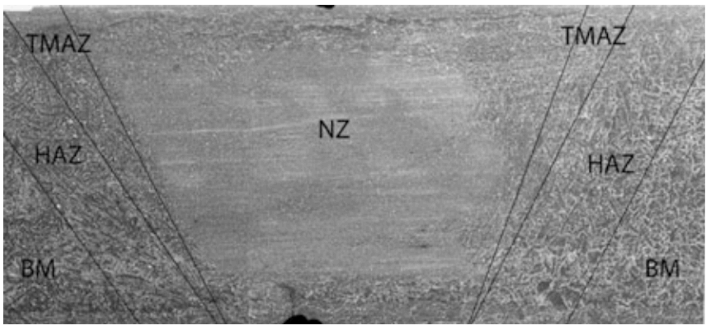


Figure 11. Welded region of FSW process (19, p. 168)

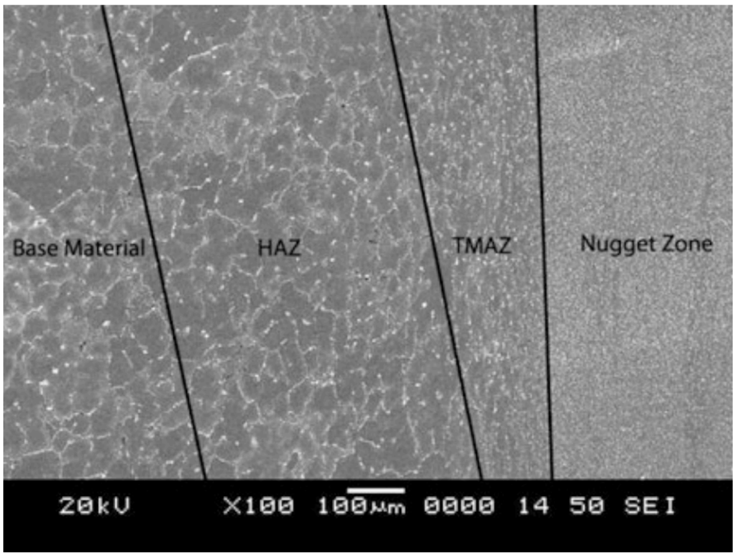


Figure 12. Typical SEM images of the TMAZ, the HAZ, BM and Nugget region Grain distribution (19, p. 169)

Friction stir welding is one of the most important and appealing welding processes in aerospace structures, as it is capable of producing excellent joints for all aluminium alloys (20) (within thickness range of 1.2 mm to 75 mm (18)) and even for Al-Li alloys that cannot be satisfactory welded with conventional fusion welding techniques. Moreover, dissimilar aluminium alloys are also weldable with FSW technique (5000 to 6000 series or even 2000 to 7000 series, for instance). Normally, no shielding gas or filler material is required (only in cases with joining of reactive metals). (18.)

FSW is also applicable to joining of steel, titanium, magnesium, zinc, copper (18) and various refractory alloys (2). In addition to this, there are encouraging results for welding of dissimilar alloys having widely different melting point (Cu-Al), having dissimilar base metals and similar melting point (Al-Mg) and welding of dissimilar alloys with similar base metals and melting point (Al – Al alloys, Mg – Mg alloys and ferrous – ferrous alloys) (21).

Furthermore FSW is the versatile process as it has no position and orientation limitations, fully automated, extremely repeatable and typically do not require any post-weld processing. Moreover FSW is environmentally friendly technology, as it produces no harmful fumes and is extremely efficient (efficiency is above 90% (22)). Therefore FSW is the great option for the aerospace industrial sector that follows the manufacturing trends of more efficient and sustainable transportation systems (3, pp. 51-54; 23).

Nonetheless, such issues as high initial investment in tooling, equipment and process sensitivity to joint tolerances (butt joint gap issue) are still limitations.

**Application**

As soon as the technique was invented, FSW has been considered primarily as an attractive alternative to riveting in aircraft construction. Furthermore, FSW has been accepted as an ideal technique for joining large aerospace structure made of high-strength aluminium alloys (14). The principal benefits include weight reduction, lower levels of stress concentration, and higher process efficiency. These factors optimize manufacturing and joint strength for the modern joint designs. (24.)

One of the most famous cases of FSW commercial applications is related to The Eclipse Aviation 500 - a small six-seat business jet aircraft manufactured by Eclipse Aviation. Friction stir welding was initially approved by The Federal Aviation Administration (FAA) for the Eclipse 500 aircraft in March 2002, and it was the first civil aircraft to use this technology. The Eclipse design was based on the use of FSW to join thin stringers (AA7055 Al alloy) to skin material (AA2024 Al alloy) in a lap configuration, with the main challenges being corrosion protection of the mating surfaces, control of distortion in the thin sheet material and control of interface deformation. The tensile strength results of AA7055-T76 friction stir welded to AA2024-T3 material of 470–480 MPa proved to be higher than the AA2024-T3 riveted equivalent of 440 MPa. Moreover, the fatigue results were also excellent, with tests running to over 4 million cycles without failure at the aircraft operating load levels. Thus, the FSW joint performance exceeded design requirements with considerable margin. Welds of 128 m (263 welds in total) were made per aircraft in the production of the cabin, aft fuselage and wing sections, replacing 6982 rivets. The FSW tools were routinely replaced after 77 m of welding as part of the total preventative maintenance system, even though they were capable of more work. (7, pp. 4-5.)

Furthermore that should be mentioned that FSW has become the preferred method for joining Al–Li space structures. Conventional welding techniques for Al–Li alloys produce unacceptable levels of porosity due to the presence of lithium compounds that may be hydrides, hydrocarbonates, and hydrated oxides. During welding, such compounds decompose with the evolution of gas bubbles (8, p. 60).

The first friction stir welded joint was implemented for the Interstage Module of a Delta-II launch vehicle and was produced by Boeing and successfully flown in 1999 (8, p. 231; 14). Then, FSW was adopted in producing the Space Shuttle External tanks that stored liquid hydrogen and liquid oxygen (8, p. 231) Delta IV, Atlas V, and Falcon IX rockets as well as the Orion Crew Exploration Vehicle, Ares I and Space Launch System (SLS). (2.)

Consequently, more and more engineering practices and successes in the abovementioned space vehicles paved the way to eventually substitute FSW for conventional fusion welding, so FSW has become a main welding process in manufacturing of aerospace vehicles and aluminium fuel tanks (14).

Lockheed Martin's Orion crew module is designed to accomplish manned missions to the Moon, an asteroid and even Mars, which is shown in Figure 13 (8, p. 36). FSW joining technology is being used, as the established joining method for Al-Li alloys, which is capable of producing 100% defectless welds. Moreover, FSW decreases the production costs and produces a stronger weld joint compared to fusion weldisng. Increased joining strength also allows design engineers to further reduce vehicle mass. (25.)

Figure 13. Artist drawing of Orion Spacecraft (25)

Friction stir welding is being used to join Orion's Al-Li AA2195 cone panels, bulkheads, tunnel, and barrel together. Orion's first spacecraft design, the Ground Test Article (GTA) utilized 33 welds. The Engineering Flight Test-1 (EFT-1) which orbited the earth twice then splashed down in the Pacific Ocean on Dec 05, 2014 utilized 19 welds. Exploration Mission 1 (EM-1), slated for launch in 2018 further reduced the total number of structural welds from 19 to 7, reducing the vehicle mass by 318 kg as shown in Figure 14 and Figure 15. The longest FS weld of 11,3 m was created for joining the forward cone assembly to the aft barrel assembly. (8, p. 60; 25.)

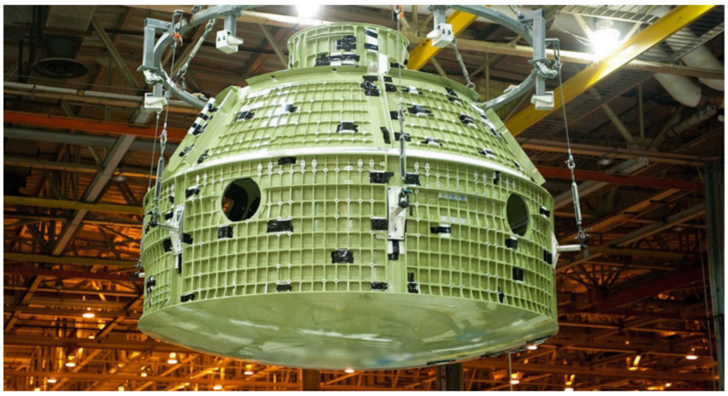


Figure 14. Lockheed Martin’s Orion crew module pressure vessel (8, p. 274)

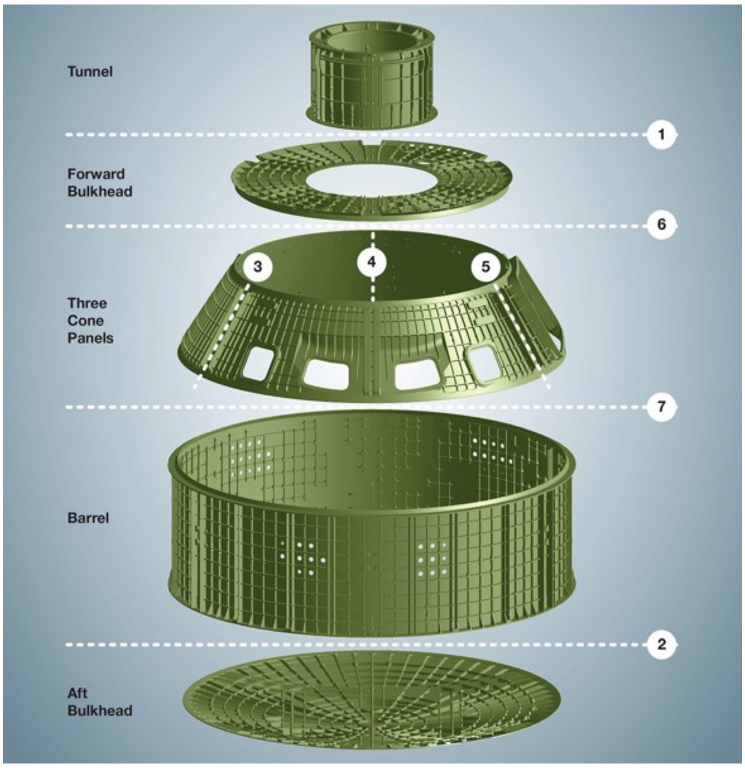


Figure 15. EM-1 SF weld locations (25)

NASA’s Space Launch System is the advanced, heavy-lift launch vehicle that will provide an entirely new capability for science and human exploration beyond the Earth’s orbit. SLS core stage, towering more than 61 meters tall with a diameter of 8,3 meters, will store cryogenic liquid hydrogen and liquid oxygen in two pressurized tanks made of AA2219, an aerospace aluminium alloy, as shown in Figure 16. (13; 26.)

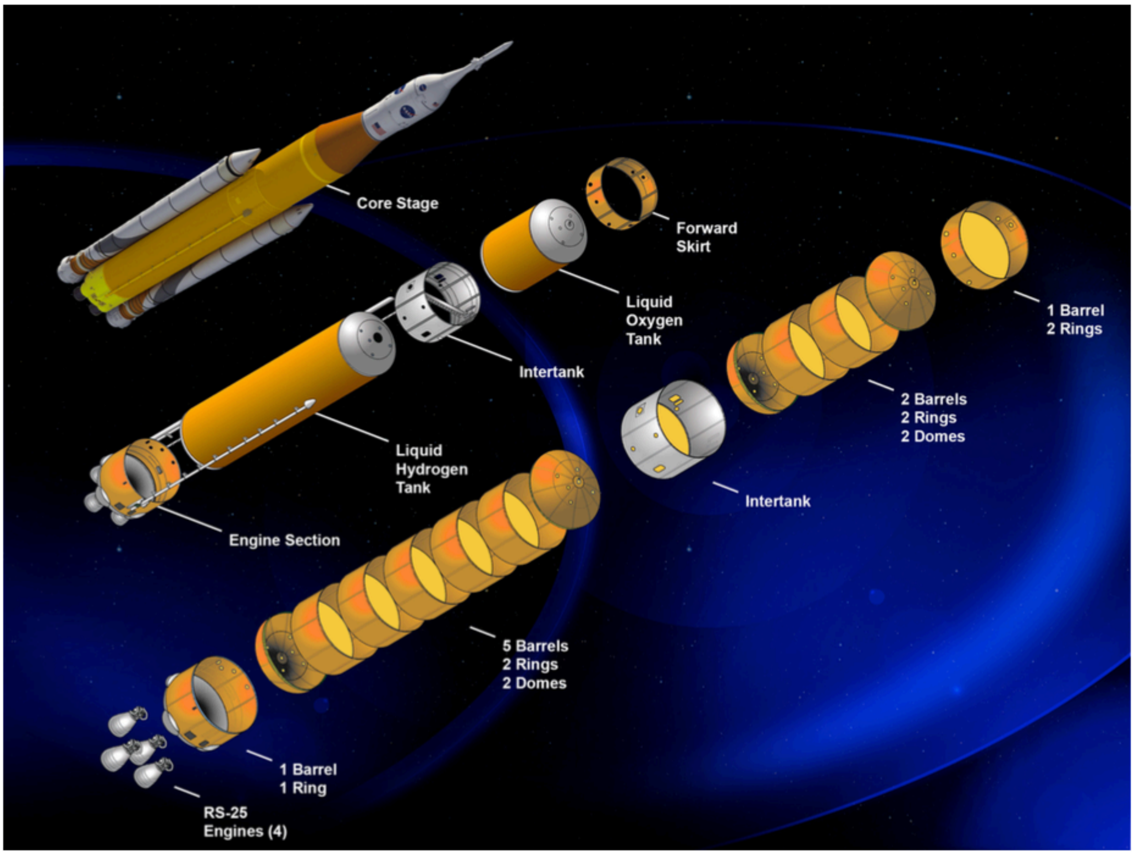


Figure 16. Schematic structure of Space Launch System (26)

Friction stir welding is being used for manufacturing of the these fuel tanks. Figure 17 shows that the welds to form an integral tank include longitudinal joints of arc plates to form a section, variable-curvature longitudinal joints and closed circumferential joints for, closed circumferential welding of dome to section and section to section. Due to the fact that the integral tank is a large thin-wall structure it should be assembled with a very high accuracy during FSW process. (14.)

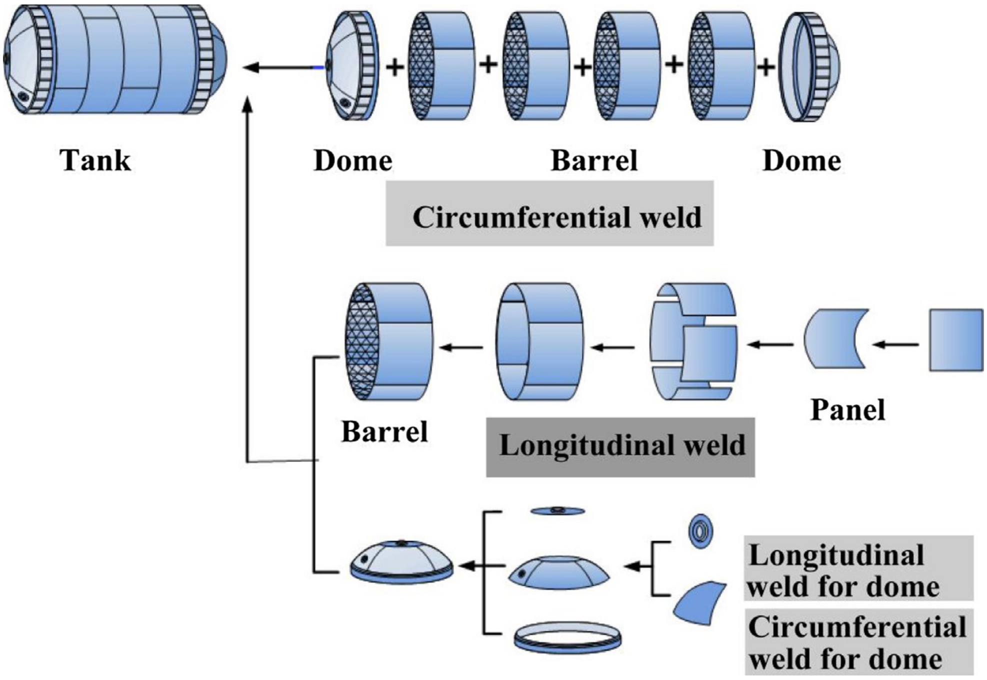


Figure 17. Schematic diagram for structure and main welds of launch vehicle tank (14)

Figure 18 illustrates the finished barrel segment that stands at 6,7 meters tall, weights 4128 kilograms and is made of AA2219 aerospace aluminium alloy. Five similar barrels and two end domes were manufacture for the final assembly of the SLS core stage liquid hydrogen tank. (13.)

Figure 18. Fully welded SLS barrel section for the liquid hydrogen tank (13)

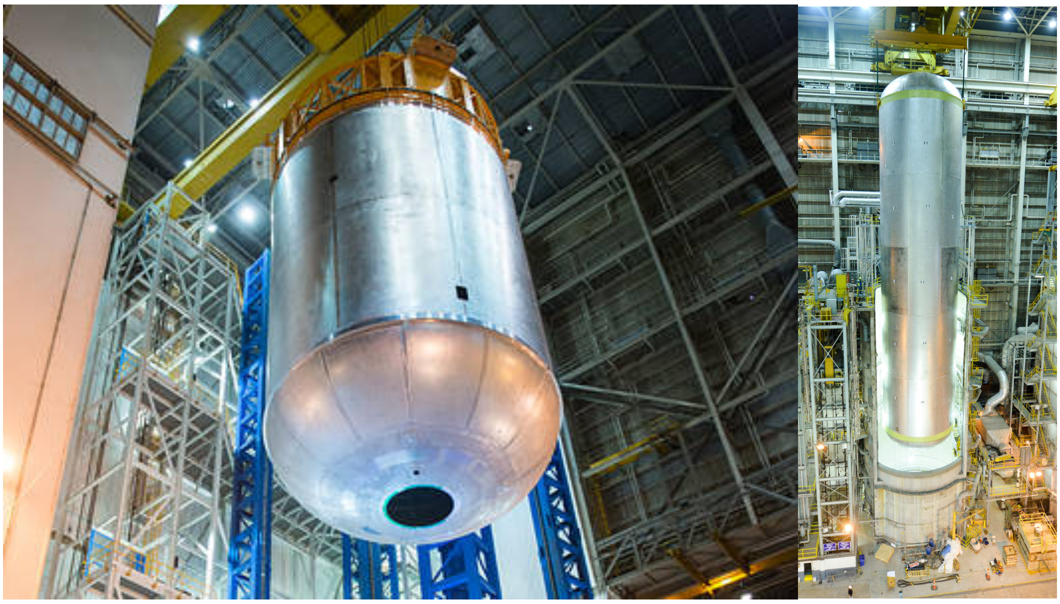


Figure 19. Left: Liquid Oxygen Tank. Right: Liquid Hydrogen Tank (27; 28)

Thus, as a substitute of conventional technologies of aircraft and tank manufacturing, FSW will give strong support for processing of materials and production of new aerospace vehicles.

