Review Article

Low-Temperature Brazing of Titanium Using Al-Based Filler Alloys

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Brazing of titanium using low melting temperature filler alloys is a preferred choice regarding cost and preserving its mechanical properties. However, brazing titanium at low temperature is still a challenge, especially regarding aluminum-based filler alloys. During the last years, several brazing methods and Al-based fillers were developed to meet industrial requirements; some of them might achieve some of those requirements. The use of ultrasound in brazing has gained increased attention recently, which helps to reduce the time and the necessity for a special brazing environment, subsequently, reducing cost and increasing applicability. Brazing titanium below the $\alpha \leftrightarrow \beta$ transformation temperature, using commercial and experimental Al-based fillers of different compositions, is presented in this review; including the procedures of traditional and ultrasound-assisted brazing methods. Correspondingly, the effects of brazing conditions and alloying elements on the mechanical properties and the intermetallic compounds formation are examined.

1. Introduction

Brazing of titanium at a temperature below $\alpha \leftrightarrow \beta$ transformation temperature has great importance in avoiding undesirable changes in its original microstructures [1, 2]. A low brazing temperature is particularly crucial for thin-wall brazing structures of aerospace components and heat exchangers [3]. The shorter brazing cycle/less brazing temperature helps to prevent the excess interaction between the joint components and growth of the intermetallic compounds at the joint interface [2]. Titanium has a strong chemical attraction of oxygen; therefore, even at room temperature, a passive amorphous oxide layer forms rapidly on its surface [4]. The oxidation of the surface makes titanium joining process challenging from the point of establishing the metal connection; furthermore, titanium should be protected from severe oxidation at temperatures exceeding 650°C [5]. In addition to susceptibility to grain coarsening and affecting strength/ductility of the parent components, high-temperature brazing requires special equipment, conditions, and longer processing time, leading to higher processing cost compared with low-temperature brazing.

Titanium joining has been widely studied [6]. Unlike brazing, welding is not used usually for titanium honeycomb sandwich structures [7–10] which require joining many points without distortion. Moreover, the welding process is not suitable for joining titanium aluminides [11]. A great number of brazing filler alloys were developed and studied for brazing titanium alloys; some of them were commercially used. In 1950s and 1960s, early work was focused upon Ag-, Au-, Cu-, and Pd-based filler alloys for $\sim(316\text{--}427^\circ\text{C})$ and Al-based filler alloys for $\sim 204^\circ\text{C}$ service temperatures. Ti- and Ti-Zr-based alloys were developed later, which showed better metallurgical compatibility with titanium [12] and produced higher joint strength when compared with the other systems of brazing fillers. Table 1 shows some examples of relatively high strength and temperature brazed joints using Ti- and Ti-Zr-based filler alloys. However, low-temperature brazing with more free conditions could find several applications: where the inert atmosphere cannot be applied, the parts to be joined cannot fit within limited and special environments such as the mass production by continuous brazing, the large brazing joints, or for in-place brazing. Furthermore, reducing the joining cost by lowering

temperature is important for reducing the total fabrication cost and maintaining titanium share in the total structural weight of aerospace systems [13].

According to the main alloying elements, filler alloys for brazing titanium and its alloys can mainly be classified into five groups: titanium-based [1, 14, 16, 18–21], zirconium-based [16, 19, 22, 23], silver-based [24–27], aluminum-based [28–31], and nickel-based [19, 32] filler alloys. Attempts of brazing titanium using Al-based filler alloys and other filler systems started over than 60 years ago [33]. Many Al-based filler alloys have been developed since that time, and many attempts were made in pursuit of achieving suitable brazing conditions. Titanium was brazed to itself and to aluminum alloys by Al-based fillers using an oxyacetylene torch with flux [30, 33], in high-purity argon [10, 33], in vacuum [28–31, 34–36], and in air conditions: in fluxless process assisted by the ultrasonic vibration (USV) [37–39] or by additional pressure [40]. Investigating and improving the mechanical properties of the produced joint through a careful design of the brazing cycle and controlling the intermetallic compound formation/diffusion zone were among the primary explored objectives in brazing titanium and its alloys. Considerable efforts have been made to reduce brazing cycle time while still achieving a suitable strength by employing new techniques and developing new compositions of low-melting filler materials. Although significant work has been done so far, brazing of titanium by Al-based fillers still needs more development to increase its share in the industrial sector.

The developed microstructure and mechanical properties of brazing joints depend on the component compositions, temperature-time cycle, and the joint design. Choosing the right cycle parameters depends, in turn, on the rate and nature of the interaction at parent/filler interface. The short temperature-time brazing cycle protects the parent component from unwanted metallurgical changes, which may occur faster as the temperature increases; for instance, the aging effects which take place in 4 h at 537.8°C (1000°F) in Ti-6Al-4V would occur in ~10 min at 579.4°C (1075°F) [41]. However, brazing time could be increased according to the parent/filler materials' compositions to allow the interface element diffusion to take place for a certain limit which is necessary to achieve the optimal joint strength. The diffusion of some brazing processes, usually in high temperature, may proceed for a relatively long holding time until achieving the microstructure homogenization over all the joint, which is particularly known as diffusion brazing. Matsu et al., Ganjeh et al. and Chang et al. [16, 17, 42] investigated the diffusion brazing of several Ti- and Zr-based fillers, which led to specific microstructures and high shear strengths (Table 1). These processes involve isothermal solidification and homogenization of the joint [43].

In metal casting, the ultrasonic vibration (USV) provides multiple significant effects such as degassing [44–47], refining, and modifying the microstructures [48–51]. Using USV in brazing is an attractive assisting tool [37–39, 52–58]; however, studying the combined effects of USV with the technological parameters of brazing process and developing a joint interface more compatible with the USV have not yet received an adequate attention. The focus in this review will

be on the titanium/aluminum interface which includes Al-based filler alloys for brazing titanium/titanium and titanium/aluminum parent (base) components, taking into consideration the technological parameters and procedures.

2. Aluminum-Based Filler Alloys

Various Al-based alloy systems have been tested for brazing titanium/titanium and titanium/aluminum parent components. The alloying additions to the filler materials serve several purposes, such as reducing melting temperature, improving wetting [28, 34], reducing intermetallic thickness [29], improving corrosion resistance [41], and improving static/dynamic strength at work temperature [29].

Lowering the brazing temperature and reducing the contact time of a molten filler alloy with a parent titanium alloy reduce the Ti erosion [26, 42] and increase the reliability of the thin-wall titanium joints [3]. Al-based filler alloys can be a suitable candidate for brazing titanium satisfying the following conditions: the melting temperature considerably below the $\alpha \leftrightarrow \beta$ transformation temperature of titanium alloys, a good metallurgical compatibility with titanium alloys, good wetting and spreading on titanium surface, good corrosion resistance [59], low density, and acceptable strength for a large joining surface [2]. Some commercial Al-based filler alloys of Al–Cu, Al–Mg, and Al–Si systems with addition of Cr and Ti were introduced [3, 19]. However, aluminum leads to fast formation of a brittle intermetallic layer at the joint interface with Ti and provides relatively low strength compared with other filler alloys; the activity of Al with Ti is considered the dominant challenge when designing Al-based fillers and optimizing the brazing process.

