ELECTRON BEAM BRAZING OF TITANIUM FOR CONSTRUCTION IN SPACE

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Abstract

An extended presence of humans in space requires an in-situ capability to construct various permanent structures to support scientific research, power generation, communication, radiation shielding and other functions. Electron Beam (EB) vacuum brazing has been identified as one of the best joining processes for in-space joining, particular for making a large quantity of permanent joints as required for construction of the sizeable truss structures. Thin wall titanium tubes are perhaps the best choice because of their high stiffness, excellent strength-to-weight ratio and great metal forming and joining ability. An innovative EB vacuum spot brazing process is being developed at Goddard Space Flight Center to be used for robotic as well as human-assisted construction in space. This paper describes experimental results obtained during the initial effort of EB brazing of titanium tubes with the special emphasis on low temperature aluminum filler metals.

Introduction

Large space-based telescopes, antennas and power generation systems as well as radiation shielding and support structures on the surface of Moon require an in-situ capability to make permanent and rigid joints [1]. In additions, the joint design and the joining process must be easily adaptable for semi-automated or fully robotic operation. This latter condition is needed in order to avoid the exposure of humans to a very high radiation during the prolonged period of construction in open space.

Welding and brazing are the only two processes outside mechanical fastening that provide permanent, rigid and non-degradable joints in space. Among various brazing processes available today for joining metallic components, EB brazing is perhaps the best choice for in-space construction, when one considers such factors as heritage, energy efficiency of the process, simplicity, "friendliness" for automation, ability to join ultra-thin components and the fact that the vacuum of space is a natural environment for the electron beam process [2].

EB Brazing System

Experimental EB brazing system was designed and assembled to develop an EB brazing process for construction in space, see Fig.1. The EB gun and the sample manipulating holder are mounted inside the bell jar chamber. The gun can generate a maximum of 50 mA of beam current at 10 kV. This amounts to 500 Watt of power. For joining thin-wall titanium tubing,

300 Watts or even less power is sufficient to rapidly reach the brazing temperature interval. In the present setup, the electron beam is stationary, but the sample can move. The computer controlled sample holder has a linear translation as well as the rotational movement capability.
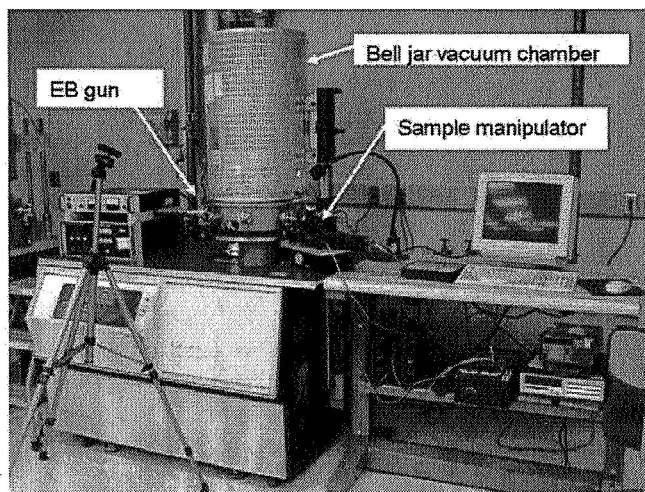

Fig. 1 EB brazing system at Goddard.

Brazing Process

The effort of developing EB brazing process for in-space assembly is still at its very early stage. Only the test specimens consisting of tubular joints have been brazed so far. Titanium Grade 2 and 12 thin wall tubes were selected for the based metal. The EB beam application and the sample configuration are shown schematically in Fig. 2.

The brazing filler metal in the form of a wire ring is pre-placed into the internal pocket prior to brazing as shown in Fig.3. To date, several silver-based and aluminum-based filler metals shown in Table below have been tried.

Filler Metals

Name	Composition	Supplier
GAPASIL-9	81Ag-10Pd-9Ga	Morgan Adv. Ceramics
TiBrazeAl-642	Al-5.3Si-0.8Fe-0.2Ti	Titanium Brazing, Inc
TiBrazeAl-645	Al-5Mg-0.2Si-0.2Ti	Titanium Brazing, inc.