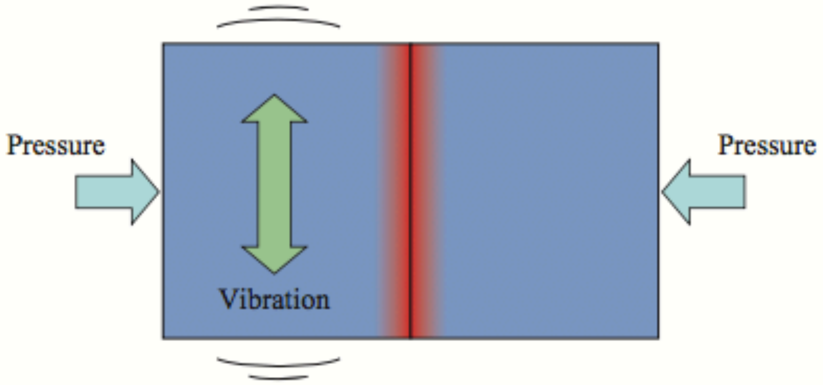
### 2.2.2 Linear friction welding

**Process**

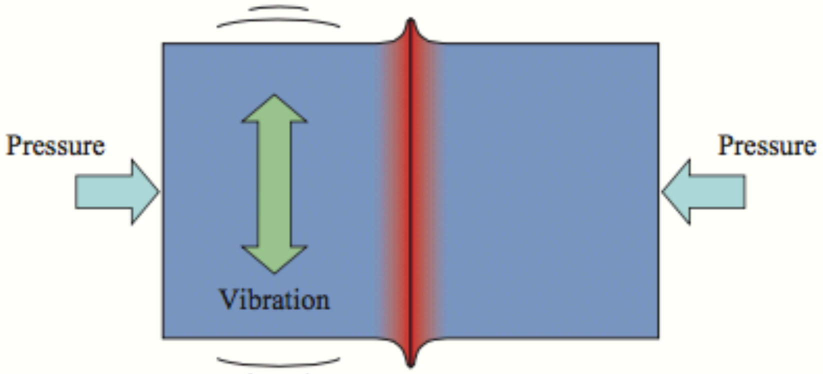
Linear friction welding is one of the configurations of friction welding technology that is achieved by the linear relative motion across the interface of the workpieces. (17, p. 2.)

Linear oscillations of one part relative to another under a large pressure are capable of frictional heat generation, which rapidly raises the temperature in a narrow interface region between joining parts, as shown in Figure 20a. Once the interface material is heated to a plasticizing temperature, the oscillating part is stopped in the aligned position with the stationary part. Further, at the last process stage, the increased axial pressure is applied to consolidate the two parts together. Figure 21 illustrates the resulted macrostructure of the joint. (29.)

(a) First stage: Temperature rise due to vibrational friction



(b) Second stage: Softening at higher temperature, expulsion of the material



c) Third stage: Expulsion of surface layer + Joining of the fresh surfaces

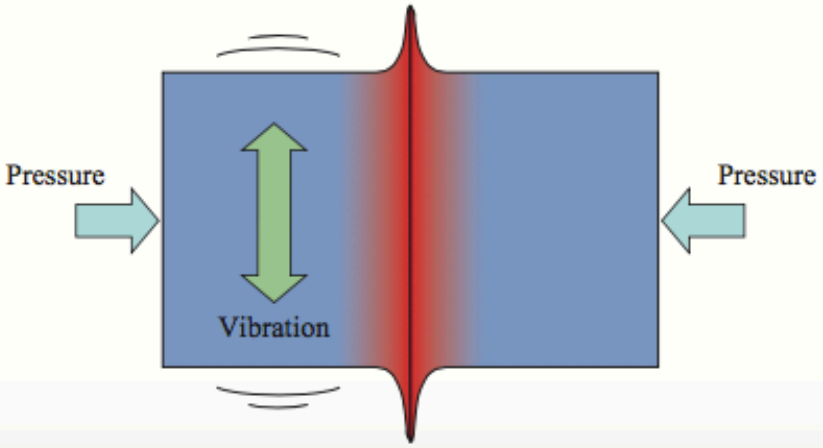


Figure 20. Schematic view of LFW process (30)

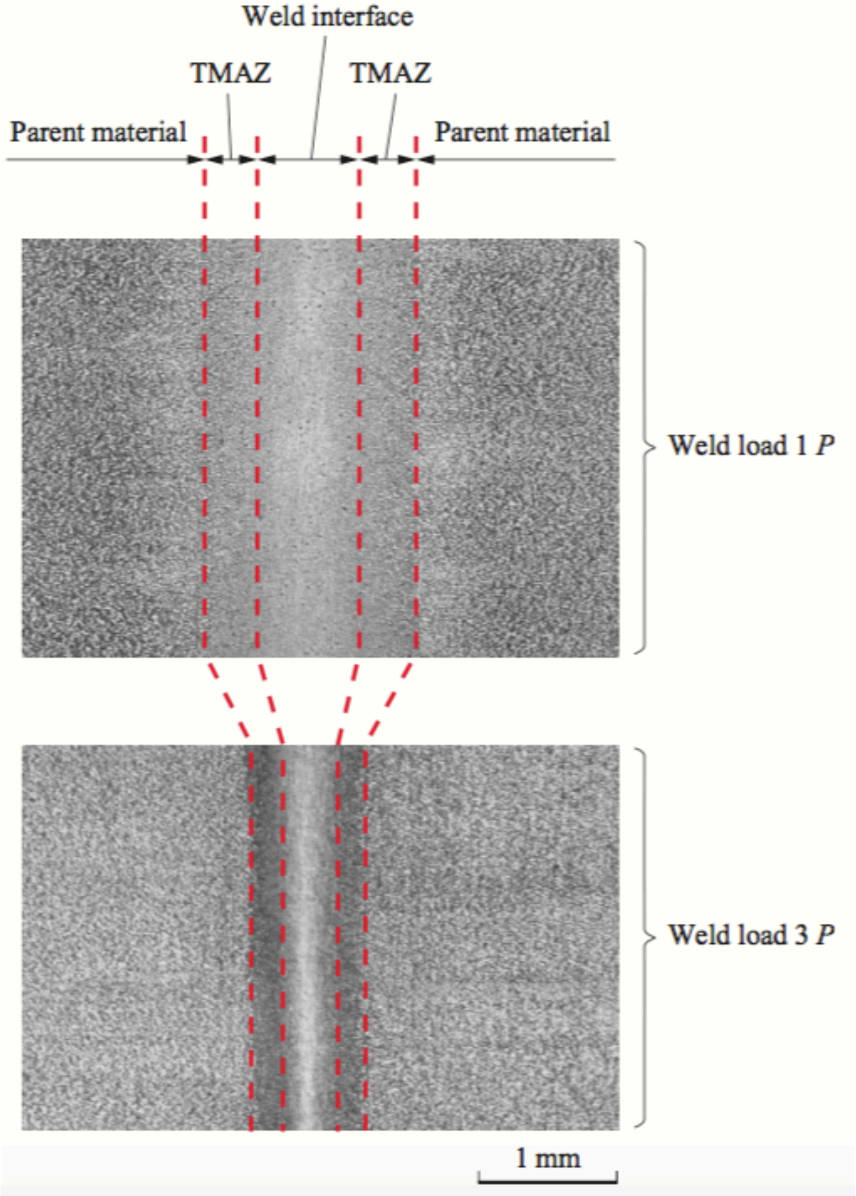


Figure 21. Macrostructure of LFW joints (30)

During the LFW process, some of the plasticized material is expelled from the interface causing the work-pieces to shorten (burn-off) in the direction of the compressive force (31). During the burn-off the interface contaminants, such as oxides and foreign particles, which can affect the properties and possibly the service life of a weld, are expelled from the weld into the flash, which is shown in Figure 22b. (29.)

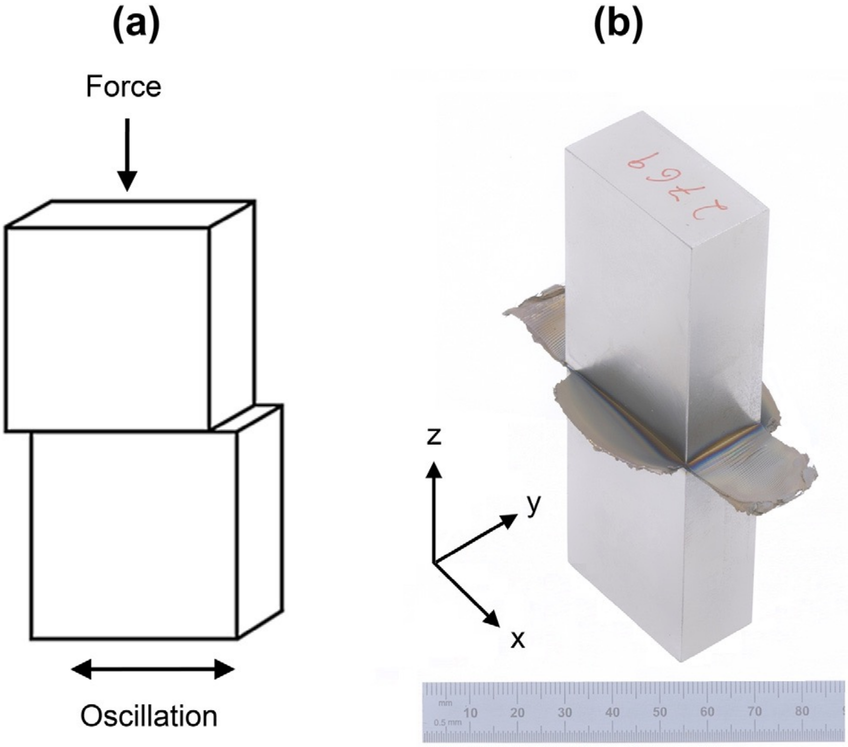


Figure 22. (a) LFW process schematic and (b) a completed Ti-6Al-4V weldment with the expelled interface material (flash), with oscillatory motion occurred in the 'x' direction (29)

Linear oscillations in LFW produce relatively low energy input that keeps the interface temperature below the melting point of the material, therefore bulk melting of the welding parts does not occur (no melting pool). This leads to reduction of weld defects associated with melting and resolidification such as solidification cracking, voids, pores, micro inclusions, slag inclusions, excessive distortions and etc. Moreover, the solid state nature of the process does not require filler metal addition, flux, shielding gas or vacuum. (31.)

The additional advantage of FLW is related to the self-cleaning nature of the process that results in reduction of surface preparations as oxides, impurities and other contaminations, which are expelled out with the plasticized material from the weld area into flash. Therefore pure and clean surfaces are pushed into close contact, meanwhile a flash is subsequently removed by machining. (31.)

Compared with fusion welding, the process is highly efficient and clean from the environmental viewpoint since it produces no harmful fumes, gases or smoke

(31). The welds are of high integrity and the developed recrystallized microstructure may lead to the increased tensile strength (16). Moreover FLW is fully automated, repeatable process (7, pp. 386-388).

All the abovementioned advantages of the LFW process bring the capability of producing welds in Ti, Al alloys, intermetallic alloys and etc. (7, pp. 386-388). During welding of Ni-based superalloys as in case with fusion welding, possible residual stresses should be considered, (31) since, these alloys are not very plastically deformable. Good mechanical properties have been reported in ferritic as well as austenitic stainless steels, with the strengths of these welds suggested to be superior than those of the respective parent materials. Moreover, LFW is the applicable process for joining of dissimilar materials, which is traditionally associated with problems such as formation of brittle intermetallic phases and segregation of alloying elements for fusion welding and deteriorate the mechanical properties of the joint (31). LFW of dissimilar materials should be considered with the assumption that the material of at least one of the two components must be plastically deformable to weld (16).

Nonetheless, linear friction welding is not an ideal process and that is illustrated via significant capital investment for the machinery and tooling (7, p. 388). Moreover, the size and geometry of the weld could be restricted with formed flash (especially when the flash has to be removed) and clamping options of the parts (31). Limited suitability of LFW for welding of thin-walled tubes and plates should be also considered (16).

### Application

Abovementioned benefits of the process, finds an increasing interest in the manufacture of aircraft structural components – particularly for Ti-6Al-4V. Preliminary investigations suggest that up to 50% of all titanium alloy aerospace structures can be manufactured using the LFW process. (29.)

The process is presently well established for fabrication of Ti alloy bladed disks (blisks), which can be seen from Figure 23 and Figure 24. In a conventional turbine stage, the blades are mechanically attached to a hub. This attachment involves interlocking parts, which add significantly to the total weight of the rotating part. In a blisk, the blades and the hub are a single piece; interlocking mechanism is eliminated with significant weight savings (5). Therefore, LFW is intensively used for manufacturing of blisks in power generation gas turbines (31), in the fan and compressor stages of modern engines such as the European Consortium EJ200, SNECMA M88-2, General Electric F414 and Pratt and Whitney F119, as shown in Figure 25 (7, pp. 386-387; 10, pp. 299-300).

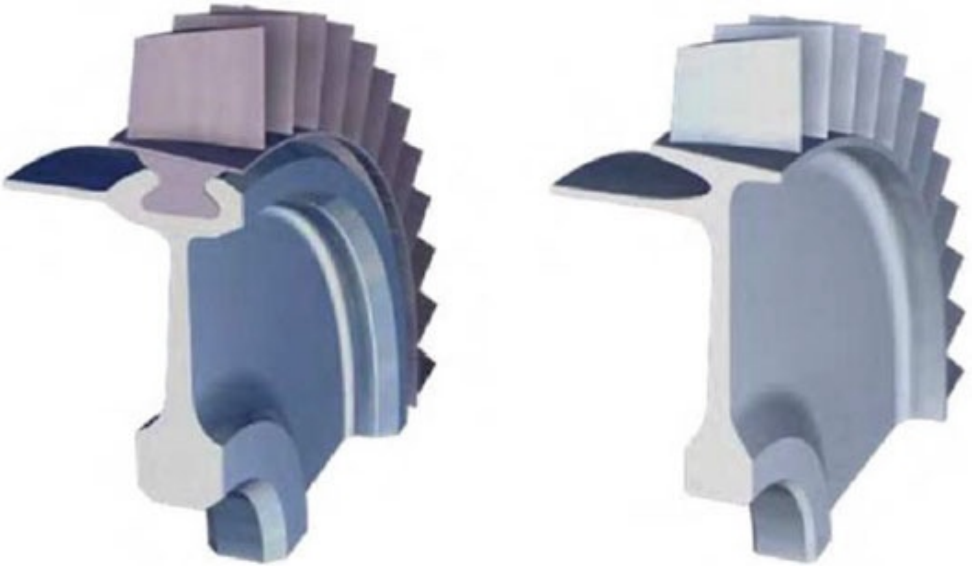


Figure 23. Conventional bladed-disc and blisk. Left: mechanical attachment of blades, right: blades are welded (10, p. 300)

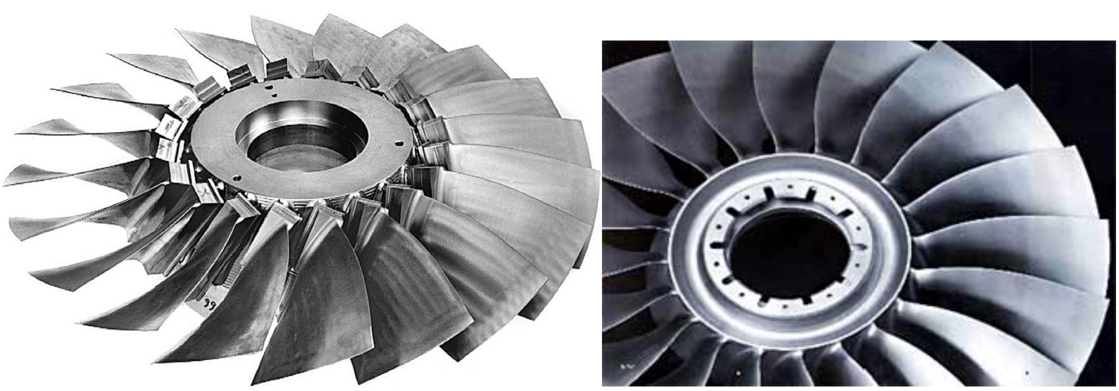


Figure 24. A linear friction welded blisk assembly produced by MTU München for Eurofighter: left (as welded), right (as machined) (6; 7, p. 387)

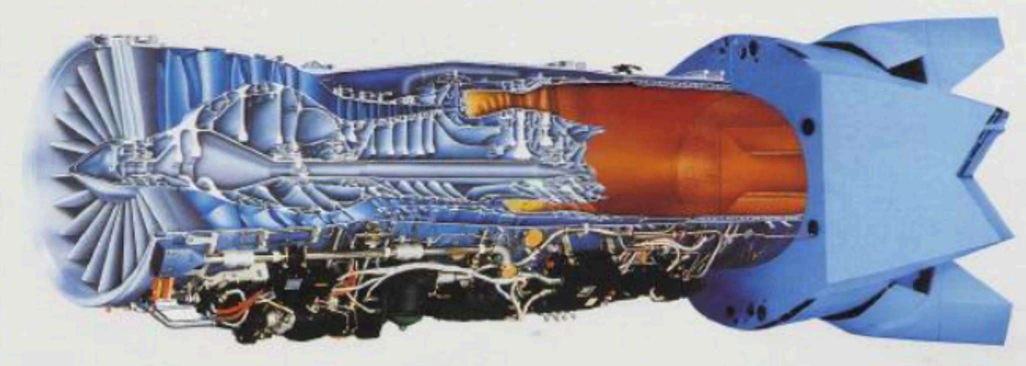


Figure 25. F119 – engine for F-22 Raptor jet fighter (32, p. 50)

In a brief, LFW is a so well established technology for blisks manufacturing due to the number of following advantages over mechanical assembly and conventional fusion welding processes:

- The replacement of conventional bladed disk in aero engines with a welded blisk can enable overall weight reduction up to 20–30%, as blisk weight reductions straightly affect the design of shafts and related parts of the engine (5; 7, pp. 386-387).

