The deposition strategies

- Single pass
- Parallel passes
- Oscillation
Ti64 // Cutting plan for static properties

a) 
\[
\begin{align*}
\text{Z} & \quad \text{Y} \\
\text{X} & \\
\end{align*}
\]

locations of coupons

substrate

deposit


dimensions:
- 500
- 150
- 600

b) 
\[
\begin{align*}
\text{Z} & \quad \text{X} \\
\text{Y} & \\
\end{align*}
\]

locations of coupons

85

22

8

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Ti64 // Static properties

Directionality

Ultimate tensile strength (MPa)

Proof strength (MPa)

Vertical Additive AMS 4999
Horizontal Additive AMS 4999
Wrought AMS 4928

Elongation (%)

All data is property of Cranfield University unless specified differently.
Ti64 // Static properties

Average values

![Graph showing average values for cast ASTM F1108, wrought AMS 4928, and additive AMS 4999.](image)

- **Ultimate tensile strength (MPa)**
  - Cast ASTM F1108
  - Wrought AMS 4928
  - Additive AMS 4999

- **Elongation (%)**
  - Cast ASTM F1108
  - Wrought AMS 4928
  - Additive AMS 4999

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Ti64 // Static properties with in-process cold work

Directionality

Ultimate tensile strength (MPa) vs. Proof strength (MPa)

- Cast ASTM F1108
- Wrought AMS 4928
- Additive AMS 4999
- Plate

Elongation (%) vs. Proof strength (MPa)

- Unrolled Vert.
- Unrolled Horiz.
- 50 kN Vert.
- 50 kN Horiz.
- 75 kN Vert.
- 75 kN Horiz.
- 75 kN plasma Vert.
- 75 kN plasma Horiz.

All data is property of Cranfield University unless specified differently.
### Average values

<table>
<thead>
<tr>
<th>Proof strength (MPa)</th>
<th>Ultimate tensile strength (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>750</td>
<td>750</td>
<td>6</td>
</tr>
<tr>
<td>800</td>
<td>800</td>
<td>8</td>
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<tr>
<td>850</td>
<td>850</td>
<td>10</td>
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<tr>
<td>900</td>
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<tr>
<td>950</td>
<td>950</td>
<td>14</td>
</tr>
<tr>
<td>1000</td>
<td>1000</td>
<td>16</td>
</tr>
<tr>
<td>1050</td>
<td>1050</td>
<td>18</td>
</tr>
</tbody>
</table>

- **Cast ASTM F1108**
- **Wrought AMS 4928**
- **Additive AMS 4999**
- **Unrolled**
- **50 kN**
- **75 kN**
- **75 kN plasma**
- **Plate**
Ti64 // Comparison against other processes

- Norsk Ti from norsktitanium.com; Sciaky from Structure-property correlations for additively manufactured Ti-6Al-4V components produced using directed energy deposition processes, 2016 Proceedings of the 13th World Conference on Titanium
- Blown-powder from IREPA lasers

Directionality

Ultimate tensile strength (MPa) vs. Proof strength (MPa)

- Wrought AMS 4928
- Vertical Additive AMS 4999
- Horizontal Additive AMS 4999

Elongation (%) vs. Proof strength (MPa)

- Wrought AMS 4928
- Vertical Additive AMS 4999
- Horizontal Additive AMS 4999
Ti64 // Comparison against other processes

- Norsk Ti from norsktitanium.com; Sciaky from Structure-property correlations for additively manufactured Ti-6Al-4V components produced using directed energy deposition processes, 2016 Proceedings of the 13th World Conference on Titanium
- Blown-powder from IREPA lasers

Average values

- Ultimate tensile strength (MPa)
- Proof strength (MPa)
- Elongation (%)

All data is property of Cranfield University unless specified differently
#### Ti64 // Fatigue durability

**High cycle fatigue, single pass (old data)**

![Graph showing fatigue data](image)

- R = 0.1, Kt = 1
- As-dep Vert.
- As-dep Vert. (run-off)
- As-dep Horiz.
- As-dep Horiz. (run-off)
- Wrought measured by Peters
- Wrought measured by Peters (trendline)
- Lamellar by Peters

**Built with local shielding**

- 75 kN Vert.
- 75 kN Horiz.
- AIMS03-20-002 forged or plate
- 75 kN Vert. (trend.)
- 75 kN Horiz. (trend.)
- AIMS03-21-002 Cast/HIP

Property of Airbus

All data is property of Cranfield University unless specified differently
High cycle fatigue // Parallel strategy

Cycles to failure

Max stress (MPa)

- Parallel Vert.
- Parallel Vert. (run-off)
- Parallel Horiz.
- Parallel Horiz. (run-off)
- Wrought measured by Peters
- Wrought measured by Peters (trendline)
- Lamellar by Peters

R = 0.1
Kt = 1
f = 50 Hz

At 600 MPa:
2 run-off in Vert.
1 run-off in Horiz.
(points overlapped)
High cycle fatigue // Oscillation strategy

At 600 MPa:
3 run-off in Vert.
(points overlapped)

- Oscillated Vert.
- Oscillated Vert. (run-off)
- Oscillated Horiz.
- Wrought measured by Peters
- Lamellar by Peters