GAPASIL-9 was selected as the most commonly used silver-based filler metal for brazing titanium alloys in applications that are not subjected to high temperature service and/or high

corrosion resistance requirements [3, 4] The main interest of the current effort, however, is focused on the low temperature filler metals. Using low melting point filler metals consumes less power. Energy efficiency is a very important factor for any activity in space, including brazing.
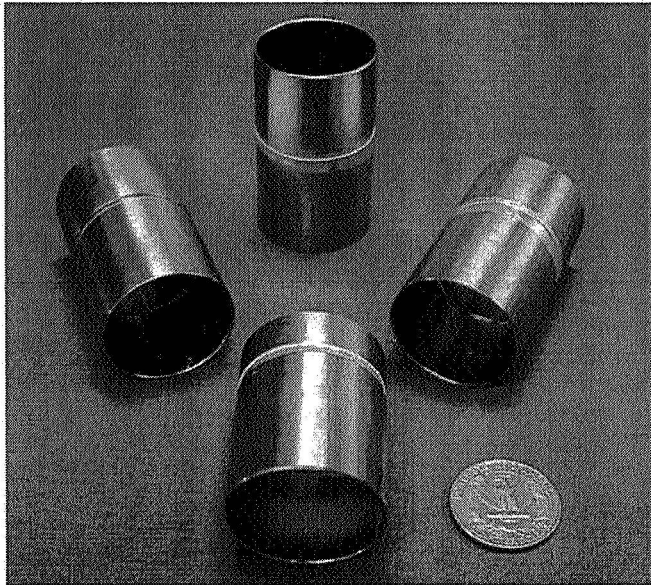

Fig. 2 Lap shear tube specimens EB brazed at Goddard.

The duration of the brazing cycle was measured using the stop watch. The start of the cycle represents the moment when the 40 mA current electron beam starts impinging on the braze assembly. The watch is stopped when the molten filler metal appears on the opposite end of the brazed joint. The brazing cycle, from start to finish, varied between 60 – 90 seconds for the silver-based filler and between 30 – 45 sec for the aluminum based alloys. EB current was between 30 - 40 mA, Voltage =10Kev.
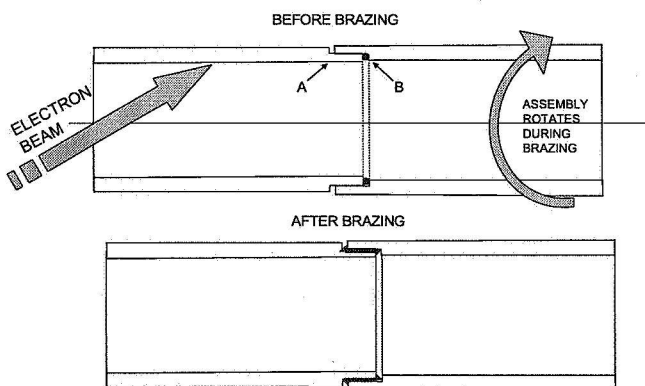

Fig. 3 Lap shear specimen design. The filler metal ring is pre-placed in the gap at location B. Electron beam is applied to the inside surface of the tube in front of location A.

Due to some ambiguity of measuring a duration of brazing cycle, the exact time within the braze interval is not known. The design of the EB gun used for this work did not have an EB deflection capability. Consequently, in order to apply the

heat uniformly around the entire braze joint, the whole assembly had to rotate, as shown in Fig.3 This presented a practical problem of measuring specimen temperature with a conventional contact-type thermocouples. Future plans include the development of a new brazing EB gun capable of deflecting EB in such a way that the braze assembly could be kept stationary allowing for the use of thermocouples enabling a more accurate determination of temperatures during the braze cycle.
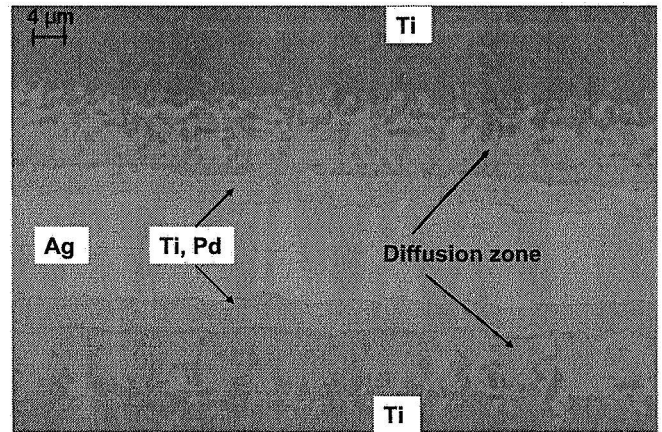