- The process is highly reliability as it has been reported by certain aero-engine manufacturers that tens of thousands of welds have been produced without a single failure (7, pp. 386-387).

- Different disc and blade alloys or materials can be welded together when producing blisks for reaching optimal performance of the welded structure (7, pp. 386-387).

- Damaged turbine blades can be easily replaced by removing the damaged blade and linear friction welding another in its place (7, pp. 386-387).

- Only limited machining is needed after weld production (mainly to remove flash), and adaptive machining can be used to accommodate potential variations in blade location owing to distortion (7, pp. 386-387).

- The severe deformation, high-temperature and high-cooling rates that are experienced close to the weld line in linear friction welds can allow a refined microstructure to form providing improved strength at the weld line relative to the parent material (7, pp. 386-387; 33).

- High integrity welds achieved with unprotected atmosphere (even for Ti) (7, pp. 386-387; 33).

- LFW is sustainable process with a wide tolerance to the process parameters (33).

Furthermore, LFW could be counted as a key technology for near-net-shape manufacturing, which provides significant material saving and consequently, cost savings versus current machining from “solid”, which are shown in Figure 26, Figure 27 and Figure 28 (29; 33). Particularly, Figure 27 illustrates sample where applied near-net-shape manufacturing principle results in -66% raw material, -49,9% production time, -23,3% production costs reductions (33).

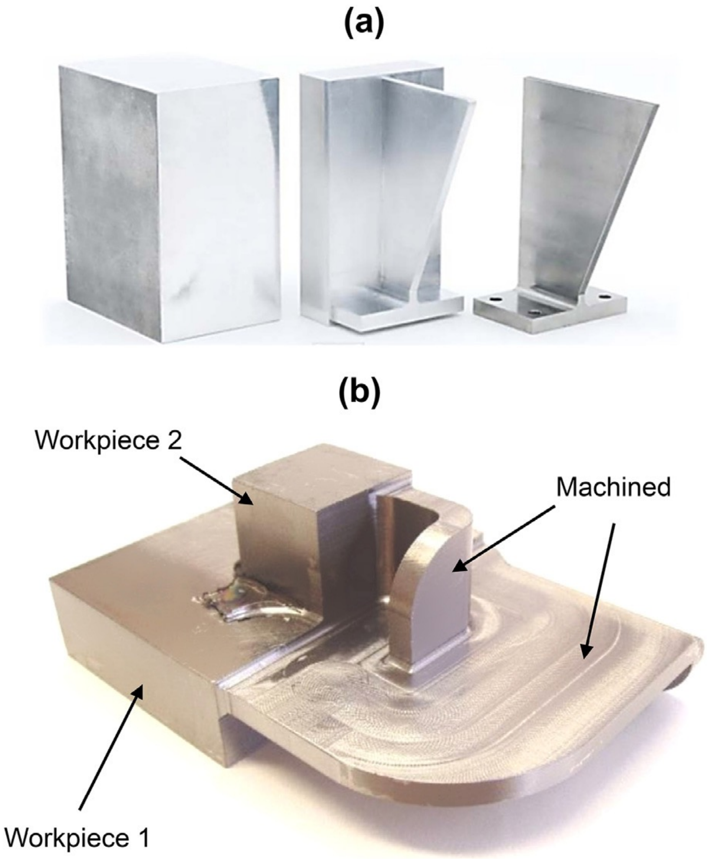


Figure 26. (a) An aerospace component machined from an oversized block of metal, and (b) A Ti-6Al-4V preform fabricated using the LFW process: on the left side – welded structure; on the right – the final machined component (29)

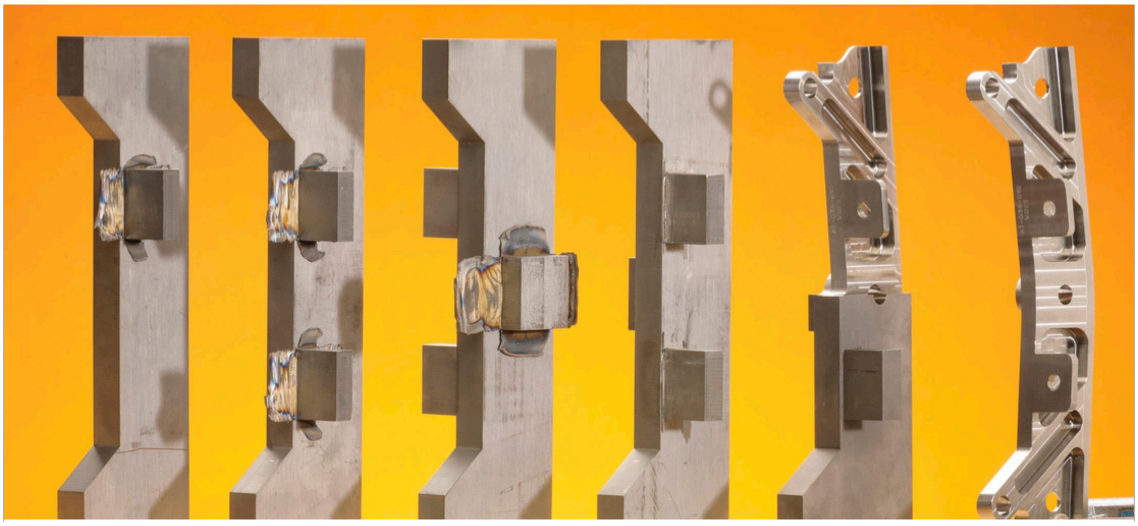


Figure 27. Step by step (from left to right) near-net-shape manufacturing with LFW (33)

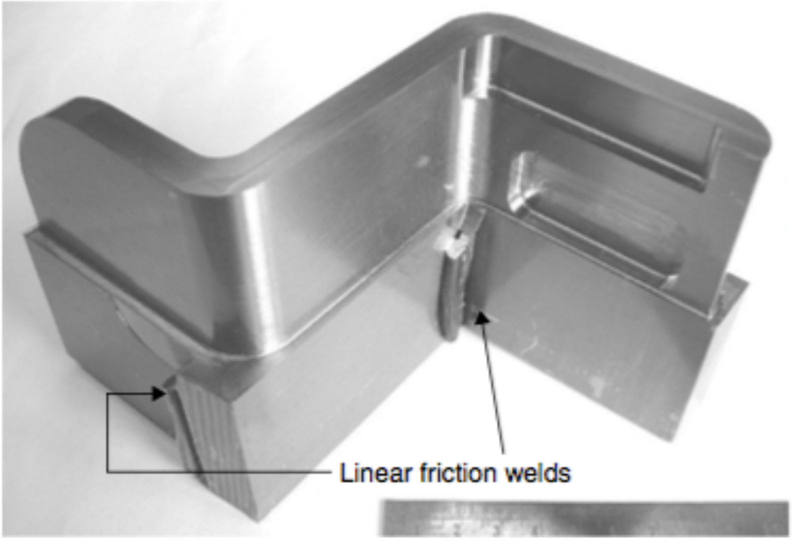


Figure 28. Near-net-shape manufacture of a Ti-64 component. Welded structure can be seen at the bottom of the image and the final machined component at the top (7, p. 387)

### 2.2.3 Inertia friction welding

**Process**

Inertia friction welding is a solid-state joining process that is based on the rotation of one workpiece relative the other under compressive axial force.

The frictional thermal energy is delivered to the interface via a rotating flywheel with initially stored kinetic energy for joining the components of cylindrical geometry, shown in Figure 29 and Figure 30. As illustrated in Figure 29, one part is clamped to the flywheel, meanwhile the other part is clamped in a non-rotating chuck connected to a hydraulic ram. Once the desired rotating speed of the flywheel is achieved, the motor is disengaged, and a forging pressure is applied to two welding components to contact with each other. During the approach the flywheel speed starts to decelerate leading to the conservation of the stored energy into thermal one, due to the generated friction. The applied pressure causes the subsequently formed plasticised materials to flow outside expelling the original surface oxide layer and other contaminants. Such a flash formation, shown in Figure 30d and Figure 31, leads to the weld energy dissipation and further cooling of the interface region even before the rotating part has stopped. (34; 35.)

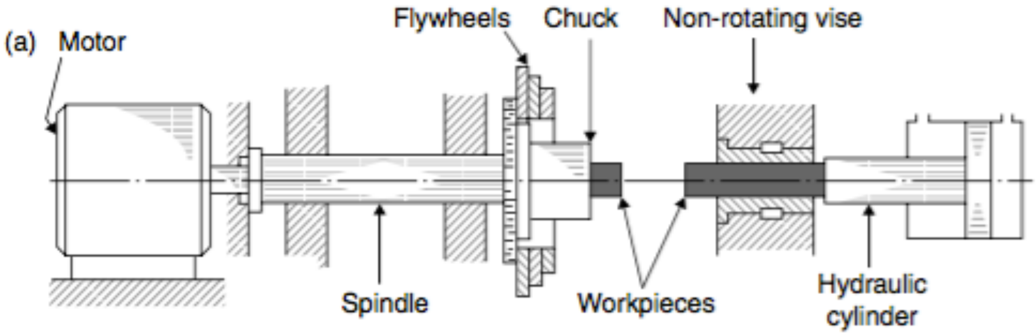


Figure 29. Schematic illustration of IFW equipment (34)

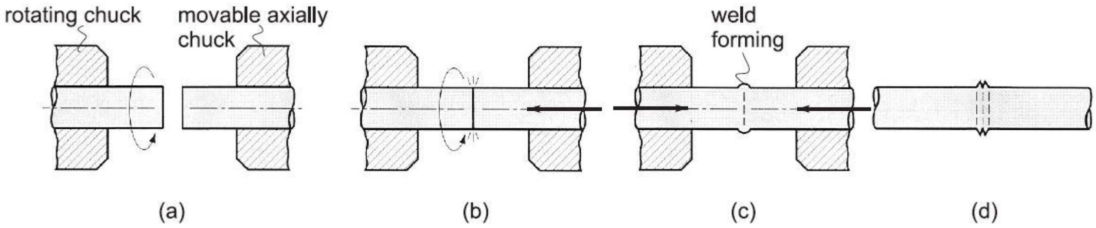


Figure 30. Inertia friction welding: (a) no contact, (b) parts brought into contact to generate friction heat, (c) rotation stops and axial pressure applied, (d) final product showing the flash (34)

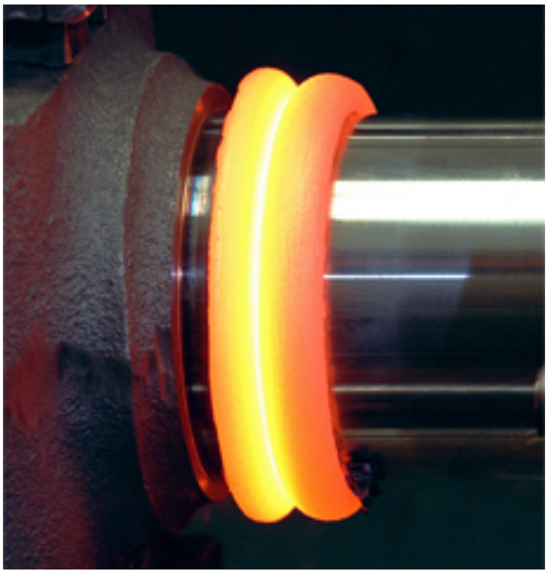


Figure 31. Weld formation with IFW (36)

The macrostructure of inertia friction welded joint is represented with several distinct zones, as shown in Figure 32: a weld centre zone (WCZ), a thermo-mechanically affected zone and a heat affected zone. The area and microstructural composition of these zones are dependent on the used material and processing conditions. The weld region is surrounded by a flash collar. (35.)

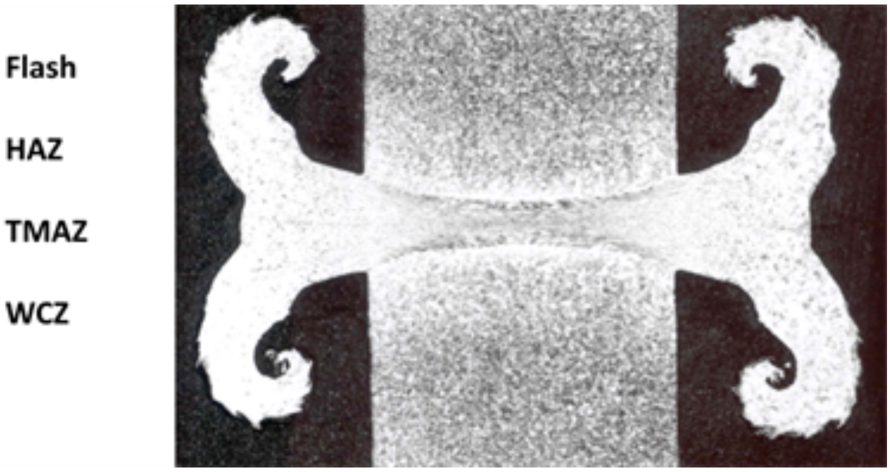


Figure 32. A macroscopic section of a titanium alloy IFW (35)

When optimum processing conditions are used, for many similar and dissimilar material combinations IFW can produce superior or similar in strength joints to the parent material. (35.)

In general, the advantages as solid state process with no filler metal, no flux and shielding addition, no surface preparation, efficient material utilization, sustainable process etc.). In case of limitations, high capital investment rate, flash machining, etc. for LFW are typical for IFW also, with the exception of the axisymmetric geometries restrictions in IFW – application of inertia friction welding in limited with round shapes, non round and complex geometries like turbine blades in gas turbine could not be treated, in particular. (31.)

**Application**

The use of inertia welding in the aerospace industry has been steadily increasing as it provides significant improvements in joint quality compared with the use of fusion welding. Among the friction-based welding processes, the use of inertia welding in the aerospace industry has been steadily increased in the past two decades, especially in joining nickel-based superalloys, titanium alloys and steel (mostly ferritic ones (7, pp. 50-52)) aero engine cylindrical components, illustrated in Figure 33 – Figure 35 (34). Nonetheless, further work is needed to investigate the utility of IFW in welding of new aerospace materials and particularly the ability to join dissimilar metals and alloys (7, p. 55).

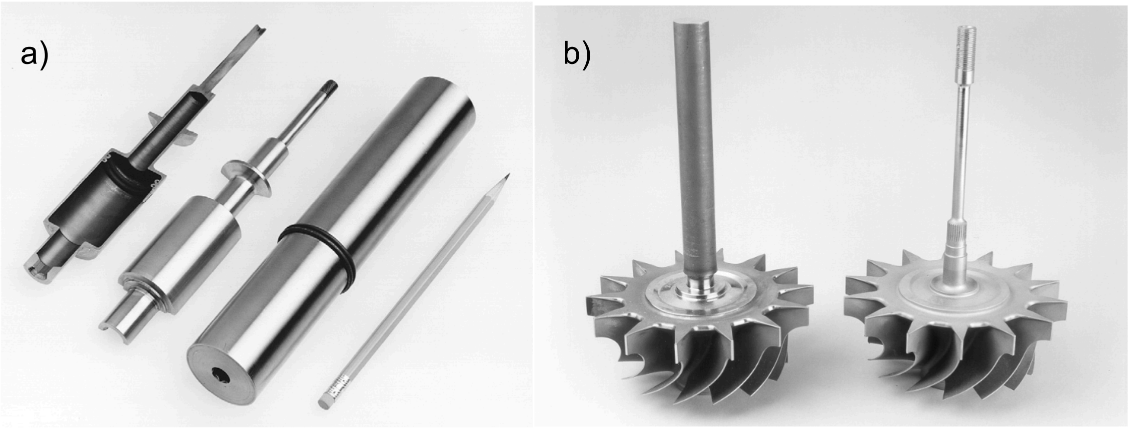


Figure 33. (a) Lightweight piston for aircraft pump, stainless steel (37), (b) Turbine wheels (7, p.32)

Figure 34. Left: stator vane root weld – as machined, center: stator vane root weld – with flash removed, right: stator vane root weld – as welded (titanium) (37)

a)

b)

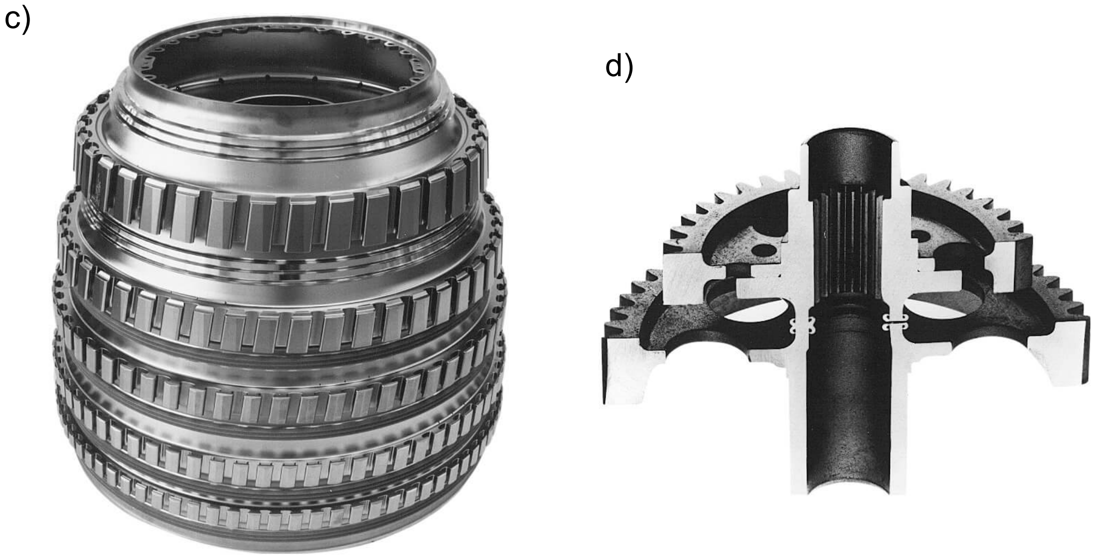


Figure 35. (a) Landing gear component, steel; (b) fan shaft for military jet engine, nickel-based superalloy; (c) low compression titanium rotor assembly, titanium; (e) cluster gear cross section, steel (37)

## 2.3 Laser beam welding

### 2.3.1 Process

Laser welding is a high-power-density fusion-welding process (7, p. 75). As an industrial heating source for this welding process $CO_2$, solid state (Nd:YAG, fibre, disc) lasers are implemented.