2.1. The Developing of Brazing Conditions/Methods in Brazing Ti/Ti and Ti/Al Using Aluminum-Based Fillers

2.1.1. Vacuum, Torch Brazing, and Other Methods. Lewis et al. [33] tested initially many of commercially available brazing fillers using careful sample preparation procedures. The obtained shear strength of the double-lap-brazed joints in a controlled-atmosphere furnace brazing was 73.77–115.69 MPa using 61S (6061) aluminum filler. Further torch-brazing tests were made by covering the specimen surfaces with a commercial titanium flux and using a slightly reducing flame. In general, the strength results were lower 44.82–88.94 MPa when compared with the controlled-atmosphere furnace brazing; the reason was explained by flux entrapment in the joint area or insufficient temperature control and oxidation protection in torch brazing. The use of torch brazing must always be accompanied by specific fluxes, choosing the suitable flux should consider the alloying elements in the molten filler and should be suitable for all joint elements. Fluxes for titanium are primarily mixtures of fluorides and chlorides of the alkali metals, sodium, potassium, and lithium [4].

Takemoto et al. [28] investigated brazing of pure Ti/Al3003 (Al–1Mn) joint in vacuum using three different Al-based filler alloys. Brazing time was short (3–5 min) and brazing temperature did not exceed 615°C. Table 2 shows the shear strength results.

TABLE 1: Examples of high-temperature brazing of titanium.

Shear strength (MPa)	Conditions	Filler	Parent metal	References
300	Vacuum + argon, 880°C, 60 min	37.5Ti – 37.5Zr – 15Cu – 10Ni	Commercially pure titanium (Grade 2)	[14]
261.7	Vacuum + argon, 870°C, 30 min	Ti–27Zr–14Cu–13Ni	Commercially pure titanium (Grade 2)	[15]
540	Argon, 950°C, 30 min	Ti – 26.8Zr – 13Ni – 13.9Cu	Ti – 6Al – 4V (Grade 5)	[16]
545	Vacuum, 1030°C, 3 min	Ti – 15Cu – 25Ni	Ti – 6Al – 4V (Grade 5)/Ti – 15V – 3Al – 3Cr – 3Sn	[17]

Pure Ti/Ti joints were investigated under the same level of vacuum using pure aluminum and Al–0.8%Si as filler materials at 680°C and 3 min holding time [28, 29]. The reported shear strength was ~92 MPa for both filler metals; anyway, increasing the holding time led to drastic decrement rate of the joint strength of the pure Al filler. It was found that the use of pure Al as a filler metal to braze Ti/Ti in 700°C led to self-separation of the joint after holding time of 30 min, and the thickness of the formed intermetallic compound layer (TiAl_3) was the greatest, which acts as an initiation site for cracks.

Sohn et al. [34] studied the diffusion between the Al–10Si–1Mg filler metal and the parent metals of CP-Ti/Al1050 by maintaining the temperature at 620°C and changing the holding time in 1×10^{-4} Torr vacuum as it is presented in Figure 1.

The best-achieved shear strength was 84 MPa for the brazing time of 25 min. For longer brazing time, bond strength decreased due to the formation of cavities in Al near Al/intermetallic interface. Shiue et al. [35] investigated a fast heating approach in joining titanium aluminide Ti50–Al50 by infrared brazing using pure aluminum and BAlSi–4 of the composition (Al–(11–13)Si–0.3Cu–0.1Mg–0.2Zn–0.15Mn–0.8Fe) as filler alloys. Brazing was done in the vacuum using a high-speed infrared source for heating of 900°C/min, and preceded by a preheating for 60 s/400°C. For the pure aluminum filler, a large formation of the brittle intermetallic phase TiAl_3 was found for all holding times, and the bonding strength was very weak. Figure 2 shows the place of the crack through the major phase of TiAl_3 in the joint.

While for BAlSi–4 filler alloy which contains Si, it was observed that the intermetallic Ti_2AlSi_3 was prominent at an early stage of infrared brazing. By increasing the time and temperature, the volume fraction of Ti_2AlSi_3 decreased dramatically and replaced by $\text{Ti}_5\text{Al}_{12}\text{Si}_3$, and then it disappeared. The highest strength 86.2 MPa was achieved for 900°C brazing temperature.

Khorunov et al. [31] investigated Al–Si and Al–Mg filler alloys in brazing OT4 (Ti–3Al–1.5Mn) titanium alloy in vacuum. The resulted strengths using Al–Mg filler alloys were relatively high (82–83 MPa), while the produced joint using Al–Si filler alloy was characterized by inferior quality with a continuous layer of silicide detected along the interface.

Some efforts have been made to simplify brazing process and carry out titanium brazing in normal ambient air conditions. These efforts were focused on developing low-

TABLE 2: Results of brazing Ti/Al3003 by Takemoto et al. [28].

Shear strength (MPa)	Brazing conditions	Fillers
38.25	615°C, 5 min, <i>vacuum</i>	Al–10Cu–8Sn
38.25	600°C, 5 min, <i>vacuum</i>	Al–20Ag–10Cu
69.88	600°C, 3 min, <i>vacuum</i>	Al–10Si–0.5Mg

FIGURE 1: Shear strength variation of brazed joints CP-Ti/Al1050 at 620°C using Al–10Si–1Mg filler alloy. Reproduced from Sohn et al. [34], copyright 2003, with permission from Elsevier.

FIGURE 2: The crack location of the brazed joint Ti50Al50/AlTi50Al50 (900°C, 30s). Reproduced from Shiue et al. [35], copyright 2003, with permission from Elsevier.

melting brazing fillers and finding a suitable technique to remove the oxide layer on the faying surfaces of the joint. In Germany, Bach et al. (cited in [2]) conducted an early attempt of Ti–6Al–4V brazing in the air by utilizing an alloy of

TABLE 3: Recent studies of ultrasound-assisted brazing of Ti/Ti and Ti/Al joints by Al-based fillers.