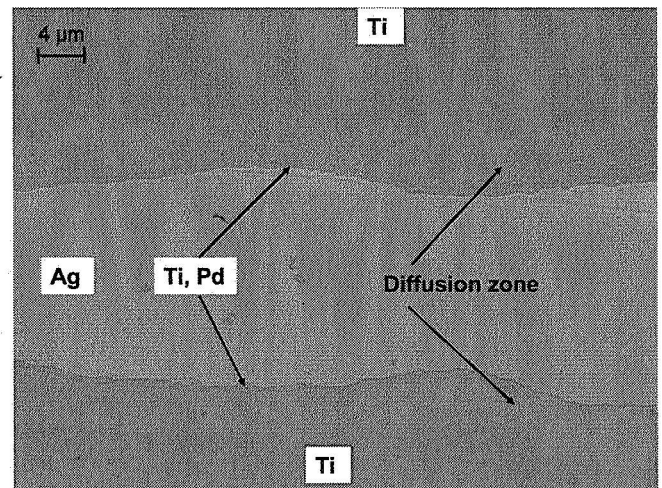Fig. 4a Cross section of the vacuum furnace brazed joint using GAPASIL-9 filler metal.

Fig. 4b Ti-GAPASIL-9-Ti joint as in Fig.4a, but brazed using EB process. Note the Ti-Pd compound layer at the interface is much thinner than in furnace brazed joint.

The specimens were machined to have a tight fit during the assembly prior to brazing. The clearance was kept under 25 μm (0.001 in). A tight fit is required in order to assure the integrity of the assembly during brazing as well as the heat transfer from the inner tube into the outer one. As the electron beam starts heating the inner tube, the latter expands and reduces the gap even more.

The EB brazed test specimens were cross sectioned and metallographically examined using optical and scanning electron microscopy. Also examined were identically prepared test specimens, but brazed in the vacuum furnace instead. The

latter was done to compare conventional furnace brazing with the more rapid EB brazing process. Figures 4-6 show the typical cross sections of the test specimens
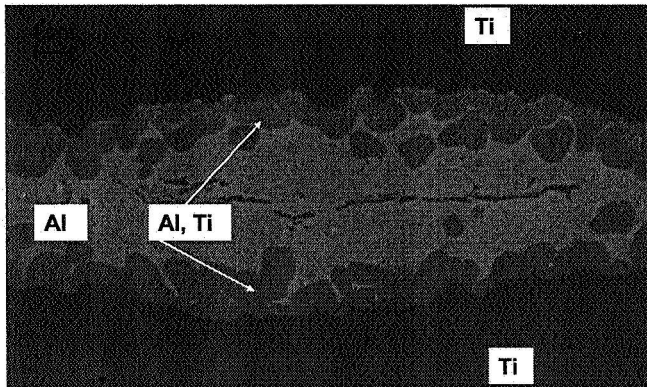
Fig. 5 Cross section of Ti to Ti joints EB brazed using Aluminum –Magnesium filler metal TiBAl-645. Note the absence of magnesium in the interface layer, consisting of Al and Ti. Magnesium is still finely dispersed in Al matrix.
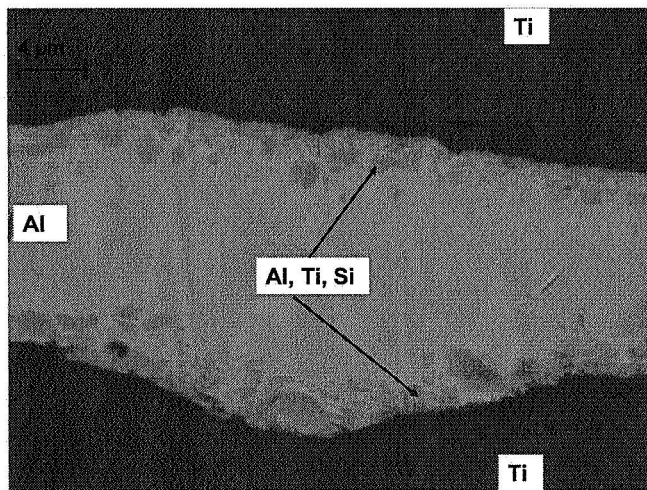
Fig. 6 Ti to Ti joint EB brazed using Al-Si filler metal TiBAl-642. In this case, an Al-Ti intermetallic compound formed at the Ti interface has also some Si. Notice the morphology of the compound is more angular and refined than in Fig.5.

Design

A number of studies and analysis of the large space-based assets such as large aperture telescopes, solar power satellites indicate that truss structures can meet such design requirements as high strength-to-mass ratio, stiffness, low cost and simplicity in terms of assembly and joining methods [5-7]. Open node architecture combined with the "snap-n-braze" joint design being developed at Goddard [2] is intended for an automated construction of the large truss beams consisting of the thin-wall tubular struts brazed to the node elements, as shown in Fig.7-9. A filler metal can be pre-placed into the joint proper when the nodes are pre-fabricated on Earth. After the tubular strut is snapped in place, the tube is permanently joined to the node using EB spot brazing, as shown in Fig.9.

