Net Shape Processing of Titanium Alloys for Enhanced Performance and Improved Affordability

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Outline

Introduction

Conventional Net Shape Processing Methods
- Casting
- Forging
- Powder metallurgy
- Linear friction welding

Additive Manufacturing Processes
- Fusion processes
- Solid state processes
- Process advantages
- Cost advantages
- Limitations

Conclusions

Introduction

Conventional titanium processing for aerospace applications is characterized by excessive cost and waste

- Buy-to-fly ratio can typically average 15:1
  - For every 100 kg of starting material, 93 kg is wasted!
  - Unaffordable except for the most demanding applications

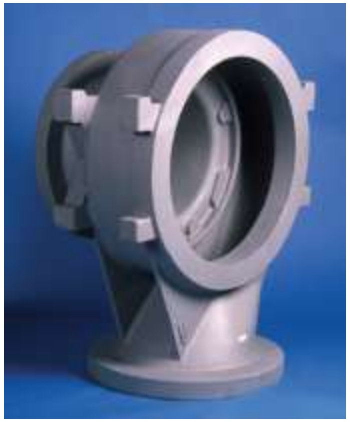
Net shape processing methods offer the ability to reduce buy-to-fly ratio and enable expanded titanium usage

- Less waste = reduced overall cost
  - enable competition with other lower cost materials (e.g. aluminum)
- Reduced processing = shorter lead time
- Net shape technologies offer novel structural configurations and the ability to produce improved or new alloy materials with tailored properties

Net Shape Casting

Casting offers capability for net shape fabrication

- Graphite mold processes
  - Rammed graphite – similar to sand casting approach
  - Machined graphite
  - Simple and economical
  - Limited in complexity and size
- Investment processes
  - High complexity
  - Prone to mold wall contamination
- Ideal for statically loaded applications
  - Casting factors can be limiting (if applied)
- Fatigue loaded applications are more challenging due to propensity for casting-related defects (porosity, inclusions, etc.)



The AMMTIAC Quarterly, Vol 2, 1 (2007)

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Net Shape Forging

In the aerospace market, forging is not generally considered a net-shape processing method

- For large structural forging, buy-to-fly is > 10:1
- Entire surface is machined/milled to final dimensions
- Design constraints (thin wall, deep, stiffened pocket design)

For small, relatively simple shapes, forging can be considered net-shape

- Usually requires high production volumes
- Thicker section sizes
- High tolerance (minimum or no machining)

Photo credit: FPD Company: www.fpdinc.com

Conventional Powder Metallurgy

Traditional powder metallurgy methods

- Cold press + vacuum sinter
- Vacuum hot press
- Metal injection molding + vacuum sinter

Features

- Pre-alloyed or elemental blended powder
- Capable of high volume and complexity
- Careful part design required due to sintering shrinkage
- Powder cost a critical limitation
  - Low cost titanium production methods could drastically improve economic advantages

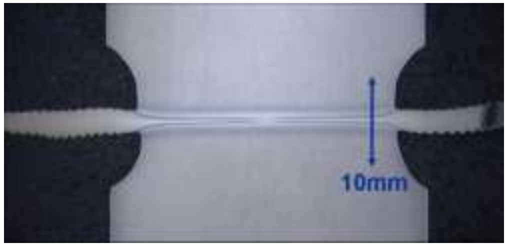
Photo credit: www.keytometals.com

Photo credit: GTI Manufacturing: www.gtimfg.com

Linear Friction Welding

Solid state joining process capable of creating complex three-dimensional shapes

- Applications include engine bladed disks and rings
- Emerging applications in airframe structures
- High capital equipment costs
- Limited weld surface area capability
- Very specialized application



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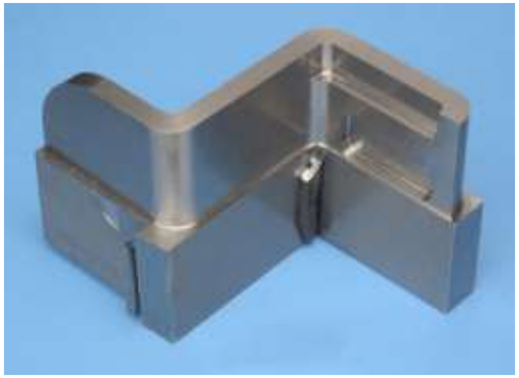


Photo credit: Thompson Linear Friction Welding: linearfrictionwelding.com

Additive Manufacturing

Additive manufacturing is broadly defined as processing methods that selectively add material in order to directly create a three-dimensional part directly from a computer model

- Enables structures impossible to make by conventional methods
  - requires re-thinking design methodology
- Can drastically lower cost and lead time – especially for high value materials (Ti)
- Can create novel materials by leveraging the process characteristics

Higher performance with improved affordability and rapid turnaround

Photo credit: Desktop Engineer: www.deskeng.com

Photo credit: Within Technologies: www.within-lab.com

Metal Additive Manufacturing Landscape

	FUSION			SOLID STATE	
	High Energy Beam		Arc	Ultrasonic	Cold Consolidation
	Laser	Electron			
WIRE	†RLMwD	EBF^3/Sciaky	†SMD †IFF †MER	Solidica †EWI–VHP	
POWDER FEED	LENS †Accufusion POM–Trumpf				Inovati CGT Obninsk CenterLine
POWDER BED	EOS 3D Systems MCP/MTT Phenix Systems Prometal Concept Laser fcubic	Arcam			

