Friction Stir Welding as an effective alternative technique for light structural alloys mixed joints

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Abstract

The increasing use of structural light alloys in the aeronautical, automotive and transportation industry is pushing researchers to find new solutions for the production of innovative components. Mixed joints made out dissimilar alloys represent a challenge for engineers to the difficulties arising in welding materials characterized by significantly different mechanical, thermal and chemical properties. In the paper, an overview of the most used process to produce dissimilar joints of aluminum, magnesium and titanium is given. Both fusion based and solid state welding processes can be used. Although the joining of these materials is possible, particular attention must be taken to the choice of process parameters in order to avoid the formation of intermetallics, often resulting in brittle behavior and poor mechanical properties of the joints.

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1. Introduction

Over the last few years, the evolution of manufacturing technology and the continuous research for optimum performance has led to a wide use of innovative materials in several sectors of the industry. The most used
materials are the “light alloys”, utilized in the automotive and aerospace fields, due to the elevated resistance to weight ratio. Materials such as aluminum, titanium and magnesium alloys allow the design of light and resistant structures resulting, for the transportation industry, in significant fuel consumption reduction and beneficial impact on the environment. However, such alloys are generally less workable compared to ordinary steels, they can present problems related to anisotropy and often they turn out to be difficult or even impossible to weld by conventional fusing techniques. Besides, in the perspective of enhanced design optimization, in the last few years industry demand is pushing towards an increasing use of mixed joints, obtained welding together two different light alloys, further reducing the weight of the structures.

Aluminum is a very widely used metal. Despite its lightness, this metal is rather resistant both to mechanical strains (particularly in tie/bond) and oxidation (thanks to the passive effect of its oxides) and it is characterized by a high level of plasticity, pliancy, malleability and electric or thermal conductivity.

Magnesium is a white colored silvery metal characterized by its reduced density in comparison to all the other structural metals. Magnesium alloys are characterized by excellent mechanical workability, good resistance to corrosion, great capacity of vibrations damping, optimum drainage, high electrical and thermal conductivity, good stress resistance and elevated elasticity to heat.

Titanium alloys present an excellent mechanical resistance (superior to that of most steels), elevated corrosion resistance (comparable to that of the aluminum alloys) and show extremely high specific resistance. Furthermore, titanium alloys are particularly suitable for high temperature applications, since titanium is characterized by a high melting point (1678°C) maintaining good mechanical properties.

In the paper, mixed joints made out of these three light alloys are considered. An overview of the main applications for the three possible joint configurations is given in the first part. Then, the most utilized techniques to obtain welded mixed joints will be described taking into account traditional, innovative and solid state welding processes.

2. Case studies

2.1. Aluminum-magnesium

The use of mixed aluminum magnesium joints is an effective solution when weight reduction is the main project driver. As a matter of fact, these alloys are the lightest among the structural materials. On the other hand, parts that are exposed to severe mechanical and chemical solicitations must be produced without compromising the integrity of the structure. The latter is the innate main criticality of the production of mixed Al-Mg joints. In the last years, the introduction of innovative joining techniques such as structural adhesives bonding, clinching, self piercing riveting and FSW has led to an increased use of these particular joints.

In the aeronautical field mixed joints are widely used in the production of the framework and internal stiffening as well as external panel systems of the jet motors and of the aircraft fuselage. However, magnesium alloys require dedicated passivation treatments, in order to be sufficiently resistant to corrosion, and must be used for applications characterized by exercise temperatures up to a maximum of about 250°C. On the other hand, the use of aluminum alloys provide high formability and good corrosion resistance due to the presence of aluminum oxides on the free surfaces of the joint.

In the automotive field, parts of the framework of numerous sports vehicles (e.g. Jaguar D and Mercedes Benz 300 SLR) have been constructed from hybrid mixed joints, containing magnesium and aluminum alloys, since the 60's. Nevertheless, in the following years such solutions were not used in the large-scale production considering the numerous difficulties arising in the production of the joint. In recent years (defined as “the second era of magnesium”), the evolution of welding fusion techniques allowed the re-introduction of mixed joints in the automotive field, albeit, only in the higher category vehicles. In fact, currently these welds are still carried out “manually” and undergo strict non-destructive controls in order to verify their effectiveness. Today, mixed Al-Mg joints can be produced “automatically” only by expensive innovative techniques such as Electron Beam Welding (EBW) and Laser Beam Welding (LBW). Unfortunately, EBW and LBW are not highly effective because of the
tendency of vaporization of magnesium and zinc and the elevated reflectivity of the alloys, respectively (Malarvizhi et al., 2012).

