Developments in Additive Manufacturing of Nickel Superalloys for Aerospace Applications

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Introduction to Materials Solutions

• Materials Solutions is an AS9100 Rev C registered AM parts supplier and consultancy specialising in nickel superalloys and high temperature applications…
  … developing AM processes towards production use.
  The combination of R&D and QA to deliver theory AND practice.
Background of Materials Solutions

• Started-up in Sept 2006 on with grant funding from DTI (TSB) & AWM from the Micro & Nano Technology (MNT) call
• Aim was to take new technologies into early stage production in the field of:
  • (near) net shape manufacturing
  • films and functionalised surfaces
• Focus is on Aerospace & high temperature applications
  • Emissions reduction- requiring development of combustion parts for jet engines
• We became the UK’s first installation of EOS M270 (full melting, not ‘sintering’) metal AM machines - one of the World’s first
• Europe’s largest and most complete commercially available centre for this technology within a QA environment allowing industrial application of our output
• Our approach:
  • AM not RP- the material, mechanical properties, accuracy and quality must be as required for use in manufacturing
  • Develop business models and support/encourage equipment development to make metals AM economically realistic for early stage production use
Status to date

• Materials focus with a sophisticated QA and production control infrastructure allowing us to ship parts for high value applications
• 12 employees
• ‘Approved’ for metals powder-bed AM by:
  • RR Plc., RR- Canada, RR-Germany, RR- Nuclear Sector- submarines, ITP and others
• Exports are 30~50% of revenues (N. America, Europe, Japan)
• We are working mostly in high temperature nickel casting alloys- because there are high value applications available - if we can solve the materials problems
• We also develop stainless steel processes for specialist applications
• We’ve avoided titanium and aluminium at this stage due to an incompatibility of customer expectation/requirements and current capabilities
• We do not design geometries but freely advise (all) clients on the best methods to optimise designs to suit AM technologies
• 14 patent families
Capability List

- Sophisticated Quality and operational control systems
- 5 EOS M270 (Argon upgraded)
- Powder processing/conditioning, de-powdering
- Heat treatments; 2 furnaces with data-logging, vacuum furnace (Sept)
- Machine shop: mills, lathe etc. with wire EDM arriving (July)
- Abrasive blasting, hand finishing
- Inspection: including programmable CMM and GOM optical scanner, with dye-pen (Dec)
- Analysis: Optical and electron microscopes and sample preparation
- Metals/powder lab: (UKAS approval requested) Chemical analysis- Leco, Perkin Elmer, and size/morphology- Malvern Mastersizer, Sieve analysis (August)
- This is believed to be one of the most complete facilities available
Materials Development Lab

- Process development
- Validation of processes
- Specification development
- Routine property testing
Superalloys

- Superalloys are nickel-, iron-nickel-, and cobalt-base alloys
  - Generally used at temperatures above 500°C
- Unique combinations of:
  - High temperature strength, ductility & creep
  - Corrosion resistance
- Used extensively in gas turbine applications
Nickel Superalloys

- Readily weldable alloys
  - Solid solution strengthened
  - Precipitate strengthened $\gamma'$ or $\gamma''$

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- ‘Difficult’ to weld alloys
  - Alloys with high Al & Ti contents prone to cracking during welding
  - High $V_f$ $\gamma'$

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<tr>
<th>Alloy Name</th>
<th>Ni</th>
<th>Cr</th>
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<th>Mo</th>
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Weldability Diagram

Weldability diagram for some γ' strengthened superalloys

- Inconel 718
- Inconel 718+
- Inconel 625
- Hastelloy X
- CMSX-4
- CM247LC
- MAR M200
- C1023
- RR1000
- Hastelloy 718
- Rene 41
- MAR M002
- Inconel 793
- Inconel 939
- Udimet 720
- Difficult to weld & strain age cracking

Materials Solutions
Rapid development to meet environmental challenges
Characteristics of AM Nickel Superalloys

- Unique microstructure
- Low levels of porosity, micro-crack free
- Fine grain size, but elongated grains
  - Epitaxial grow across layers
  - Orientated in the Z direction

In 625 As-built

C1023 Solution treated
Mechanical Properties of AM Nickel Superalloys

- Mechanical properties are very good
- Microstructure dominates high temperature properties
- But they are different to cast & wrought

Room temperature tensile results for Inconel 718
Mechanical Properties of AM Nickel Superalloys

Elevated temperature tensile (649°C) tests for Inconel 718

Combined smooth & notched stress rupture tests for Inconel 718 (649°C 689 MPa)
‘Difficult’ to weld alloys

- Susceptible to cracking during welding
  - Solidification cracking
  - Grain boundary liquation cracking
  - Strain age or Post weld heat treat (PWHT) cracking
- Thermal and residual stresses are the driving force for cracking
Residual Stress Measurements

• Measured using the hole drilling technique
  • Stresses in the as-built condition are very high
  • 800 – 1200 MPa in C1023
  • Stresses are close to the UTS for the material
  • Materials with higher UTS have higher residual stresses
• Need to remove residual stress before removal from plate to avoid distortion
CM247LC

- Best temperature capability before single crystals
- Usually used in cast directionally solidified form
- Refined composition of MAR M247 alloy
  - Tighter elemental control & lower impurities for improved grain boundary strength
- Very high content of γ’ (>60%)
- Very difficult to weld
- Conventional weld repair solutions require welding at > 1000°C
- Initial target is MAR M247 properties
CM247LC Process Development

- Developed a process to eliminate micro & macro cracking
- Fully dense small, discreet pores 5 – 50 µm
- Reduced grain anisotropy and maintained small grain size
CM247LC Components

- Successfully built a number of different geometries
- Range of geometries possible under investigation
- Not all geometries possible
  - Stress concentrations can still result in cracking
Elevated Temperature Testing of CM247LC

- AM CM247LC in the solution & aged condition
- Cast equiaxed MAR M247 & cast DS CM247LC shown for comparison*
- Elevated temperature tensile tests @ 850ºC

Stress Rupture Testing of CM247LC

• Tested @ 850°C, 500 MPa load

Larson Miller Stress Rupture
AM CM247LC vs Equiaxed MAR M247

Larson Miller Parameter, \( P = \frac{T+273}{20+\log(t)} \times 10^3 \); \( T \) in °C, \( t \) in hours

Conclusions

• Additive Manufactured Nickel Superalloys can achieve excellent mechanical properties
• Fine grained, orientated microstructure dominates mechanical properties response
• Anisotropy in the materials needs to be controlled and understood
• New processes required to fully optimise each material
• Demonstrated potential for processing ‘difficult to weld’ materials like CM247LC
• Greatest benefits will be achieved when alloys are designed to match the AM process

• A long way to go- powder bed AM is at TRL/MRL 3~4- “manufacturing concepts identified”/proof of concept ~ “manufacturing processes in a laboratory environment”. TRL/MRL 8 is required before use
• Easy to underestimate the major tasks required in getting AM technologies into production- its not attractive work and seems very repetitive - because it is
• Everyone wants to design and invent, few want to develop and perfect
Thank you for your attention

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