Reference	Materials	Heating method and best conditions (all in air)	Shear strength (MPa)
[37]	Parent metal: Ti Grade 5; filler metal: TiBraz Al-665(Al-2.5Mg-0.3Cr)/100 μ m	Induction brazing, 660°C, (5 sec, 84 W) USV, no holding time	50–60
[39]	Parent metals: Ti Grade 5/Al1060; filler metal: Al-12Si	(A = 6 μ m, 20 kHz) USV, 620°C, 4 sec USV + holding for 15 or 5 min + 4 or 0 sec USV	~68
[38]	Parent metal: Ti Grade 2; filler metal: TiBraz Al-665A (Al-2.5Mg-0.3Cr)/50 μ m	Induction brazing, (25 kHz, 120 W) USV, 670°C, holding for 5 min at 560°C, then heating to 670°C and holding for 3 min, applying USV for 6 s	~64
[55]	Parent metals: Ti Grade 5/Al6061; filler metal: Al-9.4Si-10Zn-10Cu-2Ni	(A = 6 μ m, 20 kHz) USV, 560°C, 4 sec USV + holding for 60 min + 4 sec USV	~43
[55]	Parent metals: Ti Grade 5/Al6061; filler metal: Al-15Sn-8.2Si-8.5Zn-8.5Cu-1.7Ni	(A = 6 μ m, 20 kHz) USV, 560°C, 4 sec USV + holding for 15 min + 4 sec USV	~76

low-melting temperature, which was a thin Al foil coated with copper (33% Cu) for a brazing gap of 6–20 μ m. The produced joint had a good quality; anyway, the shear strength did not reach more than 25 MPa, which serves in joining large areas only. This showed that the eutectic Al–Cu was active enough to react with titanium in the air. Karfoul and Muhrat [40] investigated Ti/Ti-brazed joint strength in relation to the filler metal compositions and brazing parameters in the air. New brazing filler alloys of Al–Cu–Ni–Ti group were studied to find the effects of the alloying elements, as well as investigating the possibility of brazing in the air. The highest average shear strength achieved was ~74–73 MPa using Al–8.54Cu–1.35Ni–0.08Ti and Al–6.44Cu–1.96Ni–0.92Ti filler alloys. Removing the oxide layers between the aluminum and titanium is the initiation key of the bonding process. Accordingly, adding pressure will lead, with the help of Ti surface roughness, to break the oxide layer of Al-based filler. Then, buckling proceeds through thickness cracking of the scale, and the stripped Al surface atoms will react with the Ti-oxide layer to reduce it to atomic Ti [40]. Using USV as an assistant tool in brazing, which leads to fast breaking of the oxide layer at the joint interface and makes the joining process possible in air conditions, is summarized in the following.

2.1.2. Ultrasound-Assisted Brazing of Ti by Al-Based Fillers. The sonochemical effects of the USV in liquids have been explored for over 80 years [60]. The interest in ultrasound-assisted brazing started more than 50 years ago. One of the early US patents was an ultrasound-assisted brazing unit using an ultrasonic tip surrounded by local heating flame [61].

Using USV for a short period results in very fast destroying of the oxide layer on the parent material and wetting it by the filler material [52], even it is effective in achieving a good wetting on ceramics by the filler materials in the air [53, 54, 62]. The acoustic cavitation generated in the liquid metal is considered as the most important physical effect of the ultrasonic oscillation propagation [63–66]. The formation of cavities starts with the half period of rarefaction at the weakest points of the melt [63]. Cavities continue to increase in size until they collapse by the compressing stresses during the next compression half period; the results

of this collapse include high-intensity pressure pulses, temperature spikes, and high-velocity jets. The important physical and chemical processes due to the ultrasonic cavitation are melt degassing, filtration, wetting of the solid inclusions, and structure modifications. Moreover, the acoustic cavitation results in ultrasound energy adsorption and formation of acoustic streaming. The sound pressure must exceed a certain level to be able to initiate cavitation in the liquid metal, which is called cavitation threshold [63].

Employing USV in brazing results in short processing time, consequently, reducing the cost, and preserving the parent components from further metallurgical changes. The advantages include less specific atmosphere requirements due to the fast-breaking of the oxide layer [39, 52], enhanced spreading of the molten filler [55, 62], and homogenizing the microstructures of the joint [39]. Table 3 summarizes the technological parameters and the shear strength results of the ultrasound-assisted brazing of Ti/Ti and Ti/Al joints using Al-based fillers.

Chen et al. [52] explored the instantaneous breakage behavior of the oxide film of Ti–6Al–4V on its interface with the liquid Al–Si alloy and the chemical interactions during the process using 20 kHz frequency and 5.5–7 μ m amplitude USV. The samples were heated to 620°C then the titanium sonotrode was quickly loaded on the titanium substrate with a constant pressure of 0.2 MPa. The applied time of USV was 2–16 s. Due to the USV effect, a large number of pits were formed on the titanium substrate as it is shown in Figure 3. The formation of the pit started by a small notch on the surface of the Ti oxide film due to “cavitation erosion” [65, 67] (N in Figure 4) which serves as a microchannel and allows direct interaction between the fresh Ti surface and molten Al alloy.

The suggested pit formation mechanism according to this study was firstly, the formation of a notch at the oxide layer of the titanium substrate and secondly, violent chemical dissolution of the solid phase Ti–6Al–4V into the liquid filler Al–Si, followed by further interfacial chemical reactions.

Chen et al. [39] conducted a further work in ultrasound-assisted brazing of Ti–6Al–4V/Al1060 in the air using Al–12Si filler. In this study, ultrasonic vibration was applied to Ti–6Al–4V plate for 4 s at 620°C followed by 0, 5,

FIGURE 3: The morphology of Ti-6Al-4V substrate surface: (a) after interaction with the liquid Al-Si alloy for 10 min without ultrasonic treatment and (b) with ultrasonic treatment for 8 s. Reproduced from Chen et al. [52], copyright 2012, with permission from Elsevier.

FIGURE 4: The microstructure (SEM) of Al-12Si/Ti-6Al-4V interface after: (a) 4 s; (b) 4 s + 5 min; (c) 4 s + 15 min; (d) 4 s + 15 min + 4 s. Reproduced from Chen et al. [39], copyright 2013, with permission from Elsevier.

and 15 min holding time, and then by a second ultrasonic vibration period for 4 s. Applying the first ultrasonic vibration for 4 s caused formation of pits at the surface of the titanium alloy (Figure 4(a)). By applying a holding time of 5 or 15 min, the dissolving continued at Al1060 and Ti sides; consequently, the oxide film detached off the titanium substrate which is called “substrate oxide undermining” (Figures 4(b) and 4(c)). In addition to the pit formation, the cavitation and the stirring action of acoustic streaming caused the following effects during the ultrasound operation:

- (i) Accelerating the dissolution process at Ti side once the pits had been formed on the Ti oxide film, as well as along Al1060 side.
- (ii) During the second 4 s of USV, breaking the floating oxide film of the titanium alloy (Figure 4(d)). Simultaneously, breaking the Al dendrites and causing the Al phases to distribute uniformly in the joint.

Anyway, increasing holding time to 15 min or adding a second USV period did not improve the shear strength of the brazed joints.