2.2. Magnesium-titanium

The excellent mechanical resistance combined with the lightweight of these alloys made them extremely attractive to the aerospace, military and, to a lesser extent, automotive fields. Mixed Mg-Ti joints play a fundamental role in the aerospace industry. Currently, the use in the aeronautical industry allows a high weight reduction compared to traditional materials, with clear benefits especially in the production of rotating components, which require reduced “passiveness”. Furthermore, due to its elevated resistance to “impact” magnesium is often used to produce camera or laptop casings, but also airbags and other safety devices. In their first applications, they were used to produce compressor palettes of aeronautical engines, whereas today mixed Mg-Ti joints are used for the construction of many structural components in airplanes (e.g. tanks, hydraulic circuits, jet nozzles, turbines etc.) (Mendez et al., 2001). Besides the aeronautical and missile field, the use of Al-Ti hybrids is increasing also in the mechanical and chemical industry, in the production of sports equipment, heat exchangers in briny water environments and in the biomedical field for orthopedic limbs and heart valves.

2.3. Aluminum-titanium

The combined properties of aluminum and titanium alloys, i.e. lightness, mechanical resistance and corrosion resistance, are very attractive to aeronautical, aerospace and automotive industries. The development of components in light alloys in the motorsport and naval fields has led to an interest for these joint configurations also by these two sectors. The unchangeable and low thermal expansion coefficient, with regards to titanium, allows the possible pairing with other materials, the “bicompatibility” and the ability to contrast the development of micro-organisms from aluminum permits them to be used also for orthopedic and dental applications boasting excellent “clinical” success, as they are retained as biochemically inactive materials.

As of today, some studies have been carried out on fusion welding techniques, such as electric arc, to electron beams, and laser of these materials. The carried out experiments demonstrated that the lack of suitable precautions and correct evaluations on the reaction of the metals to be joined (like the elevated ability of titanium to oxides at high temperatures) could lead to several issues. Often, the three above-quoted types of process can induce distortions and porosity in the welded area leading to an inevitable degradation of the mechanical characteristics of the final joints (Vaidya et al., 2010).

3. Conventional welding techniques

3.1. Fusion welding processes

Joints made out of mixed metals are widely used in industrial applications as a result of technical and economic reasons. The adoption of combined mixed metals gives the possibility of having a flexible product using each material in an efficient way, that is benefiting from the specific characteristics of each material in an operational mode. Adhesive and mechanical joining have been traditionally used for these types of joints. It is worth noticing that adhesives are not effective at high temperatures while mechanical joining, is not suitable for tin joints (Möller et al., 2011).

Different fusion based welding processes can be used for the production of mixed joints, e.g. conventional arc welding, gas metal arc and submerged arc welding. Additionally, newer and more expensive processes characterized by elevated energy density, e.g. electron beam and laser beam welding, can be used.
As far as conventional fusion techniques are regarded, interesting studies have been carried out focusing on TIG welding (Liu et al., 2007, Wang et al., 2005). The microstructure and mechanical performance of Mg/Al TIG welded joints were studied by means of metallography, micro-hardness tests and SEM in Liu et al. (2007). The test materials have been magnesium (Mg1) and aluminum (1060) used in navigation. The dimension of the test plate was 100 mm×40 mm in the test. The thickness of the test plate was 3 mm. Added welding wire SAl-3 was used. The welding equipment was TIG welding machine of WSJ-500 type. The test results indicate that the structure close to weld metal is columnar crystals, which grow into the weld metal. The weld metal was mainly composed of dendrite crystal. The micro-hardness near the fusion zone of Mg side is about HM 275–300. The brittleness phase with high hardness may be formed near the fusion zone. The fracture surface of Mg side shows a river pattern, which is a typical cleavage morphology (Fig. 1).