Using very simple calculations, it is easy to estimate the approximate area of the brazed joints required to produce the joints at least as strong as the base metal. For example, considering only a static overload in tension to be the dominant failure mode, the area of the brazed joint shown in Fig.9 can be estimated as follows:

$$A_T * \sigma_Y * K = A_B * \tau_{avg}, \qquad (1)$$

Where A_T is the cross sectional area of the tube, σ_Y is the yield tensile strength of the base metal, K is the knock-down factor that takes into consideration safety margin, joint efficiency, etc., A_B is the brazed joint area and τ_{avg} is the average shear strength of the brazed joint. If we use conservative values of 275 Mpa (40Ksi) yield strength of the Grade 2 titanium, 48.3 Mpa (7Ksi) for the average shear strength of the brazed joint with aluminum-based filler metal (8), 0.25 mm (0.010 in) tube wall thickness, 25 mm (1 in) tube outside diameter and let $K = 2$, the total area of the brazed joint would have to be $A_B = 707$ mm^2 (1.1 in^2). If we assume the thickness of the node plate to be 3 mm (0.125 in), the overlap length of the brazed joint would be about 4 cm (1.5 in).
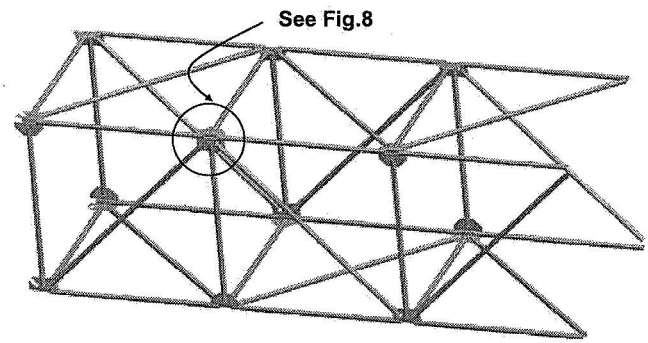
Fig. 7 An example of rectangular truss desing being developed at Goddard.
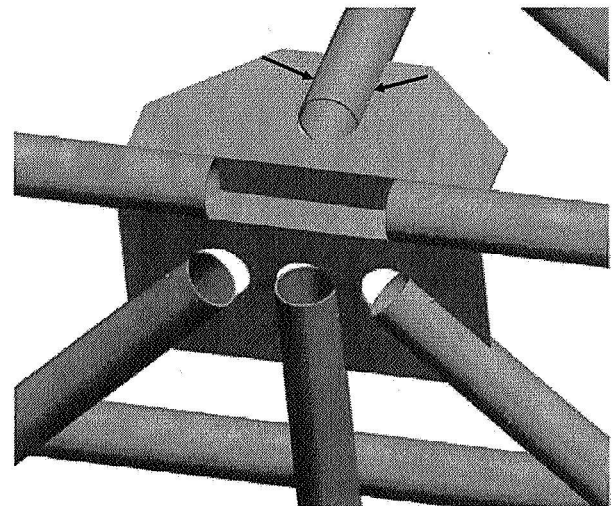
Fig. 8 A close-up of the six-way node from Fig.7.The arrows point to the typical locations where the filler metal would be pre-placed prior to launch and assembly.

$$A_b = 2 \times L \times t$$
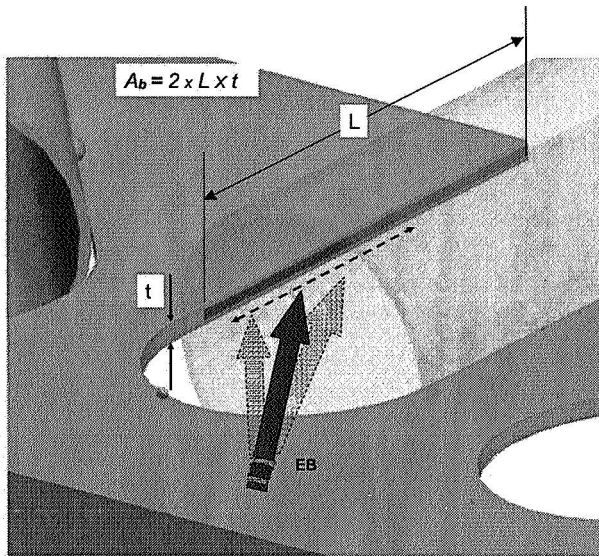
Fig. 9 A detailed view of the braze joint showing an application of the Electron Beam and its deflection along the joint. In this case, a strip of filler metal (green) is pre-placed into the slot machined in the fitting.

