Linear Friction Welding
An Alternative Production Route for Titanium Aerospace Components

Steve Dodds
Friction & Forge Processes
Linear friction welding

- **Rapid, high integrity, solid-state forging process**
- Parent material *is recovered* via heat treatment
- LFW of Ti performed **without gas shielding**
- **Time dependant** process - not area dependant
- Near-net shape solution for **part cost reduction** *(Buy:Fly)*
Time dependant process: typically <1min regardless of volume to weld
Typical positioning: accuracy <0.05mm; repeatability <0.025mm

TWI channel: youtube.com/user/twilted
TWI pioneered Linear Friction Welding

First industrial trials
FW 8 Orbital (1982)

First LFW machine
FW17 Blacks (1986)

First open bed platform
FW29 LinFric (2005)

Industrialised version
FW34 E20 (2011)
Established technology for Ti Blisk fabrication

- 5th gen fighters LPCs
  - Excellent power to weight ratio
  - Parts proven to outlast the engine

- Uptake: civil engines
  - Operational efficiency
  - Environmental regulations
Context: Civil aviation demands

- Global passenger traffic and cargo growing 4.8%/yr
  - New Aircrafts: Focus composite materials
  - Increased demand for Ti alloy structural parts
  - Limited global manufacturing capacity for titanium

- Novel manufacturing
  - Reduce costs
  - Efficient use of titanium

- Linear friction welding
  - Join smaller workpieces
  - Preforms near-net shape
  - Machined to final size

Source: Boeing
TiFab collaborative project

- **Ti-6Al-4V joint performance data**
  - Parametric assessment
  - Post-weld heat treatment
  - Static and fatigue testing

- **Economic assessment**
  - Versus current ‘machining from solid’
  - Near-net-shape benefits using LFW

- **Process monitoring and tooling design**

- **Manufacture of a demonstrators**

- **Setup UK-based supply chain for LFW parts**

Tier 1 suppliers

Accountants

Equipment

Technology
Ti-6Al-4V Joint performance

- LFW parametric assessment
- Post weld heat treatment
- Static and fatigue loading
Over 120 welds, varying:
- Pressure
- Amplitude and frequency
- Forge duration
- Atmospheric conditions

Friction controlled most effectively during the medium to high rubbing velocities

Broad effective processing envelope identified

<table>
<thead>
<tr>
<th>Envelope</th>
<th>Amplitude</th>
<th>Frequency</th>
<th>Pressure</th>
<th>Forge duration</th>
<th>Atm</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>± 3mm</td>
<td>60Hz</td>
<td>140MPa</td>
<td>25s</td>
<td>Air</td>
</tr>
<tr>
<td>Low</td>
<td>± 2mm</td>
<td>30Hz</td>
<td>80MPa</td>
<td>6.5s</td>
<td>Air</td>
</tr>
</tbody>
</table>
Weld joint micrographs

- Average rubbing velocity of 250mm/s or more:
  - All joints successfully ‘joined’ regardless of the pressure
  - Characteristic fine-grained equiaxed microstructure

- High integrity welds achieved with unprotected atmosphere
  - Without surface contaminants and alpha case ingress
  - Protective gas shielding may not be necessary

a) Low  b) medium  c) high pressure joints
Characteristic burn-off behaviour

- Successful minimum ‘burn-off’ achieved at all pressures applied
- Wide tolerance to process parameters

Friction duration:
- 50 MPa: 6.3s
- 80 MPa: 1.75s
- 140 MPa: 1.0s
- 240 MPa: 0.7s
- Positive thermal gradients up to 3600°C/s
- Cooling:
  - 6.5s to 380°C (Oxidising temp)
  - 25s to 200°C
Tensile test performance (as welded)

- Cross weld tensile test
  - (BSEN ISO 6892-1:2009 A)
- All specimens failed in parent material
Tensile performance (PWHT)

- No effect on parent material with custom PWHT
  - Values closer to parent material obtained
  - Consistent performance (failures in parent material)
Fatigue performance (as welded)

- **As-welded** above minimum allowable data
  - Low cycle fatigue (LCF) still above the MMPDS “A” basis
  - High cycle fatigue (HCF) results on par with PM
- Satisfactory for **static loaded** components

Data from CAV Advanced Technologies Ltd
Each data point based on at least 8 samples
Standard PWHT offered unsatisfactory fatigue results

**TWI developed** PWHT reduced LCF and HCF data spread ($\sigma$)
- Recrystallised processed LFW microstructure
- Satisfactory utilisation for **fatigue loaded** designs

**Fatigue performance (PWHT)**

- **Data from** CAV Advanced Technologies Ltd
- Minimum recorded values improved

### Chart

<table>
<thead>
<tr>
<th>Condition</th>
<th>Low and high fatigue</th>
<th>Alternated cycles (log scale)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCF at 700MPa Parent Material</td>
<td>19.1k (100%)</td>
<td>10.0k</td>
</tr>
<tr>
<td>LCF at 700MPa As-welded specimen</td>
<td>13.6k (71%)</td>
<td>10.0k</td>
</tr>
<tr>
<td>LCF at 700MPa PWHT specimen</td>
<td>35.3k (185%)</td>
<td>30.5k</td>
</tr>
<tr>
<td>HCF at 540 MPa Parent Material</td>
<td>74.3k (100%)</td>
<td>30.5k</td>
</tr>
<tr>
<td>HCF at 540 MPa As-welded specimen</td>
<td>76.2k (102%)</td>
<td>30.5k</td>
</tr>
<tr>
<td>HCF at 540 MPa PWHT specimen</td>
<td>1500k (202%)</td>
<td>30.5k</td>
</tr>
</tbody>
</table>
Summary of Ti-6Al-4V Joint performance

- **LFW process for Ti-6Al-4V**
  - Wide process window
  - Welding cycles under 30s
  - Free from oxides and contaminants
  - Can be welded in air

- **As-welded**
  - Tensile equal to parent material
  - LCF exceeded minimum design values
  - HCF on par with parent material

- **PWHT**
  - Reduced dispersion results
  - Equal or above parent material:
    - Tensile Rp0.2%, UTS, El, RA
    - Impact strength
    - Low cycle fatigue
    - High cycle fatigue
Economic assessment

- Current methods of machining from solid
- Near-net-shape using LFW
Tailored Blank Production

Material Preparation
- Receipt of plate
- Water jet cutting
- Weld
- Flash removal
- Additional welds
- Ultrasonic inspection
- Visual inspection
- Metrology

LFW Operations

Post weld Inspection
- Vacuum
- Inert gas
- Air

Post weld Heat Treat
- Machining
- Deburring
- Rework
- Fettle

Part Machining
- Penetrant inspection
- Metrology

Final Inspection
- QA
- Protection
- Packing
- Shipping documents

Pack and Ship
More than just cost!

Candidate Part Design and Evaluation Tool

Capacity and utilisation tool

Value Stream Tools

Data Inputs to Cost Model

Can we build it?
- Headline material savings
- Critical dimensions
- Billet volumes
- Perimeter dimensions
- Sequence of manufacture
- Weld areas
- LFW machine size determination
- Legacy part data

What do we need?
- Number of parts
- Build rate
- Working hours
- OEE
- Shift pattern
- Equipment levels

How do we make it?
- Production steps
- Manufacturing operations
- Equipment definition
- Floor space
- Cycle times
- Labour
174 candidate parts evaluated with OEM
- All components showed a minimum of 30% costs reduction
- Representing over 206 tonnes of material saved per year

Strategic control over material costs
- Reduced exposure to Ti price variations
- Control of stock costs
- Increased throughput
Savings within the supply chain

- LFW and downstream related activities account for only 18% of the cumulative production costs

% Cost per part – LFW Tailored Blank

<table>
<thead>
<tr>
<th>Process</th>
<th>% Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>19%</td>
</tr>
<tr>
<td>Material preparation</td>
<td>8%</td>
</tr>
<tr>
<td>LFW operations</td>
<td>6%</td>
</tr>
<tr>
<td>Post-weld inspection</td>
<td>2%</td>
</tr>
<tr>
<td>Post-weld heat treat</td>
<td>10%</td>
</tr>
<tr>
<td>Part machining</td>
<td>38%</td>
</tr>
<tr>
<td>Final Inspection</td>
<td>17%</td>
</tr>
</tbody>
</table>
Buy-to-fly = 3.7 : 1
-66% raw material

-49.9% production time
-23.3% production costs
- **New design freedoms**
  - Add parts to simplified forgings
  - Reduce part count
  - Next generation part design
    - Exploit multiple grain directions

- **Material tailoring**
  - Multi-material near-net blanks
    - The right material in the right location
  - Enable the use of smart materials
  - Friction welding of AM parts

- **LFW for lightweight components**
  - Investigated on Al:Li alloys
  - Promising first results
  - CFRC also being investigated

---

What’s next?

Potential Example:

- Ti6242
- Ti64
Conclusions on LFW of Ti-6Al-4V

- Clear economic and strategic benefits
  - Reduce raw material usage, delivery times and cost
  - Reduces stock and vulnerability to material price change

- Extremely high integrity, time dependant process
  - Forged microstructure
  - Parent material properties

![Tailored Blanks material savings chart]

![Graph showing LFW post weld heat treated, LFW as welded, and Parent Material (100%)]

Copyright © TWI Ltd 2017
Biennial International LFW Symposium

- Leading LFW event Worldwide
  - Industrial LFW developments
  - Presentations by field experts
- LFW 2017
  - 85 attendants
  - 21 presentations
  - 15 Demonstrators

Contact: Richard Freeman, Aerospace Sector Manager. richard.freeman@twi.co.uk

See you 20th and 21st March 2019!
Broad, global LFW audience

- +33% increase over 2015
15 industrial demonstrators

- Event extended to 1.5 day with poster session
- Demonstrators from France, Italy, Japan, UK
21 presentation from global experts
Thanks for your time

Any (very simple) questions?