![Fig. 1. Fracture morphology of Mg/Al TIG welded joint. (a) Cleavage fracture. (b) Air hole (Liu et al., 2007).](image)

The production of mixed joints has also been studied via MIG welding processes (Wang et al., 2008, Zhang et al., 2011). In particular, in Zhang et al. (2011) a zinc laminate was chosen as a material for the adhesion of the inter-bedded aluminum and magnesium layers using a classic MIG welding process. The superficial microstructure aspect and the mechanical traction properties of the lap joint obtained from aluminum/magnesium was then analyzed. It was found that the presence of zinc foil as interlayer prevents weld burn-through allowing the joining of materials with no Al–Mg compounds generated. In Wang et al. (2008), an AISi5 filler metal was used to inhibit the creation and growth of brittle intermetallic compounds. Additionally, super low heat input was conferred to the weld. However, a brittle fracture was observed due to the presence of a multilayer microstructure characterized by intermetallics. Arc welding was used to join titanium alloy Ti-2Al-Mn and an aluminum alloy 1060 with filler wire AISi5 (Shouzheng et al., 2013). P-GMAW, with different welding heat input, was investigated. Fusion zone near aluminum is composed of α-Al dendrites and Al–Si hypoeutectic structures as found also in Enjo et al. (1986). A few TiAl3 precipitations appear in the weld metal owing to metallurgical reactions of Al with dissolved Ti. Microstructure of the fusion zone changes with different welding heat input. The morphology of TiAl3 precipitation is greatly influenced by the welding heat input.

Electron beam welding (EBW) has been developed for many years and is being increasingly implemented in several industrial applications. However, most of the papers in literature focusing on dissimilar joints take into account steels, due to the advantages this technique provides using these materials (Sun et al., 1996).

Laser welding is the fusion welding process with the highest potential for effective production of hybrid joints for a number of different applications as the process is particularly suited to reduce the heat affected zones and provide deep penetrative beads. Nevertheless, many challenges arise in welding dissimilar metals and the aim is further complicated considering the specific features of the alloys taken into account, being them susceptible to oxidation on the upper surface and porosity formation in the fused zone. As many variables are involved, a systematic approach should be used to perform the process and to characterize the beads referring to their shape and mechanical features, since a mixture of phases and structures is formed in the fused zone after recrystallization (Li et al., 2005). In Caiazzo et al. (2013), the combination of titanium and aluminum was studied by means of laser welding for the case of aircraft structures. Titanium alloy Ti-6Al-4V and aluminum alloy AA2024 were considered. Laser brazing of Ti6Al4V and AA6061 T6 alloys with 2 mm thickness was conducted by focusing laser beam on aluminum alloy side in Song et al. (2013). The effect of laser offset was investigated finding increasing joint
mechanical resistance with increasing offset. Additionally, the authors highlighted that the joining mechanism of Ti6Al4V/A6061 dissimilar alloys by laser brazing is the formation of intermetallic phase TiAl3 at the interface, which metallurgically connects Ti6Al4V and A6061 plates together (Fig. 2).

Dissimilar welds of aluminium alloy AA6056 and titanium alloy Ti6Al4V were produced by a novel technique in Vaidya et al. (2010). AA6056 sheet was machined at one end to a U-slot shape, enabling the intake of the Ti6Al4V sheet. The laser split-beam, operated in the heat conduction mode, melts only the Al-alloy U-slot and the butt-weld is produced without a filler wire. Internal defects such as cold shuts were not observed and in this sense the coupons were sound. The grain size in the fusion zone was reduced and the intermetallic phase formed at the interface was thinner. Specimens could be mechanically tested without formation of cracks in the reaction zone and premature pullout or debonding. This change, seemingly insignificant, refined the microstructure of the joint increasing the hardness and tensile strength of the welded joint. The most impressive feature was the improved resistance to fatigue crack propagation.

As far as titanium and magnesium are considered, in Gao et al. (2012) laser welding was used to join titanium alloy Ti-6Al-4V to magnesium AZ31B. The correlations between the process parameter, the properties of the joint and the bonding mechanism were studied. The results show that the offset of the center of the laser bundle on the side AZ31B at the edge of the welded beam plays an important role in changing the joint property. Optimal welding parameters permitted to reach the maximum UTS of 266 Mpa. The bonding mechanism of the Ti–weld interfacial layer is summarized by interface properties and fracture behaviors, which change from mechanical bonding to chemical bonding as the laser offset decreases to 0.4 mm or smaller (Fig. 3).
Fusion based welding techniques are poorly adapted to the realization of mixed joints given the problems arising in the solidification of metal containing different alloy elements. The problems mentioned, i.e. the formation of large quantities of intermetallic compounds and the porosities, greatly weaken the welds. This makes the process automation extremely difficult.