FIGURE 5: The formed voids and gaps in Ti-6Al-4V/Al-2.5Mg-0.3Cr/Ti-6Al-4V brazed joints by different ultrasound-assisted brazing parameters: (a) 100 μm , 670°C, 5 s, 60%, (b) 60 μm , 660°C, 5 s, 50%, and (c) 100 μm , 660°C, 5 s, 80%. Reproduced from Tillmann et al. [37], copyright 2015, with permission from Springer.

Tillmann et al. [37] studied the ultrasound-assisted brazing of Ti-6Al-4V using Al-2.5Mg-0.3Cr filler and induction heating. The studied parameters were the layer thickness (60–200 μm), brazing temperature (660–680°C), and acoustic power (60–96 W), and then the sample of the best ultrasound-assisted brazing parameters was compared to a traditional vacuum brazing one. Increasing temperature over 660°C or reducing the thickness to less than 100 μm resulted in big voids in the brazed area. Increasing the acoustic power up to 70% (84 W) resulted in a considerable reduction of the oxide layer at the interface, and less intensities could not remove the oxide layer, while the highest one of 80% caused a significant cavitation leading to gap formation in the joint (Figure 5). The highest shear strength obtained using the sample of 100 μm , 660°C, 5 s, 70% did not reach more than 60 MPa and between 30 and 40 MPa for vacuum-brazed samples.

The lower strength values for the samples brazed in the vacuum were attributed to the low heating rate which resulted in an excessive formation of a low-ductility intermetallic at the interface.

Elrefaey et al. [38] conducted a preliminary investigation of the microstructure and the fracture behavior of ultrasound-assisted brazing of Grade 2 titanium using 50 μm TiBrazreAl-665A (Al-2.5Mg-0.3Cr) filler alloy. The results showed the formation of the thin interaction layer of Ti_3Al , and the joint failed mainly at Ti/Al interface due to the brittle nature of the intermetallic. Chen et al. [55] investigated the addition of Sn to Al-9.4Si-10Zn-10Cu-2Ni in ultrasound-assisted brazing of Ti/Al joint. In a similar way in other works [39, 62, 68], a simple overlap assembly was used with a preset joint clearance of 200 μm . The addition of Sn caused the widening of the melting range; before reaching the solidus temperature, the residual Sn-rich liquid filled the capillary gaps between the solidified CuAl_2 grains which significantly reduced the residual thermal stresses and enhanced the joint strength [55].

To guarantee the efficient transfer of USV to the joint, the fixing rig and the mechanism by which the USV is being transferred should be designed carefully. This includes the consideration of the acoustic properties of the fixing rig components, the applied force on the joining area, and the location of the sonotrode tip [69]. Elrefaey et al. [38] used, for instance, an apparatus where the horn was installed

FIGURE 6: Schematic illustration of an ultrasonic-assisted brazing apparatus used by Elrefaey et al. Reproduced from Elrefaey et al. [38], copyright 2013, with permission from American Welding Society (AWS).

vertically, and the sample which was mounted into a steel holder was under 0.2 MPa pressure as a result of the horn weight (Figure 6). While, Tillmann et al. [37] used overlapped brazing joints with a torque of 8 Nm introduced by a screw connection.

Even though using USV is a valuable way to break up the oxide layer and improve the properties of the joint, the results of ultrasound-assisted brazing of Ti/Ti and Ti/Al confirm that the process needs more control and investigation on the brazing conditions/materials to achieve higher mechanical properties.

2.2. The Intermetallic Compound Formation at the Ti/Al Interface. Several intermetallic phases occur in the Ti-Al system such as $\alpha_2\text{-Ti}_3\text{Al}$, $\gamma\text{-TiAl}$, TiAl_3 , TiAl_2 and Ti_2Al_5 [70]. In fact, only Ti_3Al and TiAl are technically interesting [71].

Since almost all filler metals form intermetallic compounds with titanium [29], therefore, studying and controlling their formation/development at the interface largely determine the mechanical behavior of the brazed joints. The formation and growth of the intermetallic compound at the interface is related basically to the compositions of the filler materials, the parent material, and the temperature-time parameters. Brazing titanium with pure aluminum, for instance, mainly leads to the formation of TiAl_3 at the interface; adding Si ($\geq 3\%$) to the aluminum filler alloy will lead to formation of $\text{Ti}_7\text{Al}_5\text{Si}_{12}$ and $\text{Ti}_9\text{Al}_{23}$; however, adding Cu or Ag will not change the probability of TiAl_3 formation [29]. The predicted phase by the effective heat of the formation rule does not necessarily form at the moving reaction interface if it is difficult to nucleate [72]. Many studies showed that TiAl_3 would form at the expense of the preexisting Ti_3Al or TiAl phases in the presence of excess Al. Sujata et al. [73] calculated the free energies of formation of different titanium aluminide compounds in the temperature range $\sim(0\text{--}1200^\circ\text{C})$, and they found that the free energy of TiAl_3 is less than that of Ti_3Al and TiAl but slightly higher than that of TiAl_2 and Ti_2Al_5 . The preferred formation of TiAl_3 as the only product during solid Ti/liquid Al reaction was explained by two factors: the first one is the additional steps in TiAl_2 and Ti_2Al_5 formation which include TiAl as one of the starting phases and the second factor is the presence of the excess amount of liquid Al which minimizes the trend of TiAl or Ti-rich compound Ti_3Al formation. Wöhlert and Bormann [74] investigated the phase selection mechanism of intermetallic compounds in Ti/Al phase reaction. The predeposited layers of Ti_3Al and TiAl , between Al/Ti elemental layers after annealing for 50 and 20 h at 400°C , respectively, were disappeared and replaced by TiAl_3 . Accordingly, the phase selection during the interface reaction was explained by the differences in growth velocities of the competing phases. Similar main phase selection reason was concluded by Michaelsen et al. [75] including the nucleation as a first step in TiAl_3 formation. Analogous results of TiAl_3 formation on a Ti_3Al -based alloy were reported by Zhang et al. [76] by using hot dip aluminizing (750°C -15 s) followed by interdiffusion treatment (600°C -30 h). It was found that the addition of Si, Mn, or Ag to the pure Al coating improved the thickness uniformity and reduced the formation of the transverse cracks. Further intermediate layers consisting of $(\text{TiAl}_3 + \text{TiAl}_2)$ and/or TiAl were formed after high-temperature oxidation for all the coatings. Zhang et al. [77] reported in another work using similar aluminizing and interdiffusion procedures the growth of TiAl_2 and TiAl , as solid state reaction products at the interface of TiAl_3 and Ti-6Al-4V substrate after the subsequent oxidation at 700°C and 300 h, whereas $\text{TiAl}_3 + \text{TiAl}_2$ and Ti_3Al layers were formed at 800°C and 300 h of oxidation in air. The mixed $\text{TiAl}_3 + \text{TiAl}_2$ layer resulted from O_2 reaction with TiAl_3 . Xu et al. [78] applied vacuum hot pressing on Ti/Al laminates followed by annealing and found that the next reaction phase after TiAl_3 was TiAl at the Ti/Al interface after consuming Al layer and during a second-stage annealing treatment at higher temperatures. The diffusion at the Al/Ti interface can be accelerated with the amount of cold/hot rolling reduction [78,79]. In brazing

titanium alloy OT4 by Mg-containing aluminum alloys, the formation of TiAl_2 between TiAl_3 and titanium also could take place [31].