Discussion

The development of EB brazing of the thin-gage titanium components, described in this paper, is still at its very early phase. However, the limited results obtained at Goddard to-date are quite promising. The EB process can be made as rapid as the induction brazing. Only a very specialized process such as resistance spot brazing (a variant of the resistance spot welding) used in electronic industry is faster than the EB or induction brazing. Very short brazing cycle helps to minimize or completely eliminate erosion of the base metal by the molten filler alloy, reduce or eliminate volatilization of alloying (active) elements present in brazing filler metal and make the brazing process less sensitive to the various contaminants that may be present in the atmosphere during brazing. The latter is of particular importance if the EB brazing process to take place on the surface of other planets. Finally, a rapid brazing process will help to reduce a total construction time during the assembly process of a large truss structure in space.

Preliminary observations of the joint formation during EB brazing of the thin-wall tubular specimens indicate that the method of applying electron beam only to one side of the braze joints as described earlier (see Fig.3) is working quite well. An excellent filler metal fluidity and its complete penetration by capillary action through the entire length of the braze joint is demonstrated even for a higher melting point silver-based filler metal as GAPASIL-9. In vacuum furnace brazing, GAPASIL-9 is somewhat sluggish and is typically pre-placed into the joint proper prior to brazing. The EB brazing demonstrated that the capillary action is so vigorous that even GAPASIL-9 filler metal penetrates through the braze joint with practically zero gap!

The microstructure of the test joints EB brazed with GAPASIL-9 filler metal appears to be similar to the brazed joints produced by conventional vacuum furnace brazing process. A layer of Ti-Pd compound is formed on titanium along the entire interface as has been reported previously [3] regardless of the process used. In the EB brazed joints, however, this layer appears to be much thinner, see Fig. 4. The morphology of the diffusion zone in the EB brazed joints appears to be more refined compare to the furnace brazed specimens. A wavy pattern of the interface line in EB brazed joints is caused by the machining marks.

The microstructure of the brazed joints containing aluminum-based filler metals also reveals an intermetallic layers formed on titanium interfaces. Energy Dispersive X-ray (EDX) analysis indicate that these layer are a Ti-Al-Si compounds for Al-Si filler metal and Ti-Al for Al-Mg filler alloy, as reported in previous publications [8]. More work is needed to determine how the braze gap size, the braze time and other EB brazing process variables affect the formation of these interfacial layers so the best combination of strength and ductility of the brazed joint could be obtained.

An application of the heat only to one side of the brazed joints adds another variable to a long list of other parameters influencing the brazing process. This variable is the temperature difference ΔT between the hottest or leading edge of the joint and the coldest or trailing edge. The higher ΔT, the higher the driving force of the capillary flow of the liquid filler metal through the braze gap. The driving force can be viewed as an additional pressure ΔP on the liquid in the capillary gap. The expression for ΔP in the parallel gap [9] during isothermal case can be modified to account for the temperature difference ΔT:

$$\Delta P = 2(Y_{lv} * \cos \Theta) * f(\Delta T) / D, \qquad (2)$$

Where Y_{lv} the liquid surface tension, Θ is the contact angle, D is the braze gap and $f(\Delta T)$ represents an influence of ΔT. An attempt to define the function $f(\Delta T)$ will be made during the future work.

Finally, the EB brazing of the tube assemblies showed that there is no need for a precision accuracy in pointing electron beam to any particular location at the braze joint. As long as the beam is applied to a location in a close proximity to the joint, the heat propagates through and melts the filler metal resulting in formation of the brazed joint. Consequently, the process does not require a highly trained operator to perform the EB brazing. This is very advantageous for an autonomous construction and assembly in space. Temperature control may be a critical factor in controlling the microstructure and properties of the EB brazed joints. Future work will address the effect of base metal overheating on possible base metal dissolution and homogenuity of the alloy distribution in the filler metal within the brazed joint.

Conclusion

Preliminary results of EB brazing thin gage titanium components indicate that this joining method holds a big promise for in-space construction of multi joint truss structures. More work is needed to evaluate the properties of the EB brazed joints, optimize the braze process to have a best combination of the duration time, energy consumed and the performance achieved. Future work will include an even lower melting point filler metals, such as 80Au-20Sn, for example, to reduce the amount of energy and time required to make a brazed joint. Also, more work is need to optimize the design of the braze joint to make it as "robot"-friendly as possible.

Acknowledgements

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