The operational principle of LBW is based on the laser beam irradiation on the surface of the material. The absorbed energy causes the heating, which leads to melting and/or evaporation of the materials depending on the absorbed laser power density. The core objective of laser welding technique is creation of weld pool at the contact surfaces of the workpiece.

There are two general approaches for laser welding processes. The first approach, referred to as conduction welding, is based on the energy distribution into the depth of the treated material implemented by conduction, as shown in Figure 36a, therefore the laser beam is parameterized to keep the surface of the weld poll unbroken. The second and the most important approach for the aerospace industry, in particular, referred to as deep penetration or keyhole welding and would be discussed in more details. This operational mode is characterized by the creation of a keyhole in the weld pool with the help of parameterized laser beam heat source. Generally, the transition from the conduction mode to the deep penetration welding is associated with the increase in laser power intensity or irradiation time such that surface vaporization at the molten weld pool begins. The resulting evaporation-induced recoil pressure forms a small depression in the weld pool, which subsequently develops into a keyhole by the upward displacement of molten material sideways along the keyhole walls, as shown in Figure 36b. The subsequent ionization of the vapor results in the formation of the plasma plume, which greatly absorbs laser energy and is therefore responsible for the attenuation of the laser beam entering the keyhole. Further, within a keyhole, the laser energy is reflected repeatedly (multiple reflection) which is accompanied with efficient absorption of energy at the keyhole walls. Therefore the forming keyhole structure, participates in transferring and distribution the laser energy deep into the material. Newly formed walls of the keyhole act as the vaporization surfaces leading to the further cavity growth. The vaporized materials act against the surface tension to keep the keyhole open and as a consequence accelerate the continuous upward melt flow out of the cavity. (38, pp. 412-413.)

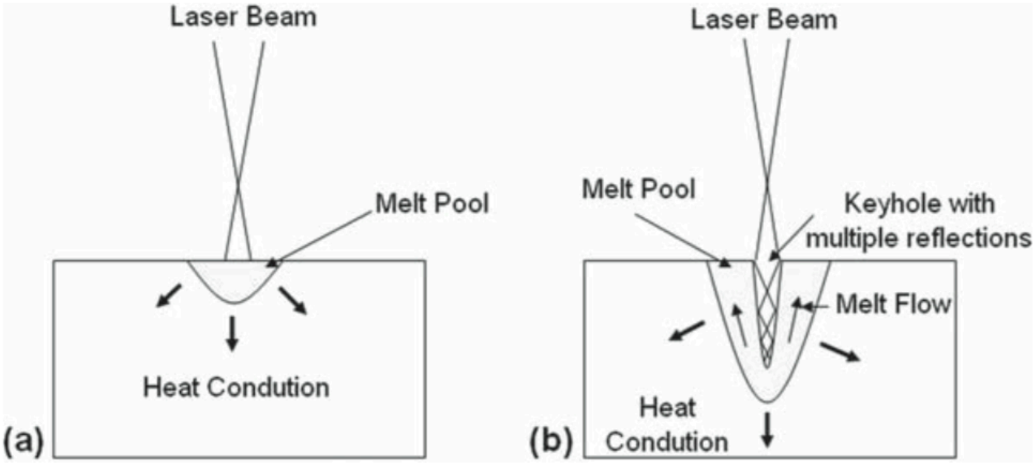


Figure 36. Schematic of (a) conduction and (b) deep penetration laser welding showing various effects (38, p. 412)

In fact, the keyhole is not cylindrical in shape. Figure 37 clearly illustrates a characteristic curve to it, which is determined by the travel speed, thermal conductivity of the substrate material and etc. The resulting characteristic profiles of keyhole laser welds produced in Ti-6Al-4V with a 1 μm laser source could be seen in Figure 38. (7, p. 90-92.)

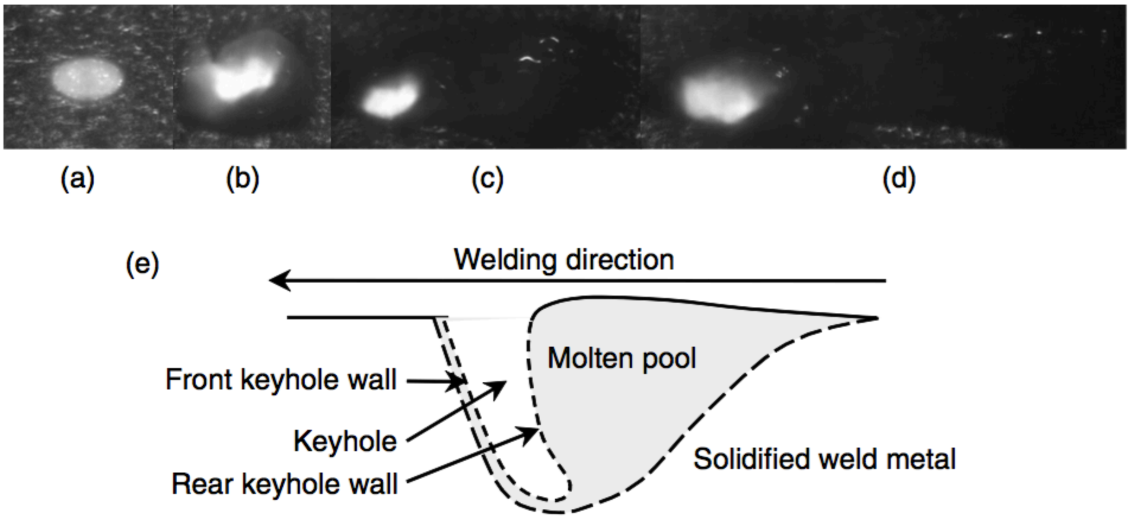


Figure 37. Formation of keyhole laser-welding process in C-Mn steel, (a) surface melting, (b) vaporisation of substrates occurs, (c) keyhole traverses across the workpiece and weld pool begins to form, and (d) the weld-pool length increases and stabilises; (e) schematic of the side view of a keyhole (7, p. 91)

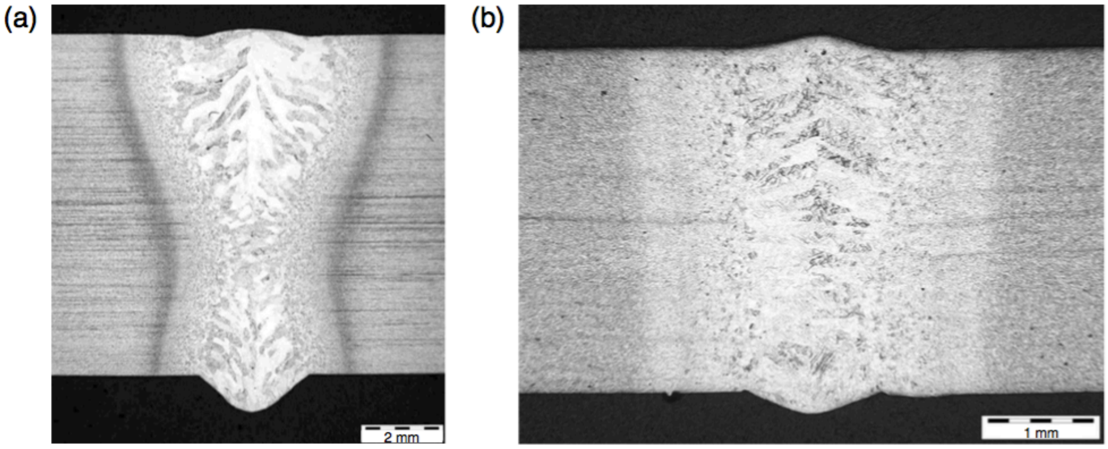


Figure 38. Profiles of keyhole laser welds produced in Ti-6Al-4V, (a) 9.3 mm thickness, and (b) 3.2 mm thickness. Note: different scales (7, p. 92)

There are many laser welding parameters affecting the welding quality such as laser power, welding speed, focal position, shielding gas flow, laser pulse frequency and etc. (39). Optimisation of the process parameters is crucial, if high-quality welds with the ideal weld bed should be formed (7, p. 92). When the process parameters are incorrectly chosen, many defects appear such as an unstable weld pool, porous oxide inclusions, loss of alloying elements, liquation, and solidification cracking (39).

The main characteristic of laser beam welding is its high energy controllable focusing and accurate heat input control that makes available precision and clean welds with high penetration depth and lower heat input in comparison with conventional welding processes providing narrow heat affected zone, as shown in Figure 39, and rapid cooling (19, p. 116; 40). Since low heat input is used, heat induced distortions and residual stresses (40) of the work-piece are minimized that results in high quality welds and reduction of post welding machining. (12, pp. 61-64.)

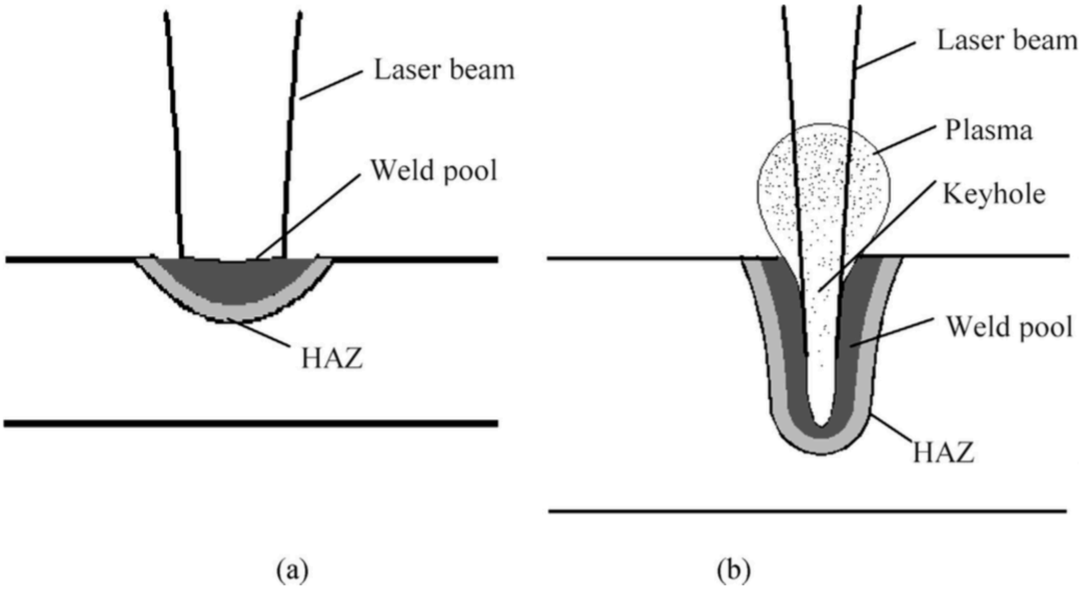


Figure 39. Schematic diagram of HAZ for different operational modes: (a) thermal conduction mode and (d) deep penetration/keyhole mode (41)

The proper selection of the process parameters brings possibility to weld a wide range of materials and joint configurations (12, p. 63). Most light metals, such as aluminium, magnesium, titanium (11) and their alloys could be welded with the important consideration that many metals exhibit high reflection and low absorption of laser light. However, the susceptibility of metal alloys to the loss of alloying elements during laser welding should be taken into account, as this factor determines the reduction of the hardness and tensile strength of the joints (42). Welding of such non-metallic materials as ceramics, plastics and composites also seems attractive (19, p. 116; 38, pp. 438-440). Furthermore, laser welding parameters can be optimized to cover a range of dissimilar joints combinations, with such significant advantages over conventional fusion welding processes as better weld quality, higher productivity, and better flexibility (38, pp. 442-443). The following dissimilar combinations like aluminium-steel, aluminium–copper, aluminium–magnesium, copper–steel, steel–kovar, steel–nickel, dissimilar metal grades, and composite-metal joint has been successfully obtained with laser beam welding (19, p. 117).

Laser beam welding is a highly flexible and repeatable welding technique as it is a non-contact process that could be easily automated and robotized. As a consequence, LBW provides higher workpiece accessibility in comparison with other welding processes such as resistance and arc welding. Moreover, laser welding process is suitable for welding large structures as well as micro welds (12, p. 63) and complex shapes in all welding positions (40) with the foregoing advantages brings additional economic benefits in the typical industrial environment. (38, p. 412.)

Additional operational advantages of LBW welding are correlated with the energy sources configurations. Typically, laser welding could be classified as single beam welding, dual beam welding and laser-arc hybrid welding as illustrated in Figure 40.

For a T butt joint, dual beam welding is preferred for lower distortion resulting from symmetric welding, meanwhile single beam welding for this configuration easily causes residual stress and distortion. Laser-arc hybrid welding introduces a secondary energy source to the weld pool, which brings additional process advantages, that are discussed further in more details in chapter 2.3.2. (11.)

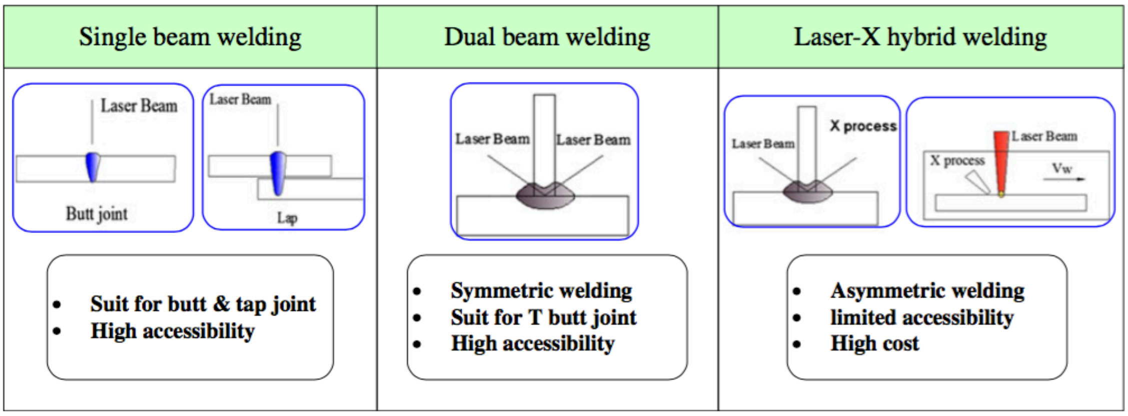


Figure 40. Schematic representation of single beam welding, dual beam welding and Laser-X hybrid welding (X is a different arc based welding method) (11)

Despite of the numerous advantages, LBW process still involves some imperfections**.** The main disadvantage is the relatively high cost of laser welding equipment, especially with increase in power level. Nonetheless, by sharing the system to other processes, such as laser cutting, surface hardening and trimming this issue could be reduced (11; 40).

Another drawback is based on the high focusability of the laser beam. On the one hand the small focused spot size of laser beam is a positive aspect playing a crucial role in deep beam penetration and reduced HAZ. On the other hand focused laser beam limits joint positioning tolerances. Therefore close fitting, well clamping and exact positioning are required; otherwise, the accurate beam/joint alignment cannot be achieved and the workpiece cannot be welded properly. (12, p. 64.)

Relating to the weld structure, LBW still suffers from statistically occurring seam issues like cracking (38, pp. 429-431), notches or holes in the seam, high weld hardness and poor toughness (40). Most of the cracks in the welds originate from the restrictions to the free contractions of the material during the cooling cycle (38, pp. 429-431). Notches are the other issues, which reduce the mechanical properties of the joint. The reason for these process instabilities is laser beam refraction by the vapour plume, which induces varying laser intensity distribution (40). Furthermore, due to low heat input, fast cooling rates induce refinement of the microstructure, which generally leads to high weld hardness and poor weld toughness (38, pp. 432-433).

### 2.3.2 Hybrid laser welding

The hybrid laser arc welding process was introduced in the late 1970s by Prof. W. M. Steen (43).

In hybrid laser arc welding process, the laser beam and the electric arc interact in a common weld pool to provide primary and secondary heating sources for the joining process, as shown in Figure 41. (7, pp. 109-112; 43.)