The diffusion of the chemical elements across the interface of the brazing joint is high at the beginning of the brazing process since the diffusion at the beginning is between liquid and solid phases. As soon as the formation of the intermetallic compounds takes place, the diffusion rate is reduced and becomes less and less by increasing the intermetallic layer thickness until the growth of the intermetallic compound is suppressed. Considering, in titanium-rich aluminide, titanium can diffuse faster than Al [80, 81]. The thickness of the intermetallic layer when using pure aluminum as a filler is the largest one, and any addition or impurity elements will suppress—but differently—the growth of the intermetallic layer [29].

Brazing titanium aluminide TiAl at 900°C for 30 s using pure Al filler produced very weak joint, and the primary phase in the joint was the brittle TiAl_3 phase [35]. On the other hand, for a different case with longer bonding cycle under pressure and without any additional filler, the “diffusion bonding” of two-phases gamma-based titanium aluminide Ti-45Al (in at.%) produced α_2 - Ti_3Al phase at the bonding interface. It was concluded by Buque and Appel [82] that the unavoidable contamination of the diffusion couple with oxygen leads to the formation of a thin layer of α_2 - Ti_3Al phase. Similar result was found by Herrmann and Appel [83] for various two-phase gamma-based titanium aluminides, even considerably higher vacuum was used.

2.3. Main Aluminum-Based Filler Systems

2.3.1. Pure Aluminum as a Filler Metal. Pure aluminum is highly active with titanium at brazing temperature causing high erosion level, consequently, unreliable brazed joints specially for the thin-wall titanium structures [2]. Takemoto et al. [28, 29] found that the highest thickness of the intermetallic compound TiAl_3 was caused by using pure aluminum as a filler. The small additions of alloying elements or impurities to the pure Al filler reduced the intermetallic layer thickness at the brazed interface. It was found that the addition of 0.8%Si greatly reduced the thickness and the growth rate of the intermetallic TiAl_3 , and the produced Ti/Ti joints using Al-0.8Si filler maintained higher joint strengths after brazing for relatively higher temperatures and longer holding times comparing with pure Al filler [29]. In the same context, Shiue et al. [35] found that the bonding strength of $\text{TiAl}/\text{Al}/\text{TiAl}$ joint was very weak to be evaluated due to the extensive presence of the stable TiAl_3 phase in the joint.

The minor modifications in the alloying elements affect the wetting and spreading behavior and should be designed according to the type of the Ti parent metal. For instance, comparing the fillers Al-4.5Mg-0.4Si-0.1Cr and Al-4Mg-0.5Si-0.4Mn [30], the former with more 0.5%Mg and 0.1Cr instead of 0.4Mn, has a lower contact angle and better spreading on Grade 5 titanium; by contrast, these

TABLE 4: Ti/Ti–Ti/Al-brazed joints using pure or low-alloyed Al fillers.

References	Materials			Filler	Conditions	Bonding		Shear strength (MPa)	Intermetallic compounds at Ti/filler interface
	Parent 1	Parent 2	Type			Thickness/gap width (μm)	Temperature (°C)		
[29]	Pure Ti	Pure Ti	Pure Al	100	Vacuum 2.7×10^{-3}	680	3	~92*	TiAl ₃
			680			10	~42*		
			Al-0.8Si			680	3	~94*	TiAl ₃
						680	10	~75*	
[31]	OT4 titanium	OT4 titanium	AD1 (Al-0.4Si-0.3Fe)	60	Vacuum 5×10^{-5} mmHg	685	3	76	
Cited in [2]	Ti Grade 5	Ti Grade 5	Al-0.3Si-0.8Fe-0.2Mg			>660		72	
[35]	Ti50-Al50	Ti50-Al50	Pure aluminum	75	Vacuum 8×10^{-5} mbar	900**	0.5	Very weak joint	TiAl ₃

*The shear strength values calculated according to Figure 11 in [29]. **Infrared brazing 900 $^{\circ}\text{C}/\text{min}$, preheating in 400 $^{\circ}\text{C}$ for 60 s.

modifications have a different effect in brazing Grade 2 titanium. Table 4 shows a summary of Ti/Ti–Ti/Al-brazed joints using pure or low-alloyed Al fillers.

2.3.2. Al–Mg-Type Filler Alloys. Flom [84] reported the disappearing of magnesium from the interface layer between Al–Mg filler alloy and titanium parent alloy during vacuum brazing. Similarly, Khorunov et al. [31] found, after brazing using AMg6 alloy containing 6% of Mg, that only 1.5% of Mg remained in the joint and no Mg remained at the interface; the reduction of Mg was explained by the evaporation of Mg from the filler during the heating and melting in vacuum. The volatility of magnesium in elevated temperatures [85] and the reaction of the magnesium vapor with the oxide surface of aluminum make Mg an excellent wetting promoter [86]. Mg reacts with aluminum oxide forming a complex oxide MgAl_2O_4 [87] or reducing it to $\text{Al} + \text{MgO}$ [34], which forms inclusions and induces bonding to occur; as a result, the content of Mg is reduced in the joint considerably [31]. The improved wetting of Al–Mg filler alloys was also confirmed by Khorunov et al. [31], where Al–Mg filler showed better wetting on titanium alloy OT4 for a temperature less than 700 $^{\circ}\text{C}$ comparing with Al–Si. Raising brazing temperature more than 700 $^{\circ}\text{C}$ resulted in reducing the contact angle for all the fillers containing Si or Mg. Mg content in the filler and the brazing conditions must be taken together into consideration when designing the brazing alloy, for example, Al–4Mg–0.5Si–0.4Mn alloy showed a good result of 117 MPa in torch brazing but produced only 61 MPa in vacuum brazing [30]. Another example, the vacuum brazing by Mg-containing filler alloys of 6% and 2.5% Mg showed almost identical strengths which were higher than the one using the Si-containing fillers [31]. Eckardt et al. [30] reported the formation of a variable and discontinuous intermetallic layer of TiAl₃ between the Al–Mg fillers and the titanium parent metal. In addition, it was reported that a thicker intermetallic layer was formed on Grade 5 titanium comparing with Grade 2 titanium. The high-Mg alloys did not show better fillet formation properties compared with the average-Mg braze alloy such as

TiBraze 665 which contains only 2.5% Mg [30]. Table 5 shows a summary of Ti/Ti–Ti/Al-brazed joints using Al–Mg-type filler alloys.