3.2. Other welding processes

A few alternatives exist in order to successfully weld dissimilar light alloys. For sake of simplicity, two examples are reported in this paragraph regarding solid-state techniques.

Diffusion welding involves the interdiffusion of atoms according to Fick diffusion law across the interface of the weld at a temperature below the melting temperature (usually > 0.5 Tm) for a defined time. After reaching the activation energy level (which is dependent on lattice imperfection), diffusion takes place (Wilden et al., 2006). A few examples of diffusion bonding of dissimilar alloys can be found in literature. In Alhazaa et al. (2010), a mixed joint made out of AA7075 and Ti6Al4V was produced using a combination of Cu coatings and Sn–3.6Ag–1Cu interlayers. Cu coatings were used to inhibit oxide formation at the Al7075 alloy surface. The diffusion of Sn into the Al7075 and Ti–6Al–4V alloys formed a variety of intermetallics with copper, magnesium and titanium. Similarly to the previous case studies, fractography of the joints showed that a fracture initiation and propagation took place along the joint region which was dominated by the intermetallic phases (Fig. 4).

In Jiangwei et al. (2002) again diffusion bonding was used to join titanium (TA2) and aluminum (L4). Intermetallics TiAl and TiAl3 were formed in the transition zone on Ti substrate and aluminized coating. However, the formation of intermetallics in the interface zone of Ti/Al has a delay time, and controlling the technology parameters of diffusion bonding may reduce the formation of intermetallics.

Aluminum AA6061/titanium laminates were produced by single-shot explosive-welding for applications requiring light-weight structures (Ege et al., 2000). The thicknesses of the aluminum and titanium sheets were in
the range 0.508 to 1.600 millimeters. Planar (straight) interfaces were assured in the laminates, since a wavy configuration would possibly be accompanied by excessive heat generation and an attendant intermetallic formation resulting in weaker interfaces. Strengths as high as 825 MPa were achieved, depending on the relative amounts of aluminum and titanium (Fig. 5).

Fig. 5. Optical micrographs of the explosively-welded Al-Ti laminates (Ege et al., 2000).

4. Friction Stir Welding

Friction Stir Welding (FSW) is a solid state welding process patented by TWI in 1991. Initially developed for aluminum alloys, during the last few years it has been successfully used also to produce dissimilar joints, taking into account materials which are retained as non weldable or those which present particular problems with the traditional fusion techniques (Mishra et al., 2005). FSW can be successfully used to weld homologous joints made out of aluminum, magnesium and titanium sheets. In particular, titanium joints do not present ZTMA. In turn, a transition area exists between the very fine structure of the nugget and the altered thermal zone. In all of the joint areas the microstructure turns out to be thinner compared to that of the base material and the smaller sized grains (a few microns) are those on the superficial part of the nugget. The hardness profile does not show any decrease in the ZTA (typical of precipitation hardening aluminum alloys). As magnesium alloys are considered, the joints microstructure is not different to the one previously described. Again, the absence of a clear ZTMA can be noted.

FSW of mixed aluminum and magnesium joints was studied by a number of authors. In Kwon et al. (2008) butt joints were produced out of AA5052 and AZ31B sheets. Maximum tensile strength obtained was about 132 MPa, which was about 66% of the tensile strength of the A5052P-O alloy. No formation of a eutectic microstructure suggests that temperatures in the nugget were below 460°C, which is about the temperature of the eutectic Al/Mg phases (Fig. 6).

Fig. 6. Micrographs of the cross-sections perpendicular to the tool traverse direction of the plates friction-stir-welded with tool rotation speeds of (a) 1000, (b) 1200, and (c) 1400 rpm (Kwon et al., 2008).
Mixed aluminum AA1050 and magnesium AZ31 butt joints were considered in Sato et al. (2004). The aluminum was placed on the retreating side and the magnesium on the advancing side. The change of the disposition caused failure in the weld. It was noted that although the weld did not have any particular defects, such as tunnels or cracks, an irregular area was found in the center of the weld. In this area a solidified structure is present. The intermetallic compound Al$_{12}$Mg$_{17}$, due to constitutional liquation during the process, caused higher hardness in the weld center and a brittle behavior of the joints.