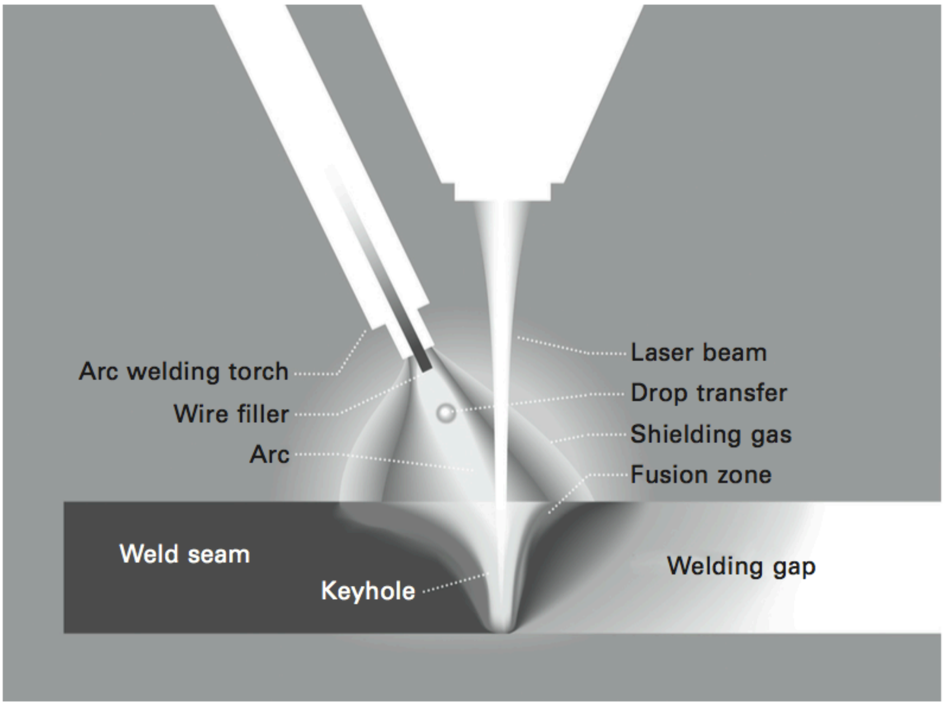


Figure 41. Principle of laser hybrid welding (44, p. 98)

According to the combination of various heating sources used, hybrid welding can be generally categorised as:

1. Laser- GTA welding;
2. Laser-GMA welding;
3. Laser-plasma welding.

In lase-arc hybrid welding, $CO_2$, Nd:YAG and fibre lasers are commonly used as the primary heating sources, meanwhile the electric arcs are mainly used as the secondary ones. There are major configurations based on GMA welding with consumable electrodes, and GTA welding with non-consumable tungsten electrodes. In GMA welding, the arc is burning between a mechanically supplied wire electrode and the workpiece. Hence, GMA welding can be subdivided into metal inert-gas (MIG) and metal active-gas (MAG) welding according to the type of shielding gas used. In GTA welding, a chemically inert gas, such as argon or helium, is often used. A special configuration is the plasma arc welding (PAW), which produces a squeezed arc owing to a special torch design and results in a more concentrated arc spot. (7, pp. 111-112.)

Laser beam is focused and high density heat source that allows to produce narrow and deep high quality welds, as shown in Figure 42a and Figure 43a. The tight focus of the beam allows higher welding speed, which in turn reduces the heat input and the chances of thermal distortion in welded parts. However, laser welding systems are relatively expensive and electric efficiency for most of these systems is still very poor. Moreover, poor gap bridging ability of LBW leads to the demanding fit-up tolerances for the work-piece and edge preparations. Additional challenges arise during welding of highly reflective materials like aluminium, copper, gold and etc. Contrary to the abovementioned issues, arc welding technique could be characterized with excellent gap bridging ability, high electrical efficiency and ease in processing of highly reflective materials. Additionally, arc welding systems are much cheaper than laser welding ones of equivalent capacity. However, significantly lower energy density of the arc heating source leads to lower welding speeds and subsequently high heat input. This consequently results in higher with of the weld pool, shallow penetration, illustrated in Figure 42b and Figure 43b, and increased thermal distortions of the welded component. (43.)

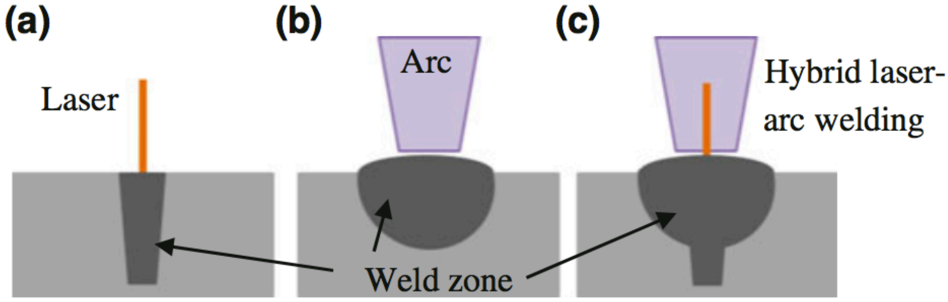


Figure 42. (a) Weld bead of laser welding, (b) Weld bead of arc welding, and (c) Weld bead of hybrid laser-arc welding (19, p. 131)

Therefore, hybrid laser-arc welding compensates the drawbacks of both the processes and offers many advantages over laser welding and arc welding, such as higher welding speed, deeper penetration (44, p. 120) due to enhanced arc stability (7, p. 111), better weld quality with reduced susceptibility to pores and cracks, requirement of less number of welding passes, enhanced gap bridging ability, as well as process stability and efficiency (44, p. 120). Furthermore, the use of secondary heat source, as electric arc, compensates the requirement of high power laser source, which considerably reduce the set-up costs, and as a consequence the welded parts costs. (43.)

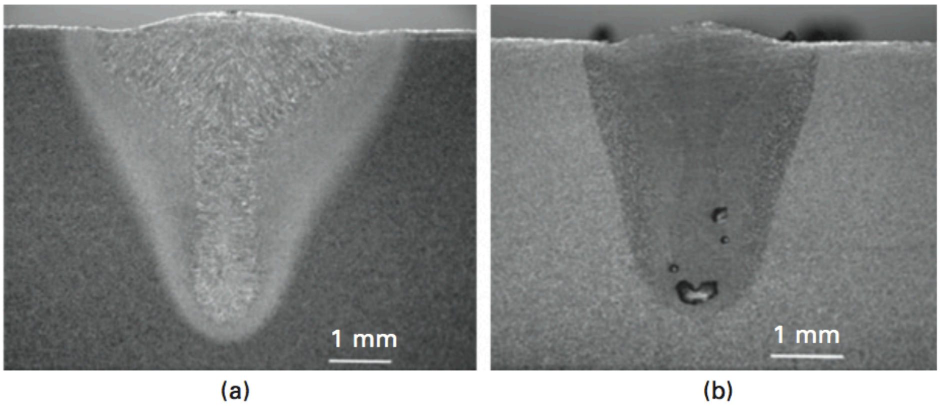


Figure 43. Comparison between (a) laser welding and (b) hybrid laser-arc weld in 250 grade mild steel (44, p. 120)

Hybrid laser arc is capable of welding a wide variety of metals including highly reflective and reactive ones (43) that brings possibility to successfully join such aeronautical materials as stainless steels, titanium (7, pp. 130-132), magnesium (7, pp. 125-130), nickel (43), aluminium and their alloys (7, pp. 132-135). Hybrid laser arc welding is used for welding thick as well as thin materials. (43.)

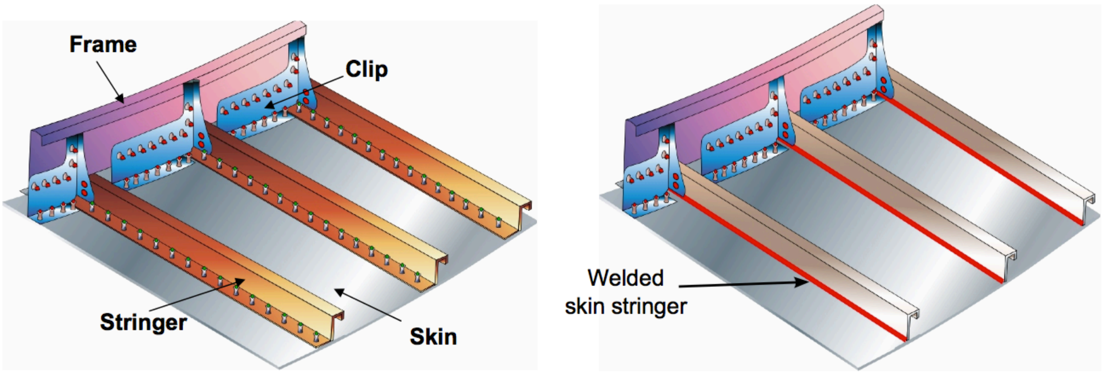
In spite of the advantages, laser-arc welding also involves some disadvantages related to the process set-up, which is complex due to a wide range of welding parameters including parameters of laser and arc welding processes separately and some of the parameters combination: distance between laser and arc, shielding arrangements, welding speeds and power level of arc and laser (19, pp. 130-131). Moreover, there is a probability of such defects like lack of fusion as the profile of hybrid weld beads is wide at top surface and narrow at the root, as shown in Figure 42c. (12, p. 74.)

### 2.3.3 Application

The main concerns of the aircraft industry lead to a trend of the development of the metal fuselage as it is capable of integrating and simplifying the structure (45), as well as reducing the weight and cost (55% from all structural costs (3, p. 147)), which meet the main concerns of the aircraft industry (11). The conventional manufacturing of an aircraft aluminium alloy fuselage is based on implementation of typical stringer-skin panels. These panels form the skin of the aircraft with the stringers and the frames that support it in the longitudinal and lateral directions, the clips that are present at every stringer-frame junction and the rivets that fasten the assembly together, as shown in Figure 44a and Figure 45a (3, pp. 92-93). The main disadvantages of the riveting process are the low efficiency and high cost. Moreover, it is an extensively researched mature technology in which it is difficult to make further improvements (42). Driven by improving those limitations, double-sided fiber laser beam welding technology, illustrated in Figure 46, was first proposed within Airbus Germany to substitute the riveting for joining skin-stringer T-joints. In process of time, double-sided fiber laser beam welding has become an established process for aircraft manufacturing which offers (46) decreased weight owing to removal of fasteners and sealant, what is shown in Figure 44b and Figure 45b (47), cost reduction due to a high degree of automation (12 m/min welding speed for LBW (48) while the comparable riveting process is only 0.15 to 0.25 m/min (11)), fewer manufacturing steps, and better corrosion resistance due to fewer fastener holes, gaps, and crevices (49). Moreover, manufacturing of the component with the LBW process is more sustainable, since it produces 53% less $CO_2$ emissions than the corresponding riveted process (47).

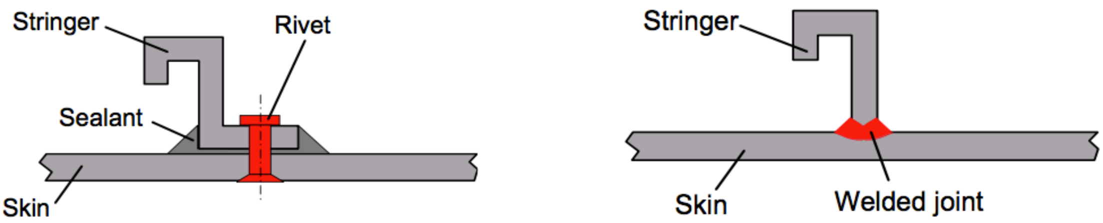
The limiting factor for manufacturing skin-stringer joints with convention fusion welding techniques, related to the fact that they tend to induce relatively high residual stresses and distortions that directly affect fatigue crack initiation and fatigue crack propagation properties of the thin-walled welded components. Meanwhile, LBW of aerospace Al-alloys induces much lower residual stresses and distortion. Even so, LBW integral panels present less crack arrest features in comparison with riveting due to the continuous paths for a crack growth.

Therefore this damage tolerance and fail safety issues limit the widespread application of the welded integral panels and require further investigations. (50, p. 1.)



**(a)** Differential panel **(b)** Integral panel

Figure 44. Differential and integral panel (3, p. 92)



**(a)** Riveted stringer **(b)** Welded stringer

Figure 45. Riveted and welded stringer (3, p. 93)

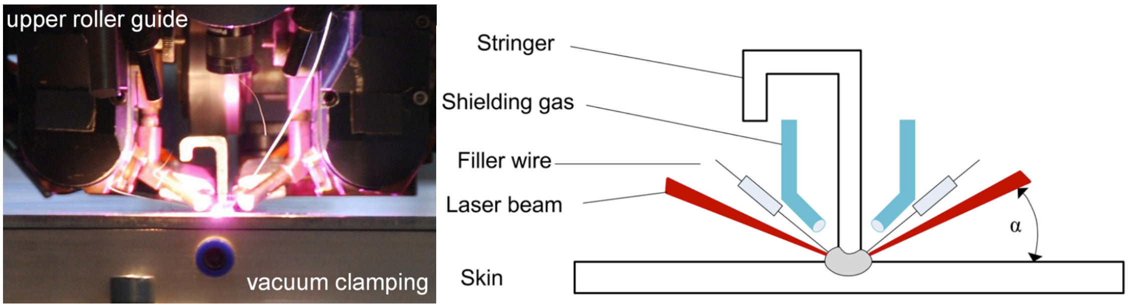


Figure 46. Schematic configuration of the dual laser welding skin-stringer process (45)

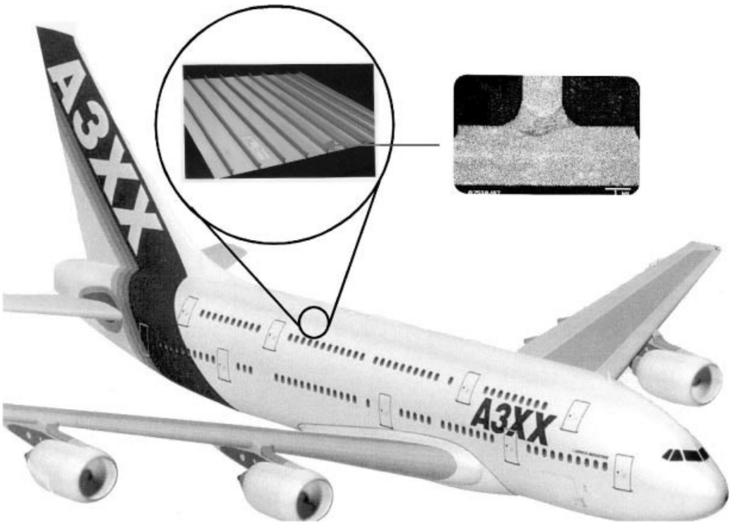


Figure 47. Application of laser beam welded structures in the aircraft industry (51)

The application of LBW for production of these stringer-skin panels made of 6XXX series weldable Al-alloys (49; 50, p. 1) has been adopted intensively by Airbus, mainly in three models of aircraft, as shown in Figure 47: A318 (2 panels, corresponding to more than 50 m of welds in each aircraft), A380 (8 panels, corresponding to more than 300 m of welds) and A340 (14 panels, corresponding to more than 400 m of welds in each aircraft). It is figured out that more than 1200 welded plates were produced until 2010 for Airbus aircrafts. The weight savings of applying LBW to join the stringers to the fuselage skin are significant compared with riveting. The replacement of riveting stringers by welded ones provide savings of 0.18 kg per meter of joint, what corresponds to savings of 9 kg in the A318, 54 kg in the A380 and 72 kg in the A340**.** These values can be considered modest weight savings, although they correspond to approximately 10% of weight savings in these panels. (12, pp. 228-229.)

Consequently, the development of LBW technology will eventually lead to the creation of such joints as “skin-clip”, “clip-frame” or “frame-skin” which will result in further weigh and cost saving in future metallic airframes. Figure 48b and Figure 49 schematically illustrate the “skin-clip” concept, in particular. (50, p. 1.)

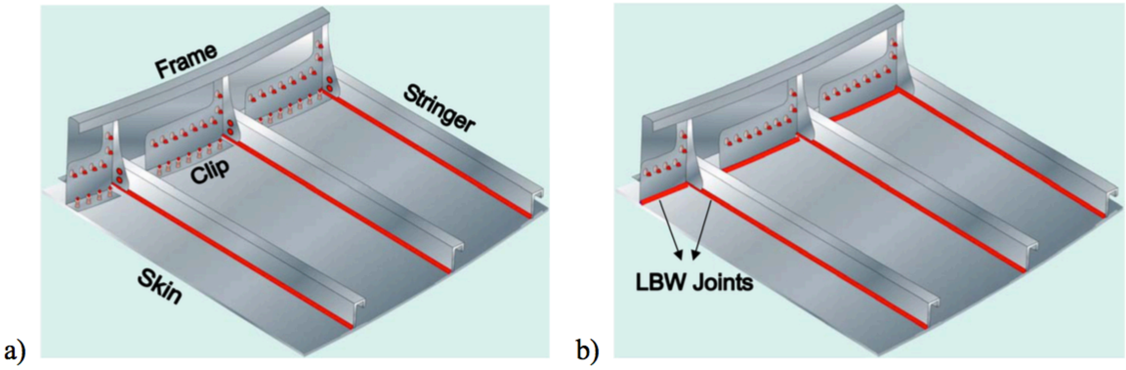


Figure 48. a) the application of LBW to the currently used panels with welded skin-stringer joints, b) possible future application of welding for clip-skin joints (50, p. 2)

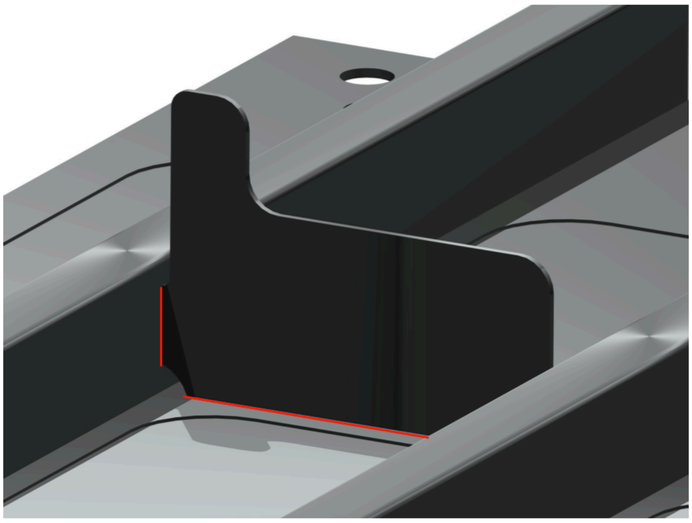


Figure 49. Concept clip design for welded clip-skin joint (50, p. 132)

Another advantage of the LBW application for reinforced stiffened panels is the capability of the production larger panels or ‘superpanels’ for the final assembly of the fuselage, as illustrated in Figure 50. This concept has been investigated by several aircraft manufactures and based on the increase of the fuselage panels and consequent number decrease of the required panels for a fuselage barrel assembly, as shown in Figure 51 and Figure 52, which could result in a huge reduction of part fabrication and assembly costs. Further possible concept development based on the increase of the panel length, thus reducing the number of barrels for the final fuselage assembly. (3, pp. 158-160; 12, pp. 226-227.)