Additive Manufacturing Process Comparison

	Resolution	Deposition Rate	Power Efficiency	Coupling Efficiency	Cleanliness
Laser (low power)	↑	↓	↓	↓	↔
Laser (high power)	↓	↑	↓	↓	↔
Arc-based	↔	↑	↔	↑	↓
Electron beam	↔	↑	↑	↑	↑
Ultrasonic	↔	↔	↑	N/A	↔
Kinetic	↓	↓	↑	N/A	↓

Fusion Processes – Laser

First commercial development of additive manufacturing

- Commercial systems appear mid-to-late 1990s
  - AeroMet Corp. (service bureau)
    - large CO2 laser with blown powder
    - capable of large-scale deposited structure (> 1m)
  - Sandia/Optomec LENS (equipment manufacturer)
    - small YAG laser with blown powder
    - low deposition rates, smaller scale, but higher fidelity
- Recent proliferation of powder bed systems (e.g. EOS)
  - higher complexity parts
  - inability to mix powders and make gradient structures

Photo credit: Optomec Inc.: www.optomec.com

Brice et al, AeroMat 2010 Conf. & Expo. (2010).

Photo credit: Morris Technologies: www.morristech.com

Arcella et al, JOM May 2000

Fusion Processes – Electron Beam

Electron beam energy source

- Scalable output energy – watts to 10's of kilowatts
- Extensive capability for manipulating beam
  - focus
  - raster
  - power

  allows for rapid system control
- Requires hard vacuum (<100 µTorr)
  - provides clean environment
  - requires increased cycle time/cost
- Wire feed (Sciaky Inc) or powder bed (Arcam AB)
  - powder bed limited in size (20 cm x 20 cm x 20 cm) but much higher resolution and complexity
  - wire feed unconstrained by size but relatively low resolution

Brice et al, AeroMat 2010 Conf. & Expo. (2010).

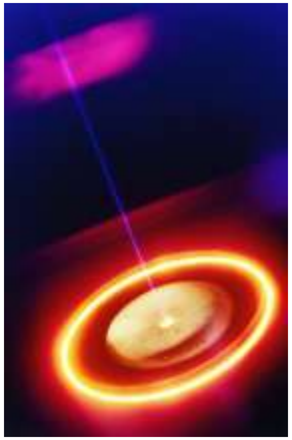


Photo credit: Arcam AB: www.arcam.com

Fusion Processes – Arc Based

Arc based processes utilize conventional welding techniques combined with sophisticated three-dimensional motion control

- GMAW, GTAW, PTA
- Can be done “out-of-chamber”, though challenging to do with reactive materials such as titanium
- Less thermally efficient versus high energy beam processes
- Much lower cost – capital and operational
- Scalable deposition rates

Photo credit: Cranfield University: www.cranfield.ac.uk

Solid State Processes

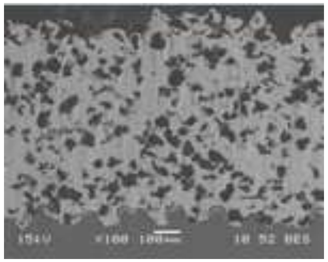


Photo credit: US Army Research Laboratory: www.arl.army.mil

iTTSe Newsletter, Vol 5, 10 May 2010.

Cold Spray

- High velocity powder stream deposited onto substrate with no bulk particle melting
- Low three dimensional fidelity
- Good for coatings – low heat input to substrate
- Good for repair
- Limited to certain material systems

Ultrasonic Consolidation

- Thin foil tapes ultrasonically welded together
- Low temperature, solid state process
- Unique layered/embedded arrangements possible
- High power needed for many engineering alloys

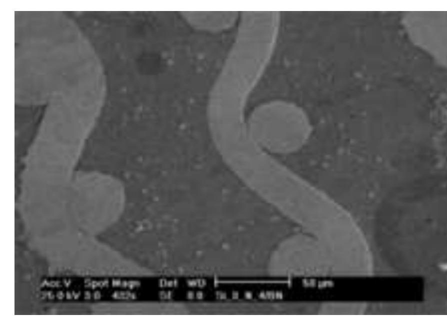


Photo credit: Solidica Inc.: www.solidica.com

Novel Materials

Additive manufacturing enables the creation of novel alloy materials due to the unique features inherent to the process

- Rapid solidification (100° C/s to 10,000° C/s) allows for non-equilibrium processing
  - extended solubility
  - metastable phases
  - unique microstructural features
- *In-situ* alloying using blended powders, reactive gasses, etc.
- Compositional gradients through the use of multiple feedstock materials
- Metal-matrix composites – discontinuous and continuous reinforcements

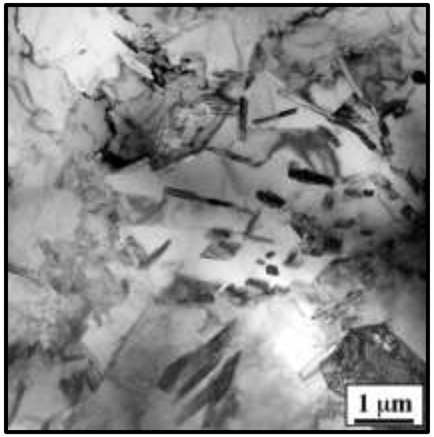