2.3.3. Al–Si-Type Filler Alloys. Takemoto and Okamoto [29] reported that the small addition of 0.2–0.8%Si is highly effective in suppressing the intermetallic layer growth of TiAl₃. However, further additions $\geq 3\%$ of Si increased the intermetallic thickness and promoted the formation of additional intermetallic compounds: $\text{Ti}_9\text{Al}_{23}$ and $\text{Ti}_7\text{Al}_5\text{Si}_{12}$ at the interface, where $\text{Ti}_7\text{Al}_5\text{Si}_{12}$ was adjacent to the titanium parent side. Using Al–10Si–1Mg mainly produced $\text{Ti}_7\text{Al}_5\text{Si}_{12}$ and a small quantity of $\text{Ti}_9\text{Al}_{23}$ intermetallic compounds. The best result of tensile test was for Al–10Si–1Mg comparing with the other two filler materials Al–10Cu–8Sn and Al–30Ag–10Cu. It was found that the fracture occurred within the filler metal when using Al–10Si–1Mg [29]. Under almost similar conditions, but for longer brazing time, Sohn et al. [34] investigated the diffusion brazing of Al/Ti joint by Al–10Si–1Mg. The bonding at the Ti/filler interface started as soon as the filler had been melted; two intermetallic compounds were observed, the continuous $\text{Ti}_7\text{Al}_5\text{Si}_{12}$ at the titanium side, which increased by the time due to the diffusion of Si into Ti, and the discontinuous one $\text{Ti}_5\text{Al}_{12}\text{Si}_3$ at the filler side and the fracture occurred in Al layer. In ultrasound brazing of titanium, two intermetallic compounds $\text{Ti}_9\text{Al}_{23}$ and $\text{Ti}_7\text{Al}_5\text{Si}_{12}$ were formed at Ti–6Al–4V/Al–12Si filler interface [39]. The intermetallic IMC-A ($\text{Ti}_7\text{Al}_5\text{Si}_{12}$) formed at the pit edge during the first USV, while IMC-B ($\text{Ti}_9\text{Al}_{23}$) at the wall and the bottom of the pit. Applying holding time for 5 min caused the IMC-A ($\text{Ti}_7\text{Al}_5\text{Si}_{12}$) to form at the interface between IMC-B ($\text{Ti}_9\text{Al}_{23}$) and Ti–6Al–4V; by increasing the holding time to 15 min, the thickness of IMC-B ($\text{Ti}_9\text{Al}_{23}$) increased (Figure 4). Wells [41] reported that the Al–7.5%Si alloy clad to a core of aluminum alloy 6951, which did not melt during brazing, produced stronger joint than 63Al–32Cu–5Ag–0.01Li for Grade 5 Ti. However, Khorunov et al. [31] found that Mg-containing filler alloys provided higher joint strength than the Si-containing filler alloy (5.3% Si), which was explained by the solidification of the silicide

TABLE 5: Ti/Ti-Ti/Al-brazed joints using Al-Mg-type filler alloys.

References	Materials		Parent 1	Parent 2	Filler Type	Thickness/gap width (μm)	Conditions	Bonding		Intermetallic compounds at Ti/filler interface
								Temperature ($^{\circ}\text{C}$)	Time (min)	
[33]*	Ti	Ti	Ti		61S(Al (6061)) (Al-1Mg-0.6Si-0.25Cu-0.25Cr)	76	Argon (furnace) Torch with flux	$\sim 679-707^{**}$	5	73.8-115.7
[29]	Pure Ti	Pure Ti			Al-1Mg	100	Vacuum of 2.7×10^{-3} Pa	680	3	44.8-88.9
[30]	Ti Grade 5, 2	Ti Grade 5, 2			Al-4.5Mg-0.4Si-0.1Cr	800	Vacuum/torch with flux	>638 liquidus temperature		Poor result
[3]	Ti Grade 5, 2	Ti Grade 5, 2			Al-4Mg-0.5Si-0.4Mn	500	Vacuum/torch with flux	>640 liquidus temperature		61 in vacuum and 117 by the torch
					TiBraz Al-665 (Al-2.5Mg-0.3Cr)	100	Vacuum/torch	680		110.4 G5 97.6 G2
					Al-4Mg-0.5Si-0.4Mn AMg6	320	with flux	650-700		98.8 G5 77.4 G2
					(Al-6Mg-0.6Mn-0.4Si-0.4Fe-0.1Ti)	60		685		82
[31]	OT4 titanium	OT4 titanium			AMg6 (Al-6Mg-0.6Mn-0.4Si-0.4Fe-0.1Ti)	60	Vacuum 5×10^{-5} mmHg	720	3	40
					Al-2.5Mg-0.2Si-0.4Fe-0.2Cr	100		685		83
[84]	Ti Grade 2/Grade 12	Ti Grade 2/Grade 12			TiBraz Al-645 (Al-5Mg-0.2Si-0.2Ti)	<25	EB + vacuum	$>$ melting point	0.5-0.75	
							Ultrasound- assisted induction brazing in air			
[37]	Ti Grade 5	Ti Grade 5			TiBraz Al-665 (Al-2.5Mg-0.3Cr)	100		660	5 sec USV	50-60
							Ultrasound- assisted induction brazing in air			
[38]	Ti Grade 2	Ti Grade 2			TiBraz Al-665A (Al-2.5Mg-0.3Cr)	50		670	5 min in 560 $^{\circ}\text{C}$ + 3 min in 670 $^{\circ}\text{C}$ + 6 s USV	~ 64
										Ti ₃ Al

* A double-lap joint. ** Considering 1205 $^{\circ}\text{F}$ is the liquidus temperature [88].

TABLE 6: Ti/Ti-Ti/Al-brazed joints using Al-Si-type filler alloys.