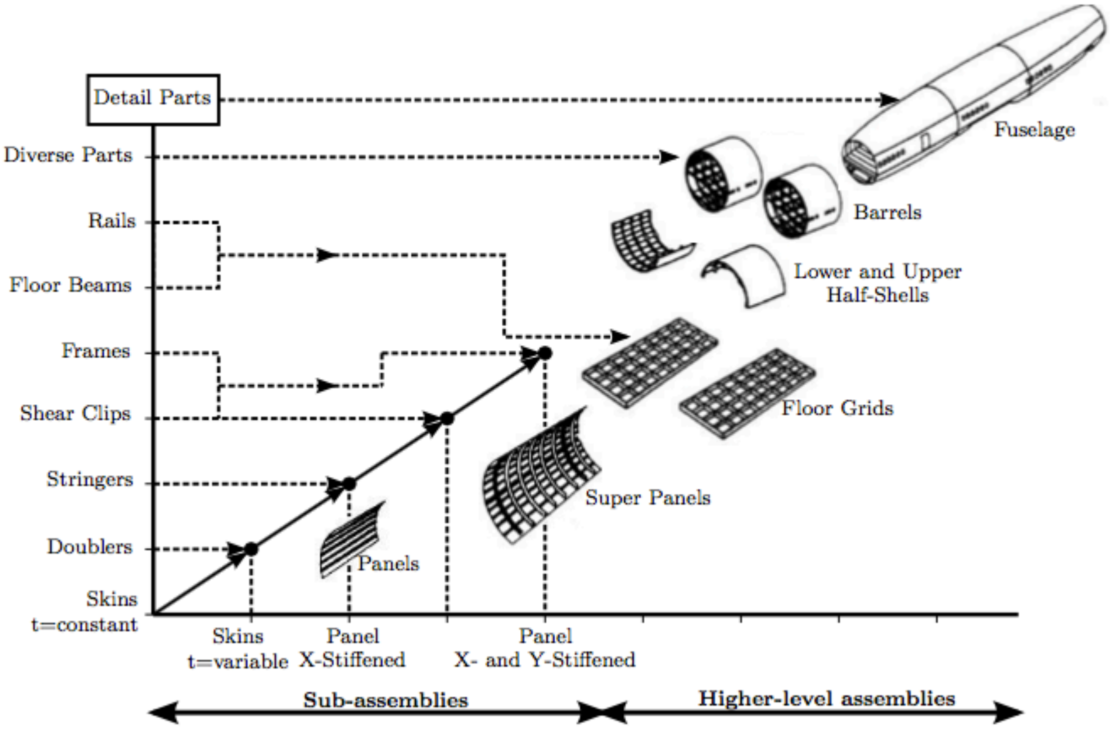


Figure 50. Aircraft fuselage assembly levels (3, p. 160)

Figure 51. Fuselage barrel (52)

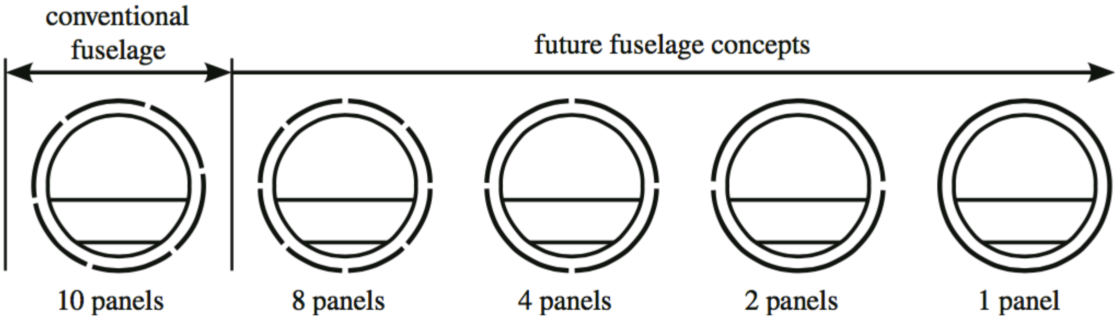


Figure 52. Reduction of the number of fuselage panels in a fuselage barrel (3, p. 163; 12, p. 226)

Some rough numbers of cost and weight reduction due to the reduction of the number of panels circumferentially required for the whole barrel are presented in Table 2. This table shows that a huge reduction of part fabrication costs and assembly costs can be achieved just increasing the size of fuselage panels. (3, p. 161)

Table 2. Cost reduction due to decreased number of fuselage panels (3, p. 163; 12, p. 227)

| **No. of Panels/Superpanels** | **10 (Basis)** | **8** | **6** | **4** |
|---:|---:|---:|---:|---:|
| Engineering Cost | 0 | -10% | -20% | -30% |
| Material Cost | 0 | -5% | -10% | -15% |
| Part Fabrication Cost | 0 | -20% | -35% | -50% |
| Assembly Cost | 0 | -15% | -30% | -50% |
| Weight | 0 | -2% | -4% | -6% |

Figure 53 illustrates that in analogy to the laser beam welded fuselage panels, the inner flap could be manufactured. LBW provides the possibility to replace classic 2024 material with Al-Mg-Sc, what in cooperation with the lightweight design could result in a 20% cost reduction and 10% weight reduction. (53.)

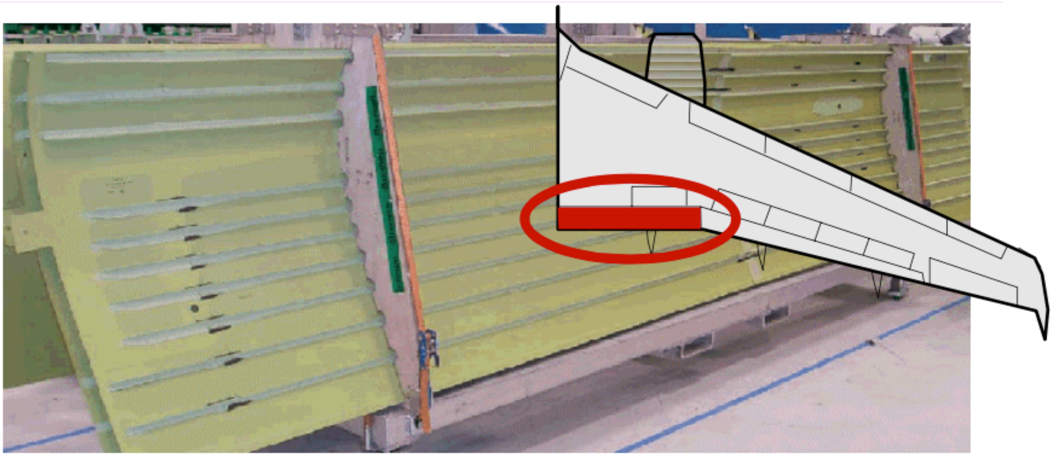


Figure 53. Application of LBW and Al-Mg-Sc to the manufacture of inner flap (53)

It is worth mentioning that laser welding has evolved as an important industrial manufacturing process for joining a variety of metallic, nonmetallic materials (38, p. 412) and their combinations, providing the prospects for application-oriented solutions based on dissimilar materials joining. One of such concepts is related to the aircraft seat track design, which is represented with the laser beam dissimilar welding of Al-alloy with Ti-6Al-4V components, as shown in Figure 54. Such a combination brings weight reduction (Al-alloy), strength improvement and corrosion resistance (Ti-6Al-4V) to the designed structure. (54.)

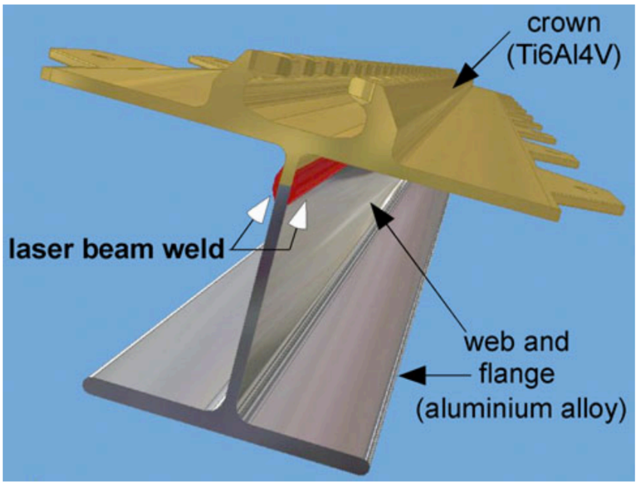


Figure 54. The passenger seat track as a laser beam welded dissimilar joint (conceptual design after AIRBUS. The total height of the assembly is about 61 mm, the web height about 45 mm and the aluminium alloy flange width about 50 mm) (54)

Finally, laser beam welding is also suitable for different repair applications such as cladding of different materials, repairing of damaged components, mold repair and so on (19, p. 116).

Considering given pros & cons in welding processes, it appears that laser beam welded structures offer great opportunities for the lightweight design of fuselage structures in order to reduce structural weight for increased fuel efficiency and further economy savings (47).

## 2.4 Electron beam welding

### 2.4.1 Process

Electron beams have been used as welding heat sources since the early 1960s and electron beam welding has become established as a high-quality precision welding process. (55, p. 157.)

Electron Beam Welding is a fusion welding process based on a beam of high velocity electrons, which is applied for joining of the materials. The melting of the work-piece material occurs as the kinetic energy of the electrons is transformed into heat, which is further conducted across the surface of the work-piece (56). Normally, the EBW is carried out in vacuum environment, as it provides protection against oxidation and removes gas molecules for guaranteed stable electron beam emission. Furthermore, low ambient pressure significantly decreases the scattering of electrons, which occurs when they hit air molecules. Therefore, decreased ambient pressure reduces the beam diameter thereby, results in a very small spot area in the range of 0.3 – 0.8 [mm] and impressive power density up to 1000 [W/m$^2$]. (8, pp. 184-185; 19, pp. 118-119; 57.)

The resulting weld seam is extremely narrow, and the significant energy density leads to high welding speed. As a consequence, the welding process occurs so fast that the adjacent material is not affected with the exceeding heat, leading to a minimal heat affected zone and post weld distortions (5), as illustrated in Figure 55. (57.)

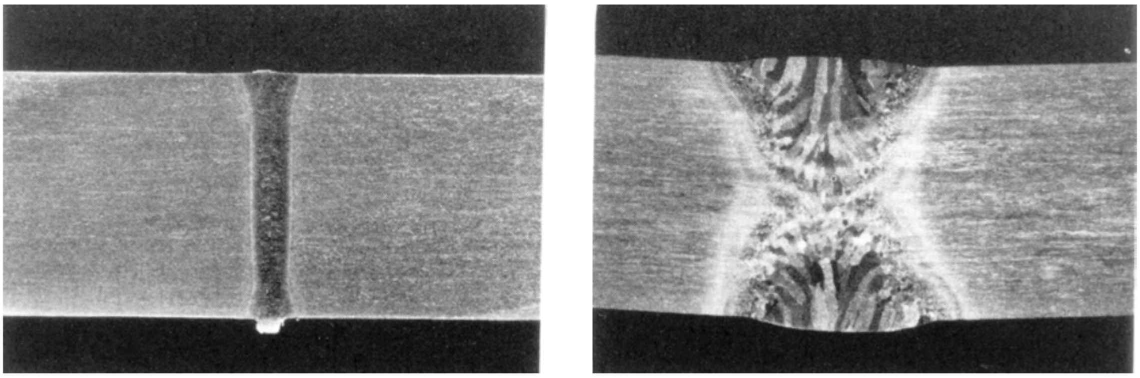


Figure 55. Cross section of welds performed with EWB (left) and GTA (right). The higher heat intensity of the electron beam creates a much smaller fusion zone and HAZ (5)

On the one hand, in the case of thin plates, the welding process is induced by the material melting within the welding pool throughout the thickness of the joint. On the other hand, when a deeper penetration is required, the high power density of the EB leads to the vaporization of the material, producing the keyhole throughout the thickness of the work-piece, as shown in Figure 56. The material flow in the molten-pool around the electron beam closes the gap of the welding joint and the following mixing produces the fusion weld. (8, pp. 184-185; 57.)

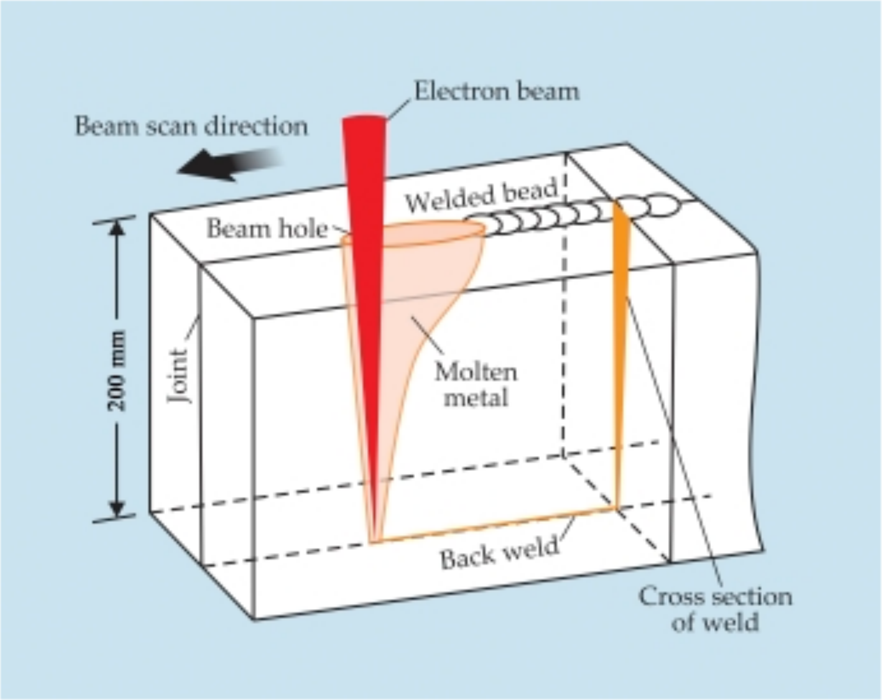


Figure 56. Schematic keyhole EBW (58)

The EBW is capable of producing continuous pulse as well as spot welds. The process itself does not require edge preparation; therefore regardless of the thickness of the work-piece material, filler material is not generally necessary. Nevertheless, for high quality welded joins of metals characterized by the limited weldability, the filler material is advisable. The process could be fully automated via computer monitoring and control of welding parameters. Despite of the abovementioned operational advantages, the operation of EBW in vacuum brings dimensional limitations, as the whole workpiece should fit the vacuum chamber. Another drawback related to the high gap tolerances between abutment faces, as electron beam obtain highest focusability. Position tolerances are so demanding that the gap above 0.1 mm cannot be tolerated. An important disadvantage of electron beam technology is high cost of the welding equipment. (56.)

Electron beam is capable of welding work-pieces, in keyhole mode, with thickness from 0.01 mm up to 250 mm of steel and up to 500 mm of aluminium. EBW technology could be viewed as a versatile one, as it is capable of joining different grades of steel with each other as well as the following typically hardly weldable with other welding methods metals: refractory metals (tungsten, molybdenum, niobium) and chemically active metals (titanium, zirconium, beryllium). Moreover, electron beam welding is capable of producing joints between different metals. Similar tendency applies to the various non-ferrous metals, plastics and composites. Nonetheless, the situation can be more complicated when totally different metals (e.g. chemical composition, thermal conductivity, solidification properties, coefficient of thermal expansion etc.) have to be joined to each other. Furthermore, an electron beam could be easily deflected by even small magnetic fields, therefore welding of the materials with retained magnetism presents challenges as the alignment of the beam is likely to be distributed by the magnetic field of the component. (19, p. 119; 56.)

Figure 57 clearly illustrates that even compared to the laser beam, the electron beam could be viewed as the most focused heat source among other welding processes, that is the core advantage of EBW (19, p. 119).

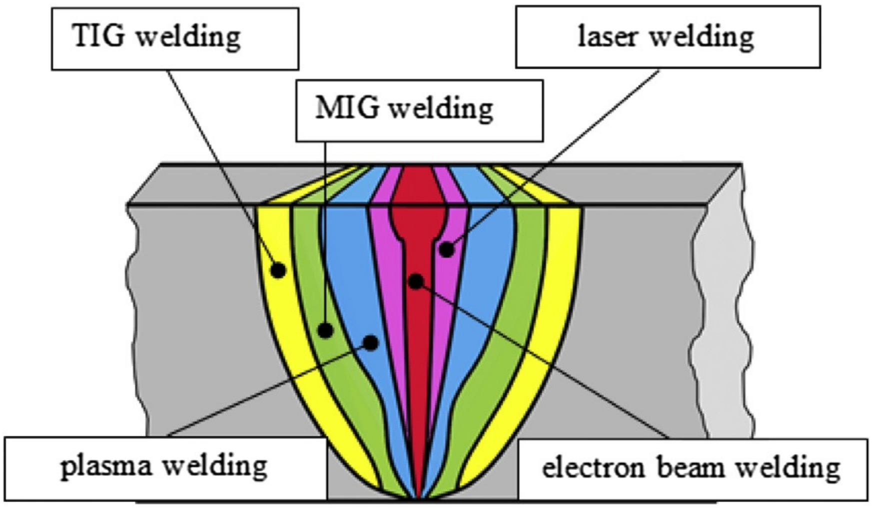


Figure 57. Comparison of a butt weld made using various welding technologies (56)

While comparing laser beam and electron beam welding processes, it could be expected that for solid-state lasers approximately 4% (Nd:YAG), 25-50% (fibre and disc lasers) and for $CO_2$ laser up to 20% of the input energy are used in the welding process. Meanwhile the efficiency of the electron beam technology ranges between 60 and 70%. However, it should be considered that the efficiency of laser beam welding strongly depends on the chemical composition and physical properties of the treated material, as well as reflectivity of the surface. (56.)

Another major process advantage over LBW, related to the fact that electron beam welding technology has no challenges with beam reflection on the molten metal. Even so, it should be considered that the operation of electron beam is mostly limited with the sizes of vacuum chamber (10, p. 69), as well as high focusability of electron bean results in the more demanding position tolerances, than in case with laser beam heating source. (56.)

In spite of quickly developing competitive laser welding technologies, electron beam welding remains indispensable in many applications due to the possibility of obtaining greater penetration depth and the metallurgical purity of a weld, as well as because of its greater welding rate. (56.)