Joining of titanium alloy TiAl6V4 and aluminum AA2024-T3 sheets was taken into account in Dressler et al. (2009). An offset was given to the tool toward the aluminum plate, which was in the retreating side of the joint. On the titanium side of the joint, a small, recrystallized band next to the titanium–aluminum interface was found. The ultimate tensile strength of the joints reached 73% of AA2024-T3 base material strength, with fracture at the interface between titanium and aluminum. A study on the microstructure and the characteristics of the interface in a lap joint of titanium TC1 and an aluminum alloy LF6 was presented (Chen et al., 2012). The aluminum sheet was used as top sheet. It was found that the amount of Ti alloy particles stirred into the stir zone by the force of tool pin decreases with decreasing heat input to the weld. However, high feed rate results in groove-like cracks on the interface (Fig. 7).

An interesting study was developed on the influence of the alloy elements on the microstructure of the interface in Mg-Al-Zn magnesium-titanium joints (Aonuma et al., 2009). Butt joints made of AZ31B, AZ61A and AZ91D and Ti were produced. In this study the Ti was positioned on the retreating side and the Mg alloy on the advancing side. Again, the tool was offset towards the advancing side, i.e. the Mg side, in a way that a small portion of the pin was in contact with the titanium sheet. After the weld, the joints were treated thermally to study the reaction of the elements tied to the interface under high temperature conditions. It was found that an Al-rich layer was formed at the joint interface. Increasing the aluminium content of the Mg alloy, a Ti–Al intermetallic compound layer was observed leading to early failure of the joints. Welds created by either magnesium alloys ZK60 or commercially pure magnesium and commercially pure titanium were carried out by friction stir butt welding technique (Aonuma et al., 2012). An offset was given to the tool towards the softer material similarly to the previous studies. It was found that the tensile strength of the Mg–Zn–Zr alloy and titanium joint was higher than that of the pure magnesium and titanium joint due to the formation of a reaction layer formed by interaction Ti, Zn and Zr (Fig. 8).
Recently, some of the authors carried out a study on mixed light alloys joints welded by FSW. First, the effect of sheets mutual position in mixed Al-Mg butt joints was investigated. AZ31 and AA7075 were used. Excellent mechanical characteristics with UTS values up to 99% of the UTS of the softer material are found. From the obtained results (in agreement with Kostka et al. (2009)) they would suggest that in fact the positioning harder material, i.e. AZ31, in the RS causes production of defective and poor quality joints (Fig. 9).

An experimental campaign was carried out with the objective of verifying the mechanical and metallurgical properties lap joints made out of titanium Ti6Al4V and magnesium AZ31 sheets. The effect of process parameters, including tool rotation, feed rate and sinking, was considered. For all the welds the titanium sheet was used as top sheet. It was found that the stir zone of the bottom sheet, i.e. the magnesium one, is characterized by a strong presence of titanium due to the vertical component of the material flow induced by the conical pin used (Fig. 10).

5. Conclusions

In the paper, an overview of the main welding techniques used to produce mixed joints between three of the most commercially used light alloys, i.e. aluminum, magnesium and titanium alloys, is given. As fusion welding processes are taken into account, both traditional, i.e. MIG and GMAW, and newer, i.e., LBW and EBW, techniques can be used. Although better results are obtained by LBW, the dissimilar welds suffer from typical defects due to the material melting, as crack, voids and porosities. Additionally, due to high temperatures reached, intermetallics are observed leading, in most of the case studies analyzed, to a brittle behavior and poor mechanical performance of the joints.

Solid state processes can be successfully used in order to overcome the above mentioned defects. Processes as diffusion bonding and explosive welding can be used for niche applications.

Finally, FSW was demonstrated to be feasible to produce dissimilar joints, even with materials which are profoundly different in their mechanical and thermal properties. Both lap and butt configurations were considered. It arises that the correct choice of welding parameter is particularly important. This is essential for a correct heat input to the welded area. Additionally, two parameters, proper of FSW of dissimilar joints, were found to play a key role in the obtainment of nugget integrity, namely tool offset and sheet mutual position. Although the process is conducted at temperatures below the melting temperatures of the base materials, intermetallics can still appear due to constitutional liquation or atomic diffusion. It was observed that in most cases the presence of intermetallics leads to increased hardness, brittle joint behavior and poor mechanical resistance.

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