References	Materials			Filler	Thickness/gap width (μm)	Conditions	Bonding		Shear strength (MPa)	Intermetallic compounds at Ti/filler interface
	Parent 1	Parent 2	Type				Temperature ($^{\circ}\text{C}$)	Time (min)		
[34]*	CP-Ti	Al (1050)	Al-10Si-1Mg	100	Vacuum 10^{-4} Torr	620	25	84	$\text{Ti}_7\text{Al}_5\text{Si}_{12}$, $\text{Ti}_5\text{Al}_{12}\text{Si}_3$	
[29]	Pure Ti	Pure Ti	Al-(0.1-10)Si	100	Vacuum 2.7×10^{-3} Pa	680	3	~94 for Al-0.8Si	TiAl_3^{**} , $\text{Ti}_9\text{Al}_{23}$, $\text{Ti}_7\text{Al}_5\text{Si}_{12}$	
[28]	Pure Ti	Al (3003)	Al-10Si-0.5Mg	100	Vacuum	600	3	~70	$\text{Ti}_7\text{Al}_5\text{Si}_{12}$, $\text{Ti}_9\text{Al}_{23}^{***}$	
[3]	Ti Grade 5, 2 OT4 titanium	Ti Grade 5, 2 OT4 titanium	AWS BAISI-4 (Al-12Si-0.8Fe)	80	Vacuum/torch with flux	600-620		74.2 G5 69.6 G2		
[31]			Al-5.3Si-0.8Fe-0.3Cu-0.2Ti	100	Vacuum 5×10^{-5} mmHg	685	3	56	Continuous silicide	
[89]	Ti Grade 5	Al (6060)	Al-8.4Si-20Cu-10Ge-0.1Re	200	Vacuum + argon	530	10/30/60	49/55/48	$\text{Ti}_7\text{Al}_5\text{Si}_{12}$	
			Al-8.4Si-20Cu-10Ge			530	10/30/60	23/17/20	$\text{Ti}_7\text{Al}_5\text{Si}_{12}$	
[35]	Ti50-Al50	Ti50-Al50	BAISI-4 (Al-(11-13) Si-0.3Cu-0.1Mg-0.2Zn-0.15Mn-0.8Fe)	75	Vacuum 8×10^{-5} mbar	900****	3	86.2	$\text{Ti}_5\text{Al}_{12}\text{Si}_3 + (\text{TiAl}_2$ for longer brazing time)	
[84]	Ti Grade 2/Grade 12	Ti Grade 2/Grade 12	TiBraze Al-642 (Al-5.3Si-0.8Fe-0.2Ti)	<25	EB + vacuum	>melting point	0.5-0.75			
[39]	Ti Grade 5	Al1060	Al-12Si		Ultrasound-assisted brazing in air	620	4 sec USV 15 or 5 min + 4 or 0 sec USV	~68	$\text{Ti}_7\text{Al}_5\text{Si}_{12}$, $\text{Ti}_9\text{Al}_{23}$	

*Transient liquid phase bonding. **For Al-0.1Si/3 min, only Al₃Ti was observed. ***Very weak diffraction line was observed for Ti₉Al₂₃. ****Infrared brazing 900°C/min.

TABLE 7: Ti/Ti-Ti/Al-brazed joints using Al-Cu-type filler alloys.

References	Materials		Filler	Thickness/gap width (μm)	Conditions	Bonding		Shear strength (MPa)	Intermetallic compounds at Ti/filler interface
	Parent 1	Parent 2	Type			Temperature ($^{\circ}\text{C}$)	Time (min)		
[29]	Pure Ti	Pure Ti	Al-1Cu	100	Vacuum 2.7×10^{-3} Pa	680	3		
[28]	Pure Ti	Pure Ti (3003)	Al-10Cu-8Sn	100	Vacuum	615	5	~38	TiAl ₃ , Ti ₈ CuAl ₂₃ *
[29]	Pure Ti	Pure Ti (3003)	Al-33Cu	100	Vacuum 2.7×10^{-3} Pa	630	3		TiAl ₃
[30]	Ti Grade 5, Grade 2	Ti Grade 5, Grade 2	TiBraz Al-635 (Al-4.2Cu-1.5Mg-0.5Si)	300	Vacuum/torch with flux	>638 liquidus temperature		140 in vacuum and 88 by the torch	TiAl ₃ , larger on Grade 5
[3]	Ti Grade 5, Grade 2	Ti Grade 5, Grade 2	TiBraz Al-635 (Al-4.2Cu-1.5Mg-0.5Si)	200	Vacuum/torch with flux	660-700		140.7 G5 100.8 G2	TiAl ₃ , larger on Grade 5
	Ti Grade 5, Grade 2	Ti Grade 5, Grade 2	Al-25Cu-9Si	100	Vacuum/torch with flux	580-620		88.6 G5 34.1 G2	
	Ti Grade 2	Ti Grade 2	Al-24Cu-8.6Si-3.5Sn	150		580-620		47.7	
(Cited in [2])	Ti6Al4V	Ti6Al4V	Al-33Cu	6-20	Air	550		25	
[55]	Ti Grade 5	Al (6061)	Al-9.4Si-10Zn-10Cu-2Ni				4 sec USV + 60 min + 4 sec USV	~43	Ti ₇ Al ₅ Si ₁₂
				~200	Ultrasound-assisted induction brazing in air	560	4 sec USV + 15 min + 4 sec USV	~76	Ti ₇ Al ₅ Si ₁₂
[40]	Ti-5 (95%)	Ti-5 (95%)	Al-15Sn-8.2Si-8.5Zn-8.5Cu-1.7Ni						
			Al-8.54Cu-1.35Ni-0.08Ti						
			Al-6.44Cu-1.96Ni-0.92Ti	100	By applying pressure/in air	647	13	74.78	
						648	9	73.66	

*Very weak diffraction line was observed for Ti₈CuAl₂₃.

TABLE 8: Ti/Ti-Ti/Al-brazed joints using Al-Ag-type filler alloys.

References	Materials		Filler Type	Thickness/gap width (μm)	Conditions	Bonding		Shear strength (MPa)	Intermetallic compounds at Ti/filler interface
	Parent 1	Parent 2				Temperature ($^{\circ}\text{C}$)	Time (min)		
[28]	Pure Ti	Al (3003)	Al-20Ag-10Cu	100	Vacuum	600	5	~38	TiAl_3
[29]	Pure Ti	Al (3003)	Al-33Ag	100	Vacuum 2.7×10^{-3} Pa	630	3		TiAl_3
[30]	Ti Grade 5, 2	Ti Grade 5, 2	Al-38Ag- 7.4Si-0.6Fe	260	Vacuum/torch with flux	>580 liquidus temperature		Poor result	$\text{Ti}_7\text{Al}_5\text{Si}_{12}$ **
[3]	Ti Grade 2	Ti Grade 2	Al-28Ag	Powder +325/-100 mesh	Vacuum/torch with flux	600-620		70	
			Al-28.5Ag- 21Cu-1.3Mg	260		650-710		67.6	

**Another undetermined very thin one.

TABLE 9: Ti/Ti-brazed joints using Al-Ni- and Al-Mn-type filler alloys.