### 2.4.2 Application

Electron beam welding is a highly efficient and precise welding process increasingly used within the manufacturing chain and of growing importance in such industrial environments as the aerospace sector (57), since EBW produces narrow welds of high integrity and with minimum distortion and is especially suitable to a range of such materials as titanium alloys, aluminium alloys, heat resisting and high strength alloys that are frequently used in aero-engines. The forgoing capabilities can be successfully applied to the fabrication of high critical components ensuring that the stringent inherent safety requirements can be met. (59.)

Therefore, the aircraft engine industry has used EBW extensively for the manufacturing of engine parts – the Rolls-Royce RB211 engine, illustrated in Figure 58, utilizes nearly 100 m of electron beam welds. The principal applications include the joining of thick-section stator assemblies in titanium alloys, compressor discs, compressor rotor shafts and other critical components **(**55, p. 160).

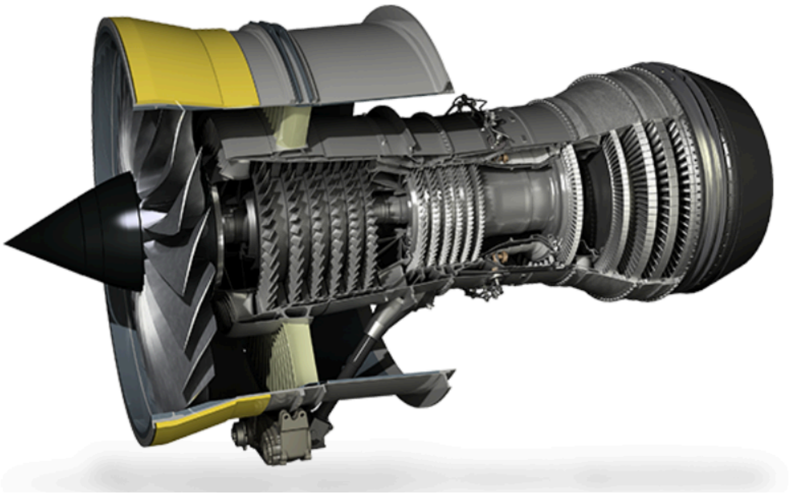


Figure 58. The Rolls-Royce RB211 engine (60)

Figure 59 shows one of the early applications of electron beam technology – the welding of groups of stator blades. The varying section of the blade platforms with the need to maintain close dimensional tolerances strictly limits the joining methods that meet all criteria. Nonetheless, electron beam has been found particularly successful in this type of application where the thickness of the section being welded may vary. (59.)

The individual blades are cast in a range of steel or nickel base alloys, invariably of a heat and/or corrosion resistant nature. Further, the weld procedure for each joint between blade platforms requires four weld passes: tack and finish weld for the outer platform, tack and finish weld for the inner platform. Each weld pass requires a different set of beam settings and a different pattern of movement of the workpiece manipulator. (59.)

Figure 59. Left: stator blade assemblies (59), right: stator blade ring (61)

An equally important application for EB welding in the aero-engine industry is the concept of repair and renovation of service exposed gas turbine engine components, which is now widely accepted by most commercial aero engine users. The predominant modes of damage for turbine engine fan blades are the foreign object damage (FOD) and erosion. FOD is primarily caused by the ingestion of birds, rocks and ice, during takeoff and landing, in particular. As a consequence these objects typically cause a twist in the blade airfoil that results in further deflection of the leading edge. (19, p. 119; 59; 62; 63.)

The EBW technique is the great choice for the titanium fan blades as the process performed in vacuum preventing oxidation and maintaining the material properties. During a typical fan blade repair, the damaged leading edge is removed and a so-called “patch” is welded, as shown in Figure 60 and Figure 61. Finally, the patch is machined to the initial shape of the blade. (62.)

Moreover, the possibility of EB to weld together certain combinations of dissimilar metals has been used as the advantage in a number of repair schemes. Mostly they have been based on the “patch” joining produced from the different material to achieve a longer operational life in comparison with the original material. (59.)

All in all, the electron beam process yields acceptable welds within the aerospace industry standards. The repair cost is 65% of the new part replacement cost and provides 100% reduction in the current FOD rejection rate for the examined engine (63). On the grounds of the abovementioned savings, most of the world's airlines have installed their own engine overhaul EB welding facilities. (59.)

Figure 60. FOD EBW Repair Process of Fan Blades (63)

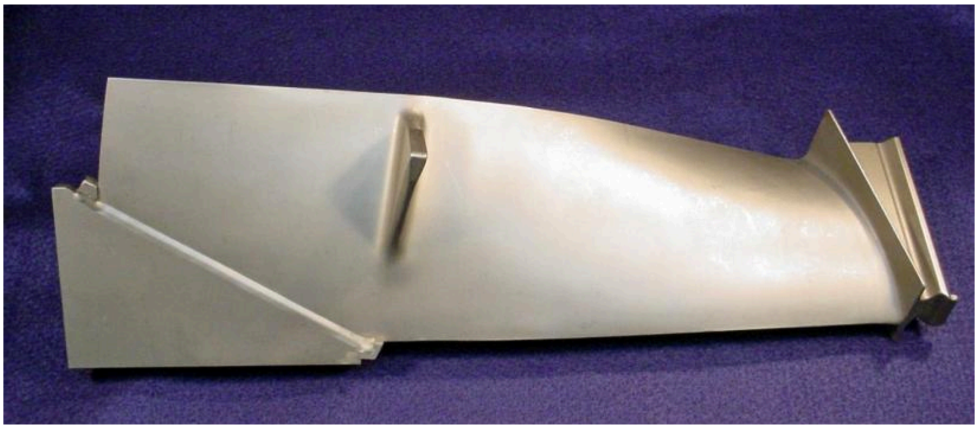


Figure 61. Ti6Al4V fan blade repair with the welded ”patch” (62)

Referring to the compressor discs manufacturing, the electron beam welding is dealing with joining already machined compressor discs into a multistage rotor or drum, without further machining, as shown in Figure 62. (10, p. 69; 62.)

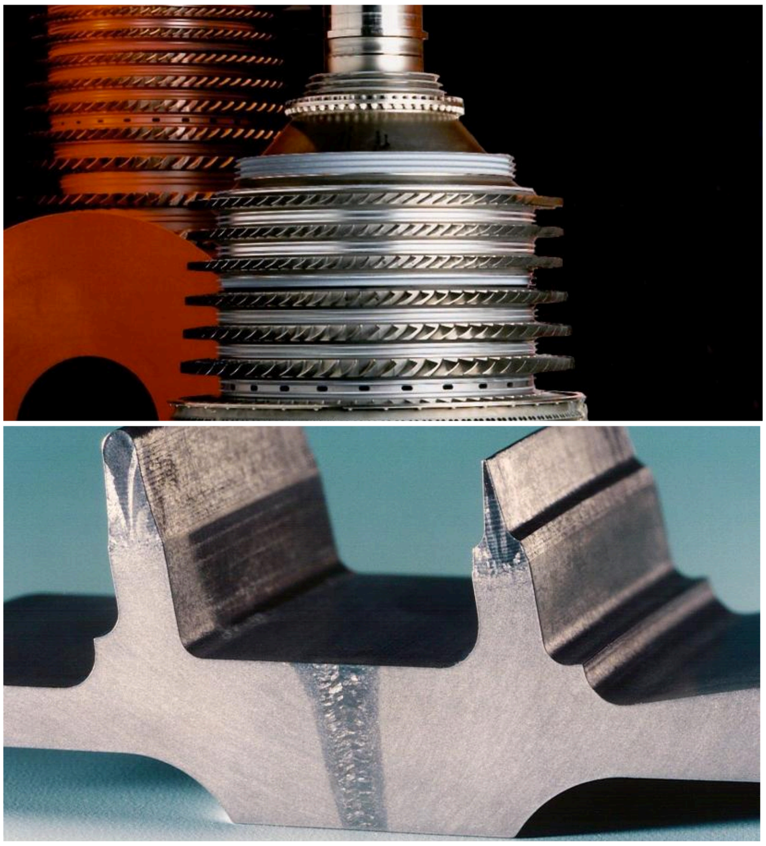


Figure 62. Compressor rotor (62)

Figure 63 illustrates the additional example of EBW implementation in aerospace industry. That is a welded spiral bevel gear, which is a flight critical component used in helicopter drive systems and aircraft engines. This high speed rotational part operates at high loads and as a consequence requires 100% defect free welds. The electron beam welding was approved as the suitable process for this application and welding of other aerospace gears by NADCAP (National Aerospace and Defense Contractors Accredetation Program). (62.)

Figure 63. Spiral bevel gear, high strength steel (62)

The application of EBW to the welding of titanium components for military aircraft has been expanding constantly. Pylon posts and wing components in Ti-6Al-4V for the F15 fighter have been EB welded by McDonnell Douglas since the mid 1970’s. The wing boxes that hold the variable geometry wings in the fighters Tornado, and F14 “Tomcat”, are also Ti-6Al-4V EB welded. (15.)

Later progress in control systems and welding process automation has made a significant boost in EBW application for military aircrafts. The new technologies were capable of producing continuous one-pass welds over curved lines, surfaces and through varying thicknesses. These process advantages were successfully implemented during the manufacturing of critical components for the Eurofighter (attachment of the wings and fin to the fuselage with EBW) and Lockheed Martin-Boeing’s F-22 “Raptor” (aft fuselage), illustrated in Figure 64 – Figure 66. (15.)

Figure 64. F-22 Raptor (64)

The F-22 is the first airplane in 60 years to feature a welded fuselage. Prior fuselages were made of riveted aluminium, but GKN Aerospace used EBW to join the different parts of the aft boom, shown in Figure 67, reducing the use of fasteners by approximately 75 percent. Therefore, it is reasonable to expect that the amount and criticality of EBW of titanium in future military aircraft will increase. (3, p. 50; 12, p. 225; 15; 65, pp. 51-58.)

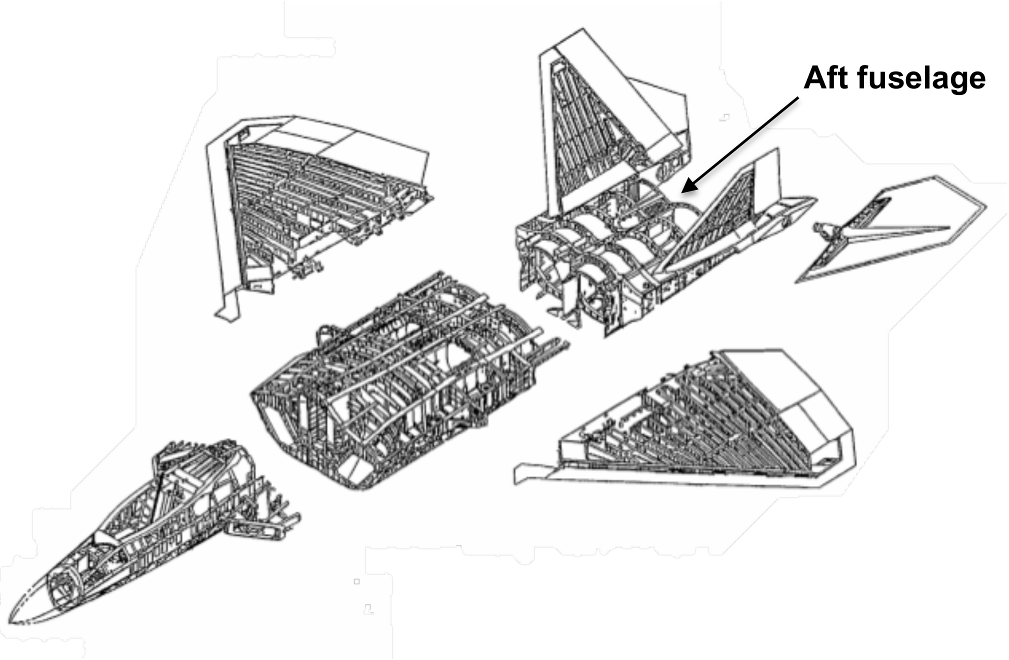


Figure 65. Schematic general F-22 structure (66)

Figure 66. The aft fuselage that support the horizontal tails and some of the vertical tail loads of F-22 (65, p. 51; 67)

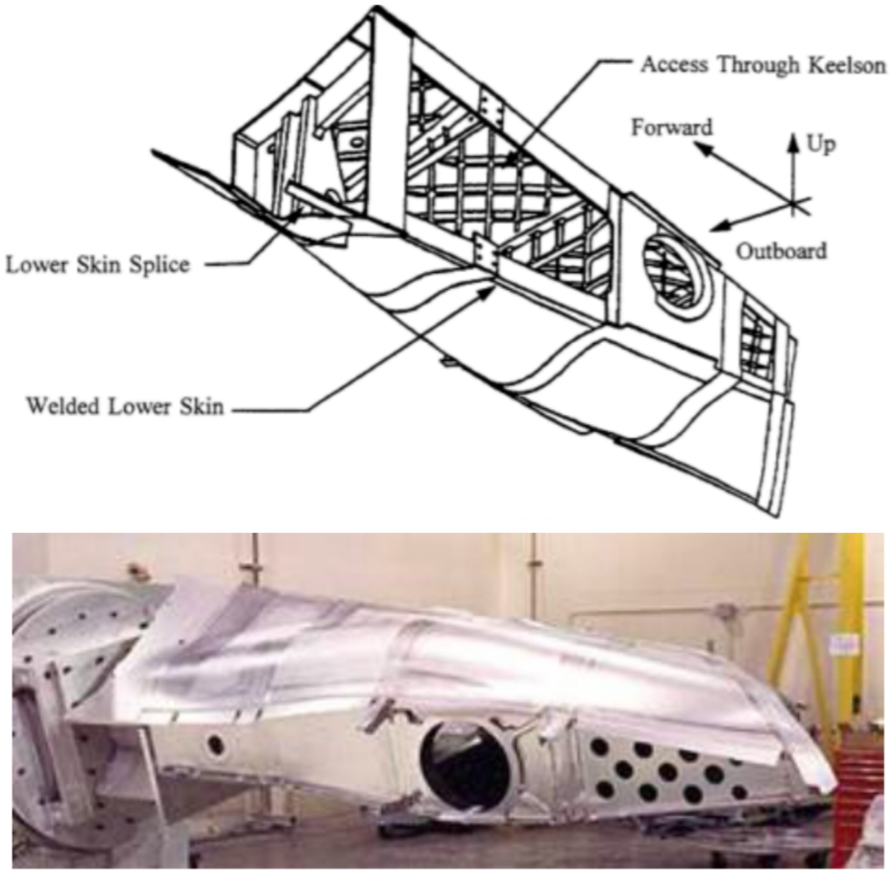


Figure 67. Welded aft boom (3, p. 50; 65, p. 54)

Another example of EBW implementation for military aircrafts related to Russian MiG-29M jet fighter. In 1985 in the Design Bureau of A.I. Mikoyan, for the first time in the world from the alloy 1420 of the Al-Mg-Li was manufactured a welded fuselage for the modified MiG-29M jet fighter. The design used more than 150 types of stamping, pressed panels, sheets from which sealed welded fuel tanks, shown in Figure 68, and a pilot cabin, shown in Figure 69, were made, which allowed to reduce the weight of structural elements up to 24%. MiG-29M aircraft with welded tanks of alloy 1420 are still in operation. (68.)

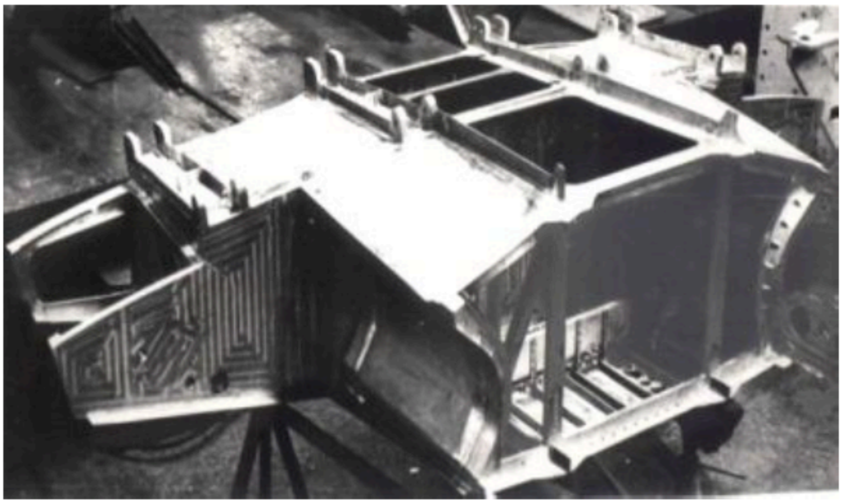


Figure 68. Welded fuel tank for MiG-29M (68)

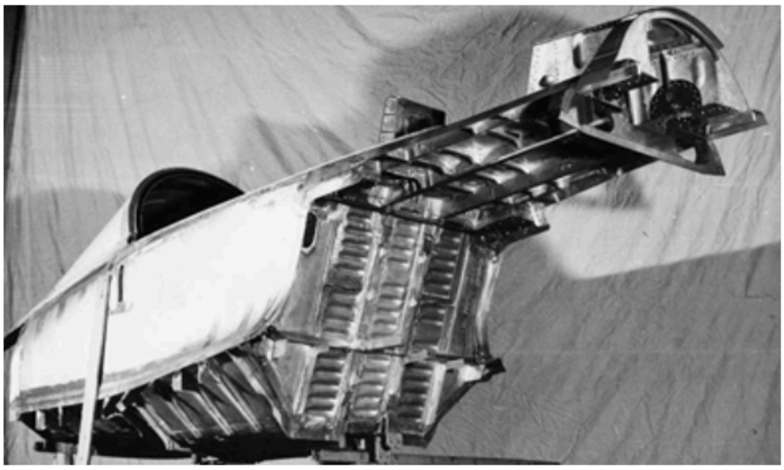


Figure 69. Welded pilot cabin for MiG-29M (68)

Along with the application of EBW for the aero-engine components and military aircraft structures, beam welding is also applicable for the space structures. Particularly, Figure 70 and Figure 71 illustrate welded titanium tanks for propylene, which are used in satellites and rockets. (56.)