R = 0.1
Kt = 1
f = 50 Hz

Wrought measured by Peters (trendline)
Fatigue crack growth rate (single bead, without and with cold-work)

- **Ti64 // Damage tolerance**

R = 0.1

No in-process cold-work

In-process cold-worked at 75 kN

WAAM: crack across layers
WAAM: crack along layers
Wrought Ti-6Al-4V (L-T measured)
Wrought Ti-6Al-4V (T-L measured)
Wrought Ti-6Al-4V (L-T MMPDS)
Cast Ti-6Al-4V (MMPDS)

WAAM: crack across layers 1 (R = 0.5)
WAAM: crack across layers 2 (R = 0.5)
WAAM: crack along layers 1 (R = 0.5)
WAAM: crack along layers 2 (R = 0.5)
Wrought NASA CR2319 (R = 0.5)
Fatigue crack growth rate (parallel and oscillated)

Parallel dep. strategy
$R = 0.1$
No in-process cold-work

Oscillation dep. strategy
$R = 0.1$
No in-process cold-work

WAAM: crack across layers Test 1
WAAM: crack across layers Test 2
WAAM: crack along layers Test 1
WAAM: crack along layers Test 2
Wrought Ti-6Al-4V (L-T MMPDS)
Cast Ti-6Al-4V (MMPDS)
Recap FCGR

All dep. strategies

\( R = 0.1 \)

No in-process cold-work

\[
\frac{da}{dN} \text{ (m/cycle)}
\]

\[
\Delta K \text{ (MPa m}^{1/2})
\]

- Single, crack across layers Test 1
- Single, crack along layers Test 1
- Parallel, crack across layers Test 1
- Parallel, crack along layers Test 1
- Oscill., crack across layers Test 1
- Oscill., crack along layers Test 1
- Wrought Ti-6Al-4V (L-T MMPDS)
- Cast Ti-6Al-4V (MMPDS)
Fracture toughness

![Fracture toughness graph](image)

- **Grade 5** parallel
- **Grade 5** oscillated
- **Grade 23** parallel
- Wrought Ref: MMPDS thickness > 25 mm plane strain cond.
- Wrought this research

- Across the layers
- Along the layers

All data is property of Cranfield University unless specified differently.
Ti64 // Properties at the interface

- Case 1: fully sacrificial

- Case 2: plate at the bottom

- Case 3: symmetric structure
Ti64 // Crack growth trajectory at the interface

Crack trajectory maintains almost a straight line

All data is property of Cranfield University unless specified differently
Ti64 // Crack growth trajectory at the interface

WAAM material

building direction

interface

substrate

A

B

C

D

E

87.5

84

445

120

40

3

3

445

WAAM: crack across layers
WAAM: crack along layers

10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9}

\frac{da}{dN} (m/cycle)

\Delta K (MPa m^{1/2})

Type A

Type B

Type C

Type D

Type E

Wrought Ti-6Al-4V (L-T)

Cast Ti-6Al-4V

Wrought Ti-6Al-4V

Cast Ti-6Al-4V

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”Other” titanium alloys (tensile test in progress)

- Ti-5Al-5Mo-5V-3Cr (5553)
  - → UTS up to 1300 MPa

- Ti64 with 2000ppm O₂
  - → + 500ppm O₂ = + 70 Mpa

- Ti64 coated with TiB₂
  - → grain refinement

- Timetal 407
  - → medium strength, high ductility
  - → energy absorption = 1.6 x Ti64
  - → machinability = 2 x Ti64

Vickers Hardness

<table>
<thead>
<tr>
<th>Material</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti 64</td>
<td>352.1</td>
</tr>
<tr>
<td>Ti 64 high O₂</td>
<td>367.3</td>
</tr>
<tr>
<td>TiB₂ coated</td>
<td>353.0</td>
</tr>
<tr>
<td>Ti 5553</td>
<td>416.22</td>
</tr>
<tr>
<td>Ti 407</td>
<td>270.09</td>
</tr>
</tbody>
</table>

All data is property of Cranfield University unless specified differently
Aluminium
All values measured in the horizontal direction

Proof strength (MPa)

Ultimate tensile strength (MPa)

Elongation (%)
Aluminium 2319

Average values

![Graph showing the relationship between proof strength (MPa) and ultimate tensile strength and elongation for different conditions such as Unroll, Unroll T6, 15 kN, 30 kN, 45 kN, 45 kN T6, and Wrought T6. The graphs illustrate the data points for each condition across the ranges of proof strength from 120 to 320 MPa and ultimate tensile strength from 260 to 460 MPa, and elongation from 7% to 17%.](image)

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Aluminium Safra 66 / ZL205A

Thin walls (single beads)

Proof strength (MPa)

Ultimate tensile strength (MPa)

Elongation (%)

Desirable
Aluminium Safra 66 / ZL205A

Thick walls

![Graphs showing proof strength and ultimate tensile strength for different conditions of Aluminium Safra 66 and ZL205A.]
Aluminium 4043 and 5087

Average values

Proof strength (MPa)

Ultimate tensile strength (MPa)