References	Materials		Filler Type	Thickness/gap width (μm)	Conditions	Bonding		Shear strength (MPa)	Intermetallic compounds at Ti/filler interface
	Parent 1	Parent 2				Temperature ($^{\circ}\text{C}$)	Time (min)		
[29]	Pure Ti	Pure Ti	Al-1Mn, Al-1Ni	100	Vacuum 2.7×10^{-3} Pa	680	3		
[30]	Ti Grade 5, 2	Ti Grade 5, 2	TiBraz Al-700 (Al-21.5Ni-9Cu- 9.6Si-1.3Fe-0.6Mn)	300	Vacuum/torch with flux	≥ 607		93 in vacuum and poor result by torch	$\text{Ti}_9\text{Al}_{23}$, $\text{Ti}_7\text{Al}_5\text{Si}_{12}$
[3]	Ti Grade 5, 2	Ti Grade 5, 2	TiBraz Al-700 (Al-21.5Ni-9Cu-9.6Si)	290	Vacuum/torch with flux	700-720		127.3 G5 81.6 G2	$\text{Ti}_9\text{Al}_{23}$, $\text{Ti}_7\text{Al}_5\text{Si}_{12}$
Cited in [2]	Ti Grade 5	Ti Grade 5	Al-1.2Mn-0.6Si-0.7Fe- 0.2Cu			>660		89	

as a continuous strip at the brazing interface. Table 6 shows a summary of Ti/Ti-Ti/Al brazed joints using Al-Si-type filler alloys.

2.3.4. Al-Cu- and Al-Ag-Type Filler Alloys. Al-Cu and Al-Ag promoted mainly TiAl_3 formation at the brazed interface of titanium. Adding Sn did not change the intermetallic type since Al-10Cu-8Sn filler metal mainly promoted TiAl_3 formation in Al(A1100)/Ti joints and very weak diffraction line corresponding to $\text{Ti}_8\text{CuAl}_{23}$. However, high peak of Sn at the interface was showed by EDX line analysis, and the fracture occurred within the intermetallic compound [29]. In a different manner, the existence of Si in the filler changes the intermetallic type; Chen et al. [55] reported the formation of the intermetallic $\text{Ti}_7\text{Al}_5\text{Si}_{12}$ at the interface between the Grade 5 Ti and each of Al-9.4Si-10Zn-10Cu-2Ni and Al-15Sn-8.2Si-8.5Zn-8.5Cu-1.7Ni fillers; it was concluded that the addition of Sn improved the strength through reducing the residual thermal stress.

Eckardt et al. [30] found that the filler alloy TiBraz Al-635 (Al-4.2Cu-1.5Mg-0.5Mn-0.5Si) had the lowest contact angle on Grade 5 Ti and a good one (second-lowest one) on Grade 2 Ti with the highest strength among the other alloys of Al-Ag, Al-Mg, and Ag-Cu-Zn-(Cd-Sn) using vacuum brazing. The interlayer between the parent metal and the filler TiBraz Al-635 consisted of variable and discontinuous layer of TiAl_3 . According to Wells [41], the addition of Mg or the small addition of Li to the filler metal improved the flow characteristics of Al-Cu-(5-50)Ag-type alloys; on the other hand, alloying with Mg significantly decreased the corrosion resistance of the joints. Si and/or Sn-containing filler metals formed weaker joints or exhibited flow temperature of $\sim 587^{\circ}\text{C}$ (860 K) or higher. It was found that the flow temperature for the Al-Cu-Ag alloys varied with the employed atmosphere; flow temperatures were 111°C higher in the vacuum than in 6.6×10^4 Pa of argon. In brazing damage-tolerant titanium structures, Al-Cu-Ag filler materials prevent the cracks from spreading by delamination in the crack arrest orientation. The behavior in the crack divider

orientation was similar to the behavior of the monolithic material [41]. Tables 7 and 8 show a summary of Ti/Ti–Ti/Al-brazed joints using Al–Cu and Al–Ag-type filler alloys, respectively.

2.3.5. Al–Ni, Al–Mn, and Other Types of Filler Alloys. Nickel addition to the pure aluminum filler had a little effect on the suppression of the intermetallic layer at the Ti/filler interface, whereas Mn addition showed a better result [29]. However, nickel addition to Al–Cu–Ti filler together with a decrease in copper ratio increased the shear strength [40]. Ge improved the corrosion resistance when added to the Al–Cu- and Al–Cu–Ag-type alloys but formed very fragile joints [41]. Table 9 shows a summary of Ti/Ti-brazed joints using Al–Ni- and Al–Mn-type filler alloys.

3. Conclusions and Future Work

In this review, the aluminum-based filler alloys for brazing titanium and the formation of the intermetallic compounds at the interface of Ti/filler have been analyzed. The proper design of time-temperature cycle and the controlled alloying additions in the aluminum filler are crucial factors for the intermetallic compound formation at the interface. The thickness and type of the intermetallic phases will largely determine the mechanical properties of the brazed joint. In the case of brazing Ti/Al joints, further decrease in brazing temperature, adequate time-temperature cycle, and the compatibility of the brazing filler on the both Ti/Al sides should be considered thoroughly.

Several technological parameters have been examined for ultrasound-assisted brazing of titanium by Al-based filler alloys, including the acoustic power, the USV period, the holding time, the filler thickness, and the brazing temperature; accordingly, the following points should be highlighted:

- (i) The holding time after USV is necessary for the diffusion process proceeding at the interface between the filler and the titanium parent metal.
- (ii) Varying the power of the ultrasound affects the oxide removal at the filler/parent metal interface directly.
- (iii) The thickness of the filler should be chosen according to USV parameters and time-temperature brazing cycle; considering the accelerated interaction between the liquid filler and the parent metal by the effect of USV.
- (iv) Brazing and ultrasound parameters/conditions should be considered together in ultrasound-assisted brazing process, for instance, the ultrasonic power/intensity, the coupling method of the ultrasound with the workpiece which insures the excellent delivery of the USV to the joint area, the USV activation time, and other traditional brazing parameters.
- (v) Studying the USV effects on the microstructure of the brazed joint should be given more attention.

Brazing process has many factors that should be considered to achieve the best possible mechanical properties of the produced joint; the quality of the filler material is one of these factors. Different processes are available for aluminum filler production; the casting process is used as a favorite way to produce new filler aluminum alloys or known ones of lab-scale size for testing purposes. However, the properties and the quality of the cast affect the mechanical properties and the quality of the final brazing joint. The impact of the cast defects and the imperfections varied according to the form of the brazing filler alloy and the brazing process. The filler alloy, as a primary consideration, should have homogeneous chemical composition, with controlled or free of inclusions, and free of porosity. Using USV in the preparation and developing specific, low-melting temperature filler alloys for brazing process from their pure elements would be a great tool in enhancing the filler alloy properties, accelerating the process, and thus, exploring more compatible brazing fillers. Due to the limited works in ultrasound-assisted brazing of Ti by Al-based fillers and the mechanical properties of the produced joints, it is tempting to investigate and seeking to develop further compositions of the Al-based fillers which can be more adequate for ultrasound-assisted brazing of Ti and to conduct deeper studies considering the integration between the USV and the traditional brazing parameters.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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