Figure 70. Bipropellant Tank for Orion's European Service Module (69)

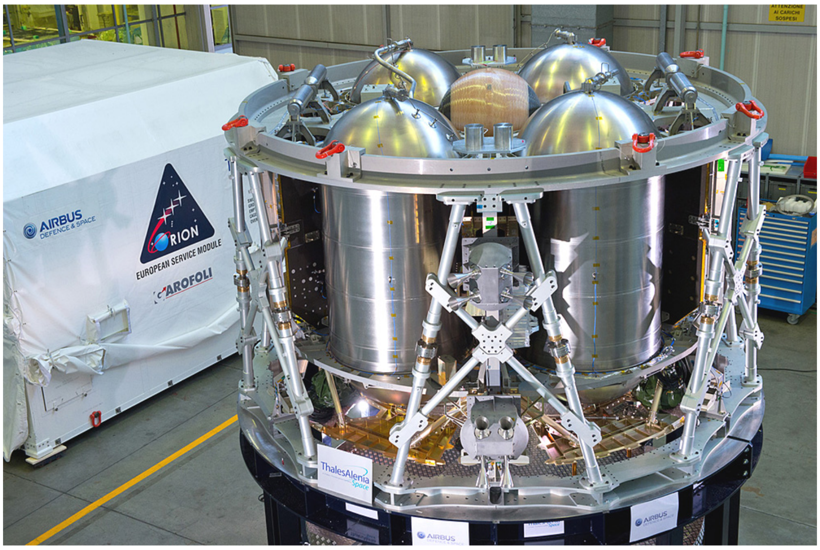


Figure 71. Bipropellant tanks integrated to the Structural Test Article of Orion European Service Module (69)

# 3 Summary and discussion

The objective of this research was a reviewing of the value of modern advanced welding technologies for aerospace industry, including their fundamentals, recent applications for aerospace structural components and trends in the aerospace industry that could be expected from progress of these welding technologies. The following welding processes were determined as the advanced: FSW, LFW, IFW, LBW and EBW.

Aerospace industrial sector is highly focused on the trend of more efficient and sustainable transportation systems, which consequently requires cost and weight reductions. The weight reduction reduces the fuel burnt during the aircraft life-cycle, reducing operational costs and environmental impact. The application of innovative materials and new structural concepts could contribute to the weight reduction of aircraft structures.

Therefore, the adoption of new materials in primary structures has been the major change in last decade in aircraft construction. Composite materials could be an example of this tendency as their application has been increasing dramatically recently, reaching 50 and 53 % of the structure mass for B787 and A350, in particular. Nonetheless, light metals, such as aluminium and titanium, still account for over 30 % of the structure mass. Moreover, the development of the third generation of Al-Li alloys presents the ongoing development of the metal technology. Thus, a study of technologies and manufacturing processes, which focuses on these light metals still has great potential.

New trends in the construction and manufacturing of aerospace transportation vehicles increasingly involve welding as a joining technology for light-weight metals. The application of welding in aerospace structures is an attractive option since it allows joints with less stress concentration points and might be applied efficiently without overlapping the two joining parts (with a butt-joint configuration) reducing the joint weight.

Nonetheless, the low weldability with conventional fusion welding processes as GTAW and GMAW of the high strength aluminium alloys (mainly 2XXX and 7XXX series) increasingly employed in the aerospace structures, and the range of other light weigh materials makes them impracticable for welding structural part, where the high strength, qualitative, defects free and reliable joints are required. Therefore, the advanced welding technologies as Friction Welding, Laser Beam Welding and Electron Beam Welding are proposed, as the processes of choice for welding of aerospace structures with high reliability and high efficiency production.

With consideration, it appears that conventional fusion welding technique is no longer competitive to fulfill demanding standards of aerospace industry, therefore such advanced welding technologies as FW, LBW and EBW are the main choice of a large global aerospace companies as reliable, sustainable and efficient joining processes, which bring prospects for further development of new light weight aerospace materials, structures and products.

## 4 Figures

## 5 Tables

## 6 References

1. Adrian P. Mourtiz, 2012. Introduction to aerospace materials. Philadelphia: Woodhead Publishing Limited.

2. S.M.O. Tavares, J.F. dos Santos & P.M.S.T. de Castro, 2013. Friction stir welded joints of Al–Li Alloys for aeronautical applications: butt-joints and tailor welded blanks. Theoretical and Applied Fracture Mechanics, vol. 65,

pp. 8-13.

3. S´ergio M. O. Tavares, 2011. Design and Advanced Manufacturing of Aircraft Structures using Friction Stir Welding. University of Porto. Faculty of Enginneering. Doctoral Dissertation.

4. Sahin Suenger, Michael Kreissle, Markus Kahnert & Michael F. Zaeh, 2014. Influence of Process Temperature on Hardness of Friction Stir Welded High Strength Aluminum Alloys for Aerospace Applications. Procedia CIRP, vol. 24, pp. 120-124.

5. Patricio F. Mendez & Thomas W. Eagar, 2002. "New trends in welding in the aeronautic industry" in Conference of New Manufacturing Trends.

6. R. E. Dolby, A. Sanderson & P. L. Threadgill, 2001. "Recent developments & applications in electron beam and friction technologies" in 7th International Aachen Welding Conference.

7. M.C. Chaturvedi, 2012. Welding and joining of aerospace materials. Philadelphia: Woodhead Publishing Limited.

8. Barrie D. Dunn, 2016. Materials and Processes for Spacecraft and High Reliability Applications. Switzerland: Springer International Publishing.

9. N. Eswara Prasad & R.J.H. Wanhill, 2017. Aerospace Materials and Material Technologies, Volume 1: Materials. Singapore: Springer Science+Business Media.

10. N. Eswara Prasad & R.J.H. Wanhill, 2017. Aerospace Materials and Material Technologies. Volume 2: Aerospace Material Technologies. Singapore: Springer Science+Business Media.

11. Xiaofeng Sun, Essam Shehab & Jörn Mehnen, 2012. Knowledge modelling for laser beam welding in the aircraft industry. Int J Adv Manuf Technology, vol. 66, pp. 763-774.

12. Pedro M. G. P. Moreira, Lucas F. M. da Silva & Paulo M. S. T. de Castro, 2012. Structural Connections for Lightweight Metallic Structures. Heidelberg: Springer-Verlag.

13. NASA - National Aeronautics and Space Administration 2013. First Liquid Hydrogen Tank Barrel Segment for the SLS Core Stage Completed at Michoud.
https://www.nasa.gov/exploration/systems/sls/sls-barrel-at-michoud.html.
Accessed on 10 June 2018.

14. Yanhua Zhaob & Yunfei Haob Guoqing Wanga, 2018. Friction stir welding of high-strength aerospace aluminum alloy and application in rocket tank manufacturing. Journal of Materials Science & Technology, vol. 34, pp. 73-

91.

15. Patricio F. Mendez & Thomas W. Eager, 2001. Welding processes for aeronautics. Advanced Materials & Processes, pp. 39-43.

16. Achilles Vairis, George Papazafeiropoulos & Andreas-Marios Tsainis, 2016. A comparison between friction stir welding, linear friction welding and rotary friction welding. Advanced Manufacturing, vol. 4, pp. 296-304.

17. Bekir Sami Yilbas & Ahmet Z. Sahin, 2014. Friction Welding Thermal and Metallurgical Characteristics. Heidelberg: Springer.

18. Stephan W. Kalle, E Dave Nicholas & Paul M. Burling, 2000. "Application of friction stir welding for the manufacture of aluminium ferries" in 4th Internationl Forum on Aluminium Ships.

19. Kapil Gupta, 2017. Advanced Manufacturing Technologies. Modern Machining, Advanced Joining, Sustainable Manufacturing. Switzerland: Springer International Publishing.

20. Akshansh Mishra, 2018. Friction Stir Welding of Dissimilar Metal: A Review. International Journal for Research in Applied Science & Engineering Technology, vol. 6, no. I, pp. 1551-1559.

21. Hrishikesh Das, Mounarik Mondal, Sung-Tae Hong, Doo-Man Chun, and Heung Nam Han, 2018. Joining and Fabrication of Metal Matrix Composites by Friction Stir Welding/Processing. International Journal of Precision Engineering and Manufacturing-Green Technology, vol. 5, no. 1, pp. 151-172.

22. Virgínia Infantea & Pedro Vilaçaa Catarina Vidal, 2010. Assessment of Improvement Techniques Effect on Fatigue Behaviour of Friction Stir Welded Aerospace Aluminium Alloys. Procedia Engineering, vol. 2, pp. 1605-1616.

23. S.P.Madavan, Manas Mohan Mahapatra & Pradeep Kumar, 2013. On Friction Stir Welding of Mg-Zn-RE-Zr Alloy Using Threaded Tools For Aerospace Application. The Minerals, Metals & Materials Society, pp. 237-244.

24. Viliam Sinka, 2014. The Present and Future Prospects of Friction Stir Welding in Aeronautic. Acta Metallurgica Slovaca, vol. 20, no. 3, pp. 287-294.

25. ASM Internationa 2015. Opening Message: Friction stir welding used on the Orion Spacecraft. https://www.asminternational.org/web/fort-wayne-chapter/asm-industry-news/-/journal_content/56/10180/25977178/NEWS;jsessionid=6DB19214FEDDA7BDAAC2223B9219A344?p_p_id=webcontentresults_WAR_webcontents

earchportlet_INSTANCE_YKFe939KArra&p_p_lifecycle=0&p_p_state=normal&p_p_mode=view&p_p_col_id=column-2&p_p_col_pos=1&p_p_col_count=2. Accessed on 9 August 2018.

26. NASA 2016. Nasa Facts. Space Launch System Core Stage. https://www.nasa.gov/sites/default/files/atoms/files/sls_core_stage_fact_sheet_01072016.pdf. Accessed on 12 June 2018.

27. NASA 2017. SLS Liquide Hydrogen Tank Test Article Preapers for a ”Shower”. https://www.nasa.gov/exploration/systems/sls/multimedia/liquid-hydrogen-tank-test-article-prepares-for-shower.
Accessed on 12 June 2018.

28. NASA 2017. Michoud Imagery.
https://www.nasa.gov/centers/marshall/michoud/images.html.
Accessed on 12 June 2018.

29. Ahmad Charamanfar, Mohammand Jahazi & Jonathan Cormier, 2015. A Review on Inertia and Linear Friction Welding of Ni-Based Superalloys. Metallurgical and Materials Transactions A, vol. 46A, pp. 1639-1669.

30. Kuroki Hiroshi, Nezaki Koji, Wakabayashi Tsukasa & Nakamura Kenji, 2014. Application of Linear Friction Welding Technique to Aircraft Engine Parts. IHI Engineering Review, vol. 47, no. 1, pp. 40-43.

31. Anthony R. McAndrew, Paul A. Colegrove, Clement Bühr, Bertrand C.D. Flipo & Achilleas Vairis, 2018. A literature review of Ti-6Al-4V linear friction welding. Progress in Materials Science, vol. 92, pp. 225-257.

32. Steve Pace, 1999. F-22 Raptor: America’s Next Lethal War Machine. USA: The McGraw-Hill Companies.

33. Steve Dodds, 2017. "Linear Friction Welding. An Alternative Production" in 4th LFW Symposium.
https://www.aerosociety.com/media/5411/6-linear-friction-welding-an-alternative-production-route-for-titanium-aerospace-components.pdf.
Accessed on 25 August 2018.

34. Enes Akca & Ali Gursel, 2016. Solid State Welding and Application in Aeronautical Industry. Periodicals of Engineering and Natural Sciences, vol. 4, no. 1, pp. 1-8.

35. TWI Ltd. Rotary friction welding. Job Knowledge 148.
https://www.twi-global.com/technical-knowledge/job-knowledge/rotary-friction-welding-148/. Accessed on 20 May 2018.

36. TWI Ltd. Rotary Friction Welding.
https://www.twi-global.com/capabilities/joining-technologies/friction

welding/rotary-friction-welding/. Accessed on 22 May 2018.

37. Manufacturing Technology, Inc. (MTI). All Geometry Sample Parts. https://www.mtiwelding.com/parts/?results_per_page=1000&industries=aerospace. Accessed on 9 August 2018.

38. N.B. Dahotre & S.P. Harimkar, 2008. Laser Fabrication and Machining of Materials. US: Springer.

39. Kamel Abderrazak, Wacef ben Salem, Hatem Mhiri, Philippe Bournot & Michel Autric, 2009. Nd:YAG Laser Welding of AZ91 Magnesium Alloy for Aerospace Industries. Metallurgical and Materials Transactions B, vol. 40B, pp. 54-61.

40. Pengfei Wang, Xizhang Chen, Qiuhong Pan, Bruce Madigan & Jiangqi Long, 2016. Laser welding dissimilar materials of aluminum to steel: an overview. Int J Adv Manuf Technol , vol. 87, pp. 3081-3090.

41. Rongshi Xiao & Xinyi Zhang, 2014. Problems and issues in laser beam welding of aluminum–lithium alloys. Journal of Manufacturing Processes, vol. 16, pp. 166-175.

42. Z.B. Yang et al., 2012 .Double-sided laser beam welded T-joints for aluminum aircraft fuselage panels: Process, microstructure, and mechanical properties. Materials and Design, vol. 33, pp. 652-658.

43. Bappa Acherjee, 2018. Hybrid laser arc welding: State-of-art review. Optics and Laser Technology, vol. 99, pp. 60-71.

44. Seiji Katayama, 2013. Handbook of laser welding technologies. Philadelphia: Woodhead Pulishing Limited.

45. Yingtao Tian et al., 2016. Process Optimization of Dual-Laser Beam Welding of Advanced Al-Li Alloys Through Hot Cracking Susceptibility Modeling. Metallurgical and Materias Transactions A.

46. Bing Han, Wang Tao, Yanbin Chen & Hao Li, 2017. Double-sided laser beam welded T-joints for aluminum-lithium alloy aircraft fuselage panels: Effects of filler elements on microstructure and mechanical properties. Optics and Laser Technology, vol. 93, pp. 99-108.

47. Nikolaos D. Alexopoulos et al., 2016. Laser beam welded structures for a regional aircraft: weight, cost and carbon footprint savings. Journal of Manufacturing Systems, vol. 39, pp. 38-52.

48. Yanbin Chen, Liqun Li, Wang Tao & Zhibin Yang, 2012. "Laser Welding Technologies for Aircraft Fuselage Panels" in International Photonics and Optoelectronics Meetings.

49. R.J.H. Wanhill, 2014. Aluminum-Lithium Alloys. UK: Elsevier Inc, pp. 503-535.

50. Funda Şeniz Bayraktar, 2011. Analysis of residual stress and fatigue crack propagation behaviour in laser welded aerospace aluminium T-joins. Humburg University of Technology. Doctoral Dissertation.

51. E. Schubert, M. Klassen, I. Zerner, C. Walz & G. Sepold, 2001. Light-weight structures produced by laser beam joining for future applications in automobile and aerospace industry. Journal of Materials Processing Technology, vol. 115, pp. 2-8.

52. Airbus A321 rear section of the fuselage,2017. https://www.reddit.com/r/ThingsCutInHalfPorn/comments/6946sq/airbus_a321_rear_section_of_the_fuselage/. Accessed on 25 July 2018.

53. M. Pacchione & J. Telgkamp, 2006. "Challenges of the metallic fuselage" in 25th International Congress of the Aeronautical Sciences, pp. 1-12.

54. W. V. Vaidya et al., 2010. Improving interfacial properties of a laser beam welded dissimilar joint of aluminium AA6056 and titanium Ti6Al4V for aeronautical applications. J Mater Sci, vol. 45, pp. 6242-6254.

55. John Norrish, 2006. Advanced welding processes. Technologies and process control. UK: Woodhead Publishing Limited.

56. M.St. ˛Weglowski, S. Błacha & A. Phillips, 2016. Electron beam welding - Techniques and trends - Review. Vacuum, vol. 130, pp. 72-92.

57. M. Chiumenti et al., 2017. Numerical modeling of the electron beam welding and its experimental validation. Finite Elements in Analysis and Design, pp. 1-29.

58. Dr. Guenther Schubert. Precision Technologies, Inc. https://www.ptreb.com/electron-beam-welding-information/technical-papers/electron-beam-welding-process-applications-and-equipment. Accessed on 5 August 2018.

59. CVE – Cambridge vacuum engineering. EB in the Aerospace industry. http://www.camvaceng.com/electron-beam-welding/industry/aerospace/. Accessed on 7 June 2018.

60. Rolls-Royce. The original record-breaker. https://www.rolls-royce.com/products-and-services/civil-aerospace/airlines/rb211-535e4.aspx#/. Accessed on 5 August 2018.

61. SST-Steigerwald Strahltechnik GmbH. Industries. https://www.sst-ebeam.com/en/job-shop/industries.html.

Accessed on 6 August 2018.

62. PTR - precision technologies. Aerospace. https://www.ptreb.com/electron-beam-welding-applications/aerospace-welding. Accessed on 6 August 2018.

63. P. Azar, Ping Li, P.C. Patnaik, R. Thamburaj & J-P. Immarigeon, 2001. "Electron Beam Weld Repair and Qualification of Titanium Fan Blades for Military Gas Turbine Engines" in RTO AVT Specialsits' Meeting on "Cost Effective Application of Titanium Alloys in Military Platforms".

64. Lockheed Martin. F-22 Raptor Photos. http://www.codeonemagazine.com/f22_gallery_slideshow.html?gallery_id=57&gallery_style=1. Accessed on 18 August 2018.

65. Committee on the Study of Live Fire Survivability Testing of the F-22 Aircraft, National Research Council, 1995. Live Fire Testing of the F-22. Washington: The National Academies Press.

66. Shery Welsh, 2004. Status of F/A-22 full scale fatigue test.

67. Bill Sweetman, 1998. F-22 Raptor.: Zenith Press.

68. Антипов В.В., к.т.н. Вахромов Р.О., Оглодков М.С., Романенко В.А. & Пантелеев М.Д. УДК 669.1. Свариваемые алюминий-литиевые сплавы третьего поколения.

69. Ariane Group - Orbital Propulsion Centre. Spacecraft Propellant Tank Manufacturing. http://www.space-propulsion.com/spacecraft-propulsion/bipropellant-tanks/manufacturing/propellant-tank-manufacturing.html. Accessed on 6 August 2018.