Elongation (%)

All data is property of Cranfield University unless specified differently
Picking the right alloy

Average values

[Graph showing the relationship between proof strength (MPa) and ultimate tensile strength (MPa)]

- 2024 Single
- 2024 Single T6
- 2024 15 kN
- 2024 30 kN
- 2024 45 kN
- 2024 45 kN T6
- 2024 Wrought T6
- 2319 Single
- 2319 Single T6
- 2319 15 kN
- 2319 30 kN
- 2319 45 kN
- 2319 45 kN T6
- 2319 Wrought T6
- 5087 Single
- 5087 Rolled

[Graph showing the relationship between proof strength (MPa) and elongation (%)]

All data is property of Cranfield University unless specified differently
Steels
Steels (work in progress)

Average values

**Proof strength (MPa)**

<table>
<thead>
<tr>
<th>Material</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ER70S-6</td>
<td>400</td>
</tr>
<tr>
<td>ER80S-Ni1</td>
<td>600</td>
</tr>
<tr>
<td>ER80S-B3</td>
<td>800</td>
</tr>
<tr>
<td>ER120</td>
<td>1000</td>
</tr>
<tr>
<td>Mar. steel 250</td>
<td>1200</td>
</tr>
<tr>
<td>Mar. steel 250 HT</td>
<td>1400</td>
</tr>
<tr>
<td>Mar. steel 350</td>
<td>1600</td>
</tr>
<tr>
<td>Mar. steel 350 HT</td>
<td>1800</td>
</tr>
</tbody>
</table>

**Ultimate tensile strength (MPa)**

<table>
<thead>
<tr>
<th>Material</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ER70S-6</td>
<td>500</td>
</tr>
<tr>
<td>ER80S-Ni1</td>
<td>1000</td>
</tr>
<tr>
<td>ER80S-B3</td>
<td>1500</td>
</tr>
<tr>
<td>ER120</td>
<td>2000</td>
</tr>
<tr>
<td>Mar. steel 250</td>
<td>250</td>
</tr>
<tr>
<td>Mar. steel 250 HT</td>
<td>300</td>
</tr>
<tr>
<td>Mar. steel 350</td>
<td>350</td>
</tr>
<tr>
<td>Mar. steel 350 HT</td>
<td>400</td>
</tr>
</tbody>
</table>

**Elongation (%)**

<table>
<thead>
<tr>
<th>Material</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ER70S-6</td>
<td>5</td>
</tr>
<tr>
<td>ER80S-Ni1</td>
<td>10</td>
</tr>
<tr>
<td>ER80S-B3</td>
<td>15</td>
</tr>
<tr>
<td>ER120</td>
<td>20</td>
</tr>
<tr>
<td>Mar. steel 250</td>
<td>25</td>
</tr>
<tr>
<td>Mar. steel 250 HT</td>
<td>30</td>
</tr>
<tr>
<td>Mar. steel 350</td>
<td>35</td>
</tr>
<tr>
<td>Mar. steel 350 HT</td>
<td>40</td>
</tr>
</tbody>
</table>
Stainless steels

Directionality

- Ultimate tensile strength (MPa)
- Proof strength (MPa)
- Elongation (%)

Materials:
- 17-4 PH Vert.
- 17-4 PH Horiz.
- 316L Vert.
- 316L Horiz.
Inconel
Inconel® 718

CMT (brushed = mechanical cleaning of surface prior to successive layer)

---

**Graph 1:**
- **Proof strength (MPa):** 300 to 1200
- **Ultimate tensile strength (MPa):** 700 to 1500
- **Data Points:**
  - As-Dep Vert.
  - As-Dep Horiz.
  - As-Dep Vert. (diff. wire)
  - As-Dep Horiz. (diff. wire)
  - As-Dep (brushed) Vert. (diff. wire)
  - As-Dep (brushed) Horiz. (diff. wire)
  - Solutionised Vert.
  - Solutionised Horiz.
  - HT Vert.
  - HT Horiz.

**Graph 2:**
- **Proof strength (MPa):** 300 to 1200
- **Elongation (%):** 10 to 50
- **Data Points:**
  - As-Dep Vert.
  - As-Dep Horiz.
  - As-Dep Vert. (diff. wire)
  - As-Dep Horiz. (diff. wire)
  - As-Dep (brushed) Vert. (diff. wire)
  - As-Dep (brushed) Horiz. (diff. wire)
  - Solutionised Vert.
  - Solutionised Horiz.
  - HT Vert.
  - HT Horiz.

---

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Inconel® 718

Plasma (including cold-work)

Proof strength (MPa)

Ultimate tensile strength (MPa)

Elongation (%)

AMS 5662 and 5663 Bars, Forgings, & Rings

As-Dep Vert.
As-Dep Horiz.
Solutionised Vert.
Solutionised Horiz.
HT Vert.
HT Horiz.
Rolled @ 75 kN Vert.
Rolled @ 75 kN Horiz.
Rolled @ 75 kN + solut. Vert.
Rolled @ 75 kN + solut. Horiz.
Rolled @ 75 kN + HT Vert.
Rolled @ 75 kN + HT Horiz.