Abstract: - The new generation Civil Aircraft utilise Carbon Composite structures with the Aluminium components replaced by Titanium. Normally fuselage and structural components are made from Aluminium but a Carbon/Aluminium combination could result with adverse galvanic corrosion. To overcome this the structural frames, stringers, ribs etc are designed to be made from Titanium based alloys which have little or no adverse corrosion reaction with Carbon Composites.

Having made this design decision the manufacturing challenge is to find sufficient titanium materials, extrusion sources, forming sources and machining houses that can produce titanium structures of similar configuration to those typically made from aluminium. It has become apparent that the choice is limited and the cost of titanium prohibitive to the extent that innovative manufacturing methods have to be developed to meet costs and weight targets. To meet this challenge, Aeromet, which has an extensive experience in forming Titanium materials, joined with the United Kingdom Welding Institute to demonstrate methods for producing thick section frames from thin plate Ti6/4 material using the Hot Forming and Laser Welding processes. This development resulted in radical cost and material savings greater than 50%.

1.0 Introduction: - Aeromet international is a Titanium Fabricator/Forming specialist based in the United Kingdom (Appendix 1). It has seventeen Hot and Superplastic forming presses, Chemical milling, Laser trimming and Fabrication equipment plus associated processes from which it produces in the order of 6000 component parts per month. These range from Aero Engine parts, Tail Cone details, Firewalls, Extrusions and Assemblies (Appendix 2 & 3). With its global experience Aeromet is well aware of the challenge that Composite Airframe structures bring and has been encouraged to develop manufacturing methods that will lead to radical cost reductions and improve the ‘Buy to Fly’ ratio. The following paper shows how Hot Forming coupled with Laser Welding can achieve lower costs and improve the ‘Buy to Fly’ ratio.

2.0 Main Section: - Throughout this main programme of work Aeromet worked closely with Boeing Aircraft Co and the UK Welding Institute who supplied the component design and the welding technology respectively. Aeromet contracted to supply all weld test piece materials, component materials, Laser Welding Jig, Hot Form tooling and the performing of the Hot Forming and Inspection operations. TWI contracted to develop weld settings, apply welds and qualify weld joints. Close liaison and collaboration between Boeing, TWI and Aeromet was maintained through all stages of the development programme.

3.0 Summary of Activities – Laser Welded & Hot Formed product: - A concise report covering the Laser Welding Development has been issued by TWI, but classed as confidential.
Any detailed information must be obtained from TWI, therefore this Aeromet paper will only cover:

(a) Design of the Laser Welded product
(b) Manufacturing methods/sequence,
(c) Supply of weld test piece blanks,
(d) Design of the Laser Welding Jig,
(e) Design and manufacture of the Hot Forming tool
(f) Manufacture of the detail parts
(g) Hot Forming of the welded assemblies
(h) Dimensional inspection.
(i) PFD
(j) Comparison of Extrusion and Fabrication costs

3.1 Design of the selected product: - The original product (Appendix 4 & 5) was designed to be machined from either a Titanium 6Al 4V slab or extrusion. It is 72” long with the short flange leg at 3” wide and 0.144” thick, shaped to the Aircraft contour and the other leg, 7.5” wide and 0.120” thick and flat. For this Laser Welding development the angle was split at the 0.120/0.144” intersection, to enable the two flanges to be produced from titanium sheet/plate with a Laser Weld applied through the 0.120” thickness to the aircraft profile. As can be seen from the picture (Appendix 4) the finished angle of the flange is acute and changing from 75.5° – 80.5° degrees around its length. To accommodate the laser beam and allow beam access, the joint angle was fixed at 90° with the intention of creating the acute angle at the Hot Forming stage and simultaneously stress relieving the applied weld and assembly.

In order to present a smooth abutment face (for the adjacent airframe component) at the exit side of the weld the 0.144” thick flange was to be positioned with a 0.050” protrusion which would be dressed back flush after welding. (see Appendix 5).

3.2 Manufacturing Methods/Sequence:- The following manufacturing sequence was adopted and applied.

Narrow flange:

(a) Guillotine 0.144” thick sheet Ti 6Al 4V to 78” long x 3” wide.
(b) Cold roll the strip to approximate contour and cut to length. (Appendix 6)

Wide flange

(a) Water Jet cut 0.120” thick sheet to 72” long contoured profile leaving 0.120” machining allowance along the weld joint edge.

(b) Machine the weld joint edge to finish size thereby removing the water jet cut edge effect. (Appendix 6)

Assembly

(a) Acid flash pickle all details.
3.3 Weld Tests: - In order to develop weld settings, sufficient to meet the AWS D17.1: 2000 Class ‘A’ welding specification, strips of Ti 6Al 4V, 0.120” thick x 36” long x 2.360” wide were supplied to TWI and also used to demonstrate beam stability over long lengths. Using an Nd YAG Laser the basic welding settings established were 2.8kW at the work piece, spot size 0.6mm and a welding speed of 2.75m/min. To orientate the Laser Beam and follow the product contour a programmed robotic arm was employed. (See Appendix 7)

3.4 Design of the Laser Welding Jig:- A full size aluminium welding jig was designed to hold and clamp the short flange leg in a 90° vertical attitude, hold and clamp the wide flat flange and maintain a weld joint fit up with gaps no greater than 0.004”. An argon purge, backing groove, was also incorporated and lined with a titanium impingement strip. (see Appendix 7)

3.5 Design and Manufacture of the Hot Forming Tooling:- The function of the Hot Forming tool suite is to stress relieve the weld joint and at the same time change the angle of the short flange from 90° to the airframe shape, which varies, between 75.5° to 80.5°. To accommodate these requirements and to ensure accurate placement of the assembly onto the tooling the angular shape was placed on its neutral axis and the bottom tool made to the male shape “inverted V”. At the extreme ends of the tool pins were located between which the welded assembly would be positioned. The top tool was made as a matching former with a material thickness offset. (see Appendix 8)

3.6 Manufacture of the Angle Details:- As previously described both the vertical and horizontal flanges of the product were cut from Titanium 6Al 4V plate material, the wide flange by water jet cutting oversize followed by machining and the narrow flange just guillotined to width. Acid flash pickle was then applied prior to welding to present a clean weld abutment condition. The detail parts (eight sets in total) were then transported to the TWI welding institute in sealed plastic bags and subsequently welded.

3.7 Hot Forming of Welded Angles: - Following the Laser Welding process, all eight assemblies were returned to Aeromet for the Weld Underbead dressing, Hot Forming, Dimensional inspection and PFD operations. As described and shown in section 4.1 and attachment 2 respectively, the protruding portion of the narrow flange was mechanically removed to present a flat smooth flange face representative of the finished configuration. Only the top bead side of the weld remained in the “as welded”
condition (see Attachment 9, photographs). The assemblies were placed on a calibrated surface table and checked for distortion; on average the wide flange was distorted/twisted up to 0.500” due to the welding stresses.

The Hot Forming operation, to be carried out at 1250°F (675°C), in a heated platen press (see Appendix 10) was applied to both stress relieve the weld joint and produce the correct finished profile whilst being held at temperature, under load, between the matching Hot Form tool. (see Appendix 11).

The sequence of operations is: - The tool is cleaned and sprayed with Boron Nitride lubricant, loaded and clamped into the press at room temperature. Heat is then applied through the electrically supplied press platens and side heaters to achieve the required settings of 1250°F (675°C) on the tool and this temperature stabilised.

The welded assembly was coated with a Boron Nitride, allowing the component to slide on the surface of the tool and placed onto the lower tool to heat up to 1250°F (675°C). Once at temperature the tool was slowly closed to form the shape, load was applied and sustained for 30 minutes. Upon completion the formed part was removed and placed upon a cooling mat. (See Appendix 11). The forming operation moved the short flange angle from 90° to within the required range of 75.5° to 80.5°.

Upon cool down the formed part was processed through Water wash, Caustic descale and Acid Pickle operations to remove any oxide layer from the product’s surface and the underbead protrusion machined flush.

3.8 Dimensional Inspection:- To demonstrate the product accuracy after forming and to show repeatability the first and last angles to be formed were CMM inspected. The CMM machine was programmed with the finish component profile as supplied by Boeing and dimensional limits of +/- 0.015” were set. The results of the inspection, across 55 points per part are extremely encouraging; all points are within the set tolerance band with the majority resulting at half tolerance. (see Appendix 12 and 13, the dimensions are in millimetres).

3.9 PFD Inspection:- Penetrant Flaw Detection (None-Destructive Crack Detection by Fluorescent Ink) was applied to all the eight parts. No defects were found on the top-side of the weld but where the underbead had been dressed off, to create a smooth surface, indications of micro porosity was evident on two parts to a level above the Weld Specification limits. The two parts were weld repaired by fusion TIG welding over the micro porosity areas. This was successfully carried out on items 6 & 7 followed by localised dressing to recreate the smooth underbead surface. During this weld repair the items distorted and in order to remove the distortion and residual stresses the hot form operation was repeated. This was followed by, descale, pickle and PFD testing. No PFD indications were present and the dimensional accuracy was maintained.

4.0 Comparison of costs for Machined Slab, Extrusion and Laser Welded & Hot Formed methods:- The appendix 14 shows Rough Order of Magnitude cost comparisons, the Laser Welded fabrication option is 70% lower than the Machined from Slab option. The major
difference is the material volume, which results with the Fabrication material being 79% lower with a resulting “Buy to Fly” ratio of 3:1.

5.0 Results and Conclusions:-

a) Components of this nature can be successfully fabricated from sheet/plate materials by the Laser Welding and Hot Forming processes. (see Appendix 15 & 16)
b) Thick sheet/plate titanium material can be formed to change angles by at least 15°.
c) An accuracy of +/- 0.015” (+/-0.4mm) or less can be maintained on a component of 72” length.
d) Residual stress after final operations is zero to minimal.
e) Material and combined Material and Labour costs are considerably reduced in the order of magnitude 79% and 70% respectively with “Buy to Fly” ratios moving from 16:1 to 3:1.

6.0 Acknowledgements:-
Aeromet acknowledges Gary Coleman of Boeing Aircraft and David Howes of TWI, United Kingdom, for their advice and support during the Laser Welding and Hot Forming development work.

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8.0 Appendix:-

No 1 Introduction to Aeromet
No 2 Product samples
No 3 Product samples
No 4 Design details and dimensions of product
No 5 Weld geometry and 0.050” protrusion
No 6 Individual flange details and welded assembly
No 7 Laser Welding Fixture design
No 8 Hot Forming Tool design
No 9 Top bead, Underbead and protrusion photos
No 10 Hot Forming press and Tooling coated with Boron Nitride
No 11 Tooling in press with formed part located and formed parts
No 12 Dimensional report for item No 1
No 13 Dimensional report for item No 4
No 14 Extrusion and Fabrication cost comparisons
No 15 Finished Angles + Before & After Hot Forming view
No 16 Finished Angles
“Attacking the Fly to Buy Ratio by Laser Welding and Hot Forming”

Titanium 2008
Bill Swale
Technical Specialist
Aeromet International plc
United Kingdom

Acknowledgements -
Gary Coleman - Welding Specialist - Boeing Aircraft Co.
David Howes - Laser Welding Specialist - TWI - UK
“Attacking the Fly to Buy Ratio by Laser Welding and Hot Forming”

Aeromet International plc based in the United Kingdom produces Airframe and Engine components From Titanium Sheet and Plate Using Superplastic, Hot Forming, Chemical Milling and & Laser Trimming

5 Axis Laser Trimming

Superplastic Forming Press

Chemical Milling Plant
“Attacking the Fly to Buy Ratio by Laser Welding and Hot Forming”

Product Examples

Engine Products

Tail Cone Products
“Attacking the Fly to Buy Ratio by Laser Welding and Hot Forming”

Product Examples

Firewalls and Assemblies
“Attacking the Fly to Buy Ratio by Laser Welding and Hot Forming”

0.25” thick x 2” leg extruded Ti6/4 angle, hot formed to aircraft contour within 0.010”
“Attacking the Fly to Buy Ratio by Laser Welding and Hot Forming”

12” wide x 0.75” – 1.125” thick ‘I’ beam formed to aircraft diameter.

Extrusions courtesy of RTI International UK
“Attacking the Fly to Buy Ratio by Laser Welding and Hot Forming”

Ti6/4 Plate 0.25” tapered to 0.16” over 120” long Hot formed to final shape.
“Attacking the Fly to Buy Ratio by Laser Welding and Hot Forming”

Acknowledgements -
Gary Coleman - Welding Specialist - Boeing Aircraft Co.
David Howes - Laser Welding Specialist - TWI - UK
“Attacking the Fly to Buy Ratio by Laser Welding and Hot Forming”

Product Selection

<table>
<thead>
<tr>
<th>Position</th>
<th>Flange Angle</th>
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<tr>
<td>BL0</td>
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<tr>
<td>3</td>
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<td>5</td>
<td>79.69</td>
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<td>75.74</td>
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<td>39</td>
<td>75.51</td>
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- 9” wide flat flange
- 3” curved flange
- 72” long

Dx=69.33 mm
Dy=236.67 mm
Dz=1819.12 mm
D=3.66 mm
D=3.71 mm
D=3.26 mm
D=3.57 mm
D=3.44 mm
D=3.70 mm
D=3.27 mm
D=2.79 mm
D=2.79 mm
D=2.79 mm
D=2.79 mm

Position Flange Angle
“Attacking the Fly to Buy Ratio by Laser Welding and Hot Forming”

Condition after Laser Welding

Condition after dressing off 0.050” protrusion on underbead side of weld

Dressed region
“Attacking the Fly to Buy Ratio by Laser Welding and Hot Forming”

Detail parts

Wide Flange

Narrow Flange
“Attacking the Fly to Buy Ratio by Laser Welding and Hot Forming”

Welding Fixture and Robotic arm
courtesy of TWI

Weld path

Component part

Argon Feed

Argon backing groove
“Attacking the Fly to Buy Ratio by Laser Welding and Hot Forming”
“Attacking the Fly to Buy Ratio by Laser Welding and Hot Forming”

Views of Top Surface

Views of Underbead Surface

0.050” raised portion

Courtesy of TWI
“Attacking the Fly to Buy Ratio by Laser Welding and Hot Forming”

Hot Form Tooling

Component part

Tool Action
“Attacking the Fly to Buy Ratio by Laser Welding and Hot Forming”

Hot Forming Tooling coated in Boron Nitride lubricant

500 ton press

Welded angle placed in Hot Form tool showing angular change required
“Attacking the Fly to Buy Ratio by Laser Welding and Hot Forming”

Hot Forming tool shown within Hot Forming press at 1250°F (675 °C)

Formed angle on cooling mat

Before & after forming
“Attacking the Fly to Buy Ratio by Laser Welding and Hot Forming”

Faro Arm measurement Minimum 50 points all within +/- 0.010"
“Attacking the Fly to Buy Ratio by Laser Welding and Hot Forming”

Finished Products
## “Attacking the Fly to Buy Ratio by Laser Welding and Hot Forming”

### Cost Comparisons

<table>
<thead>
<tr>
<th>Machine from Solid</th>
<th>Cost</th>
<th>Extruded &amp; Machined</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>100%</td>
<td>Extrusion</td>
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</tr>
<tr>
<td>Machining etc</td>
<td>100%</td>
<td>Forming &amp; Machining etc</td>
<td>73%</td>
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<tr>
<td>Total cost</td>
<td>100%</td>
<td>Total cost</td>
<td>69%</td>
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</tbody>
</table>

Buy to Fly- Utilisation typically 10%

Buy to Fly- Utilisation typically 40%

### Laser Welded & Hot Formed

<table>
<thead>
<tr>
<th>Laser Welded &amp; Hot Formed</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate materials</td>
<td>21%</td>
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<tr>
<td>Machining,Forming &amp; processing costs</td>
<td>43%</td>
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<tr>
<td>Total cost</td>
<td>30%</td>
</tr>
</tbody>
</table>

Buy to Fly- Utilisation typically 80%
Conclusions
Existing standalone processes can be linked to provide substantial benefits. Laser Welded & Hot Formed Net Shape, stress free and cost effective components can be produced to a repeatable accurate standard. Buy to Fly ratios better than at 80% utilisation can be achieved.

Thank you for being attentive