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TiAl SHEET DEVELOPMENT
for
AXISYMMETRIC HYPERSONIC STRUCTURES

FINAL REPORT

Prepared for

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TiAl Sheet Development for Axisymmetric Hypersonic Structures

Introduction:

TiAl sheet structures have the potential to reduce hypersonic propulsion system weights as a result of low density, and high temperature capability. This is, therefore, a very important technology to weight driven systems such as hypersonic cruise missiles and reusable launch vehicles. This program is intended to develop axisymmetric structural technology necessary for a lightweight component demonstration. This effort focuses on key manufacturing processes, subcomponent feasibility, and finally, component demonstration.

Task 1-Laser Beam Welding:

Titanium aluminides are characterized by low ductility at room temperature and are difficult to weld by arc, spot, friction and electron beam methods unless proper thermal management is incorporated during such procedures. Since titanium alloys are reactive at elevated temperatures, precautions must be taken to shield the joints from air.

Under the NASA GRC Enabling Materials Propulsion (EPM) nozzle program, welding of cast gamma TiAl was demonstrated by both gas tungsten arc welding (GTAW) and electron beam welding methods. However, very little is known about welding of gamma TiAl sheets, thickness of which may vary from 20- 80 mils. The grain size of cast gamma is very large (> 300 microns) and has the lamellar microstructure. In contrast, the grain size of as-rolled gamma sheets is small (~12 microns) and the microstructure is near-gamma TiAl with small volume fraction of Ti3Al being present.

Laser beam welding is a promising alternative since laser beam offers an easily maneuvered, chemically clean, high-intensity, atmospheric welding process that produces deep-penetration welds with a narrow HAZ and subsequent low distortion.

The objectives of this task are: (1) Investigate laser beam welding of sheet gamma as a function of preheating of the substrate, laser beam intensity, rate of welding, and the environment (vacuum, argon, and helium) followed by postweld stress relief in order to achieve an optimum conditions for laser weld; (2) Once an optimum condition for laser beam welding has been established, fabricate both butt and lap welding specimens such as square-groove butt joint, single-groove butt joint, double-V-groove butt joint, and single-U-groove butt joints. These specimens will then undergo mechanical testing. Commonly, bend test is conducted to evaluate the weldment, and (3) Conduct postweld evaluation by visual examination, fluorescence penetrant inspection, and x-ray radiography methods. In addition, microstructure of the weldments and post fracture evaluation will be made by optical and scanning electron microscopy.

Results:

The laser welding work was contracted to Dynamic Gunver Technologies (DGT), Connecticut known for their expertise in laser welding. Due to time constraint and a loss of a key technical person, the laser welding of sheet gamma TiAl work was performed at Acceleron, Inc., Connecticut acting as a subcontractor to DGT. The laser welding work was conducted using powder metallurgy (PM) gamma-met sheet. A PM sheet, 12" x 12" x 0.040", and some gamma-met RSR powders were supplied to DGT for this effort. Joining of ingot metallurgy (IM) gamma-met sheets was also planned but these sheets were not available in time from Plansee, Austria.

A Lasag Nd:YAG laser unit was used for this activity. It has two energy delivery systems, fiber and fixed optics, with a maximum power of 400 W pulsed. The laser is controlled by Lasag software and incorporates an Aerotec mmi500 CNC controller for motion control. Initial experiments with a CO_2 laser unit were not successful.

Room Temperature Laser Hole Drilling:

Drilling of small holes ~ 20 mils in diameter or less in thin gamma TiAl sheets by laser is thought to be a cheaper alternative to EDM and EB processes. All these processes leave behind re-cast layers consisting of fine cracks, which are a problem for low ductility materials like gamma TiAl.

The sheet material was supported on the edges and laser drilled at room temperature with the work piece blanketed by argon shielding gas. Rather than make a tre-pan cut (cut the circumference), the laser was used to percussion drill the material. This technique continuously hits the material with a high-energy laser pulse and forces its way through the material. Although drilling of hole with laser was successful, microcracks were observed stemming from the recast layer on both entrance and exit sides of the hole. (See attached report of Acceleron, Inc for details). However, a collaborative research work between P&W and Lawrence Livermore National Laboratory (LLNL) has led to the development of conditions and parameters at which the laser beam will vaporize the material rapidly, thereby reducing the recast layer and the heat affected zone (1). For example, using improved laser procedure a recast layer of 0.4 mil was obtained in gamma TiAl sheets compared to ~ 1 mil for the EDM process. Additional effort to optimize conditions could result in a condition in which virtually a recast layer-free hole could be introduced in sheet gamma TiAl.

Elevated Temperature Laser Welding of Butt Joints:

A series of experiments were performed to observe the reaction of the gamma material to the laser beam in a simulated weld pass. Rather than trying to create a weld joint with two pieces of the material, initially the effort was made to run a pass on a solid test coupon. Soon it became evident that the material was extremely susceptible to cracking across the centerline of the pass and perpendicular to the centerline. Under the EPM/HSCT program we had successfully performed EB welding of gamma sheets only when the test pieces were preheated to elevated temperatures prior to EB welding. Based on this, it was decided that preheating of the test pieces would be necessary for a successful laser weld.

For butt joints, the test coupons of ~ 2" x 1.5" were laser cut from large blanks. These pieces were cut into two equal halves, 1"x1.5", by water-jet. In preparation for butt joint, the water-jet sectioned edges were polished with 400 grit SiC papers, and subsequently cleaned with acetone. However, the sides perpendicular to the polished edges were not polished.

The coupons were clamped in a fixture and heated to 500F in argon shielding gas. Only one sample was preheated to 700F. The laser power varied from 1.68 to 1.5 J, with a feed rate of 3.5 in/min. TiAl butt weldments of coupons 2" x 1.5" x 0.040" showed complete penetration with little distortion. They also revealed minimum oxidation on the surface, proving good shielding-gas coverage. However, all three butt joints done with a 500F preheat cracked following cooling to room temperature using very low cooling rates. An examination of the failed specimens revealed that the cracks have stemmed from the microcracks in the laser recast layer on the non polished surface (perpendicular to the weld). In contrast, the butt joint conducted with a 700F preheat survived without cracking. It is believed that higher preheat temperature may have reduced the propensity of cracking. More work is needed to fully understand the failure behavior following laser welding. Experiments such as stress-relief at elevated temperature immediately after laser welding should be studied in follow-on efforts. A detailed description of laser butt welding is available in the attached report of Acceleron, Inc.

In general, the top of the weld was convex, suggesting a slightly positive bead. On the bottom was a negligible undercut but not enough to merit filler. The microstructure of the weld was essentially a cast microstructure with fine lamellar grains. The microstructure varies as a function of the thickness of the butt joint, being very fine at the top and bottom of the weld and coarse at the center (Figure 1). This may be related to a faster cooling rate at the top and bottom of the weld. A number of pores, mostly spherical with sizes ranging from 0.0001" to 0.0008" were observed in the weld particularly in the areas adjacent to the heat affected zone (HAZ). It may be speculated that the shielding gas was strong enough to blow away the molten pool of gamma TiAl and entrap argon gas that reveals as pores. A small heat affected zone accompanied the weld, consistent with the observation of low distortion of the sheets. Also, it seemed that the microstructure of HAZ was finer the parent material. A microprobe study was conducted to determine the chemical composition at various locations across the weld as shown in Table I.

Table I. Chemical composition across the weld as determined by microprobe. Concentration in at.%

Location	Al	Ti	Cr	Nb	Ta	Total
Base metal	45.855	50.294	2.4582	0.9295	0.4639	100
HAZ	44.759	51.408	2.4114	0.9745	0.4472	100
Weld	42.864	53.118	2.3432	1.153	0.5226	100

It has been observed that there was a depletion of Al and an enhancement of Ti in the weld region compared to the matrix. This is consistent with a higher loss of low melting point Al (higher vapor pressure) during laser welding. It is also evident that the HAZ region has lost a small amount of Al compared to the parent material.

Figure 1d shows Vickers hardness variation across the weld. Average hardness values of various locations are shown in Table II. It appears that the weld displayed the highest hardness followed by the HAZ and the parent material. The hardness difference between the parent material and the weld can be explained in terms of microstructural differences between the two. The microstructure in the weld region consists of fully lamellar grains, which commonly display the highest hardness. In contrast, the parent material comprising mostly of fine gamma grains is characterized by low hardness. Higher hardness of the HAZ region compared to the parent material may be due to finer grain size in the HAZ region resulting from laser welding.

Table II. Average Vickers hardness across the weld

Location	Vickers Hardness Value
Base metal	402
HAZ	485
Weld	598

Task 2-SPF/DB:

Superplasticity is the ability of certain materials, primarily metals, to undergo unusually large amounts of uniform plastic deformation before local necking occurs. The remarkable formability of superplastic materials is due to their high strain-rate sensitivity. During the EPM nozzle program, it was demonstrated that gamma TiAl sheets are capable of superplastic forming. It is a relatively new process that offers unique advantages over conventional forming operations. For example, characteristics of superplastic forming include low flow stress, reduced machining, no springback, uniform metal flow, no resultant residual stresses, in general no cavitation, and formability of shapes not possible by any other approach.

Combining it with diffusion bonding can enhance the versatility of the superplastic forming process. Both processes require similar conditions, that is, heat, pressure, clean surfaces, and an inert environment. The combined process is referred to as superplastic forming/diffusion bonding (SPF/DB). The SPF/DB process has greatly extended the applicability of superplastic forming. Using SPF/DB, a sheet can be formed onto pre-placed details and diffusion bonded, or two or more sheets can be formed and bonded at selected locations. Diffusion bonding can be applied only to selected areas of a part by using a stop-off material that is placed between the sheets at locations where no bonding is desired. Yttria and BN have been successfully used as stop-off material.

The objective of this task was to fabricate three-sheet SPB/DB structure using sheet gamma TiAl in order to demonstrate the feasibility. The task consisted of making a TZM tooling followed by trial runs. Both metallography and NDE techniques such as UT scans and thermography were used to characterize the bond.

Results:

Initial attempts involving SPF/DB were done using 2-sheet approach involving PM gamma-met material with a sheet size of 6" x 2.5" x 0.04". The EDM process created a 0.025"-diameter hole in one of the two sheets. The perimeter of the hole was cleaned to remove the recast layer. A Nb tube (I.D. 3/16" x O.D. 0.025") was brazed into the hole by Ni-V braze at 2400F/5 min. The two sheets-one flat and the other with the brazed Nb tube- were placed in a TZM moly die and the whole assembly was placed in a 500 ton press. The Nb tube was connected to an argon gas bottle outside the furnace and argon gas was introduced through this tube during inflation following diffusion bonding of the two sheets. The diffusion bond of the edges was conducted at 2000F/3ksi/3 hr in vacuum. Following diffusion bonding argon gas was introduced at a low rate at 2000F to inflate the sheets into the cavity of the die. The assembly was held for one hour when the gas pressure reached 50 psi. Figure 2a shows the inflated part that has undergone an inflation of 9/16". A second run was also successfully conducted using the similar procedure as described above except that a gas pressure of 125 psi was used instead of 50 psi as shown in Figure 2b. In this case an inflation of 5/8" was achieved that was slightly higher than the first run.

A plan was also defined to conduct an SPF/DB run using 3-sheet approach. This includes: fabrication of a tool, diffusion bond scheme, and brazing of a Nb tube to gamma TiAl sheet needed for inflation. A schematic diagram of the process and the final product is shown in Figure 3.

Task 3-Gator Hide Fabrication:

An alternative approach to making the conventional honeycomb structure is to make hot-formed core called gator hide and then braze the core with top sheet and bottom sheets.

The objective of this task is to demonstrate feasibility by fabricating a core to which two face sheets will be brazed to form a sandwich structure. For demonstrating the feasibility of this approach, an IN 100 gator hide tool, available at P&W, was used. The gator hide structure was evaluated by NDE techniques.

Results:

Subscale Gator Fabrication:

Figures 4(a) and 4 (b) show the IN 100 gator hide tool with a dimension of 14" x 7" x 2". There are numerous pins with 0.5"- dia x 0.5" high. The bottom die weighs about 27 lbs and the top die has a weight of 19 lbs.

Three initial runs were made using small 4" x 3.25" x 0.024" PM sheets as shown in Figure 5. Both dies and the sheet were thoroughly coated with BN in order to prevent any reaction with IN100 & gamma TiAl.
A stopper was placed between the top and bottom dies. All these operations were done at 1900F in vacuum with different loads ranging from 33 lbs (2.5 psi), to 1500 lbs (115 psi). The sheet shows a slight dimpling following 5 hours at 1900F under a dead load of 33 lbs (Figure 5a). As the load increased the depth of dimpling increased. For 400 lbs. load and a forming rate of 0.002"/min, a corrugation depth of ¼" was achieved with no tearing of sheets around the pins (Figure 5b). An estimated strain of 15% was achieved. For a load of 1500 lbs. and a forming rate of 0.002"/min, a corrugation depth of better than 0.5" was achieved but the corrugations around the pins were partially cracked with corrugations at the central row revealing severe cracking (Figure 5c). A typical microstructure of cracked corrugation is shown in Figure 6. It appears that the material around the pin did not superplastically form but rather tore under complex biaxial loading.

Full Scale Gator Hide Fabrication:

For full scale gator hide fabrication the staring sheet size was 12" x 5.7" x 0.024". This was hot formed at 1900F under a load of 6000 lbs. (88 psi) with a forming rate of 0.002"/min. A corrugation depth of 0.25" was achieved but a few corrugations around the pins particularly at the central row revealed slight cracks.

A second run was made keeping all other parameters the same except for forming temperature. A forming temperature of 1950 F was used in order to achieve a higher depth of corrugation. In addition, increased temperature may help with superplastic forming that may prevent cracking of the sheet around the pins. Figure 7 shows the full scale gator fabricated at 1950F. Although a higher corrugation depth (0.29") was achieved at 1950F, a few corrugations around the pins at the central row revealed slight cracks.

The gator hide was sandwiched between two face sheets (11.5" x 5.5"x 0.024") and was brazed using TiCuNi 70 filler alloy at 1850F/30 min. A temperature/time plot for the brazing operation is shown in Figure 8. Figures 9(a) and 9(b) show the brazed gator hide subelement. This subelement was inspected both by thermography and UT scans as shown in Figures 10 and 11 respectively. Figure 10 reveals a couple of unbrazed areas and the UT scan also yields a similar result [Figures 11(a) and 11(b)].

Concluding Remarks:

Task 1- Laser Beam Welding:

We have successfully demonstrated that joining of sheet gamma TiAl was possible by using laser beam. A preheat temperature above 500F is required for creating successful butt joints. More experiments are required to optimize the laser welding process which may include stress-relief following laser welding.

The weld microstructure was similar to cast microstructure observed in normal ingot castings of gamma TiAl. However, due to very fast cooling, a fine-grained lamellar microstructure was formed in the weld. In addition, a few pores of varying sizes were observed in the weld. A small HAZ was developed adjacent to the weld and was characterized by finer microstructure than the parent matrix. The development of a low HAZ was consistent with the observed negligible distortion of the sheets. Microprobe studies indicated a depletion of Al and an enhancement of Ti in the weld compared to the parent material. The hardness of the weld was significantly higher than that of the parent material.

Three point bend samples (laser butt joints) will be available soon for testing the bond strength should that be desired.

Task 2- SPF/DB:

The SPF/DB experiments involving the two-sheet approach were successful. A good deal of progress was made in SPF/DB experiments involving three sheets. However, inflation runs were not performed. Based on our experience we believe these experiments would be successful in a follow-on phase.

Task 3- Gator Hide Fabrication:

We have successfully fabricated large cores, the so-called "gator hides", of sheet gamma TiAl using the IN 100 tool and subsequently brazed an 11.5" x 5.5" subelement incorporating the core between two face sheets. This is an alternative low cost approach to making conventional honeycomb structure.

We have developed two non-destructive evaluation techniques, thermography and UT scans, to study the quality of the braze joints in the subelement.

Summary Remarks:

Feasibility has been demonstrated for laser welding, the fabrication of SPF/DB 2-sheet structures and the fabrication of gator hide sandwich structures. The efforts were somewhat handicapped in that PM sheet was used for these activities rather than ingot sheet due to the PM sheet availability. The PM sheet has a lower strain to failure than does the ingot sheet, and therefore a greater chance of cracking during the SPF processing.

Recommendations:

NASA currently has received the ingot sheet, and it is therefore recommended that the feasibility demonstration be repeated using the higher strain capable ingot sheet material. This would include laser welding, 3-sheet SPF/DB and gator hide fabrication.

Figure Captions

Figure 1. Back-scattered electron image across a laser butt weld showing the microstructures of the weld, heat affected zone (HAZ), and the matrix: (a) low mag, (b) intermediate mag, and (c) high mag. A few pores are seen in the weld mostly located adjacent to the HAZ. Superimposed in the Figure are Vickers hardness values and the corresponding chemical compositions for the matrix, HAZ, and the weld

Figure 1d. Vickers hardness indentations across the weld

Figure 2. Demonstration of SPF/DB of PM gamma-met via 2-sheet approach: (a) 2000F/3 ksi/3 hr + 50 psi argon /1hr, and (b) 2000F/3 ksi/3 hr + 125 psi argon /1hr

Figure 3. Schematic diagrams showing the proposed SPF/DB run involving 3 sheets and the final product

Figure 4a. Top and bottom dies made with IN 100 for gator hide fabrication

Figure 4b. 3-D view of top and bottom dies made with IN 100 for gator hide fabrication

Figure 5. Subscale gator hide fabrication as a function of applied load at 1900Fin vacuum: (a) dead load of 33 lbs., (b) 400 lbs. @ 0.002"/min, and (c) 1500 lbs. @ 0.002"/min

Figure 6. Typical microstructure of a cracked corrugation around the pin subjected to 1500lbs.at 1900F@ 0.002"/min. The strain is localized near the fracture leading to tearing of the material: (a) fracture end, (b) high magnification of fracture end, and (c) high magnification of area near the fracture end

List of Tables

Attachment

"Laser Welding of Gamma Ti-Al Using a LASAG 306 Nd YAG Laser", T. C. Doyle, Acceleron, Inc., 21 Lordship Rd., East Granby, CT 06026

List of References

1. G. Das. Unpublished Research Work

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13. ABSTRACT (Maximum 200 words)

Gamma Titanium aluminide sheet structure technologies are focused on in this effort, including experiments to evaluate laser beam welding of thin sheet structure; superplastic forming and diffusion bonding of thin sheet structure; and, demonstration of fabricability of a hot-formed "egg crate" type core with brazed top and bottom face sheets. The fabricated subelement is known as "gator hide" and has the potential to replace more conventional honeycomb structure. All three area demonstrations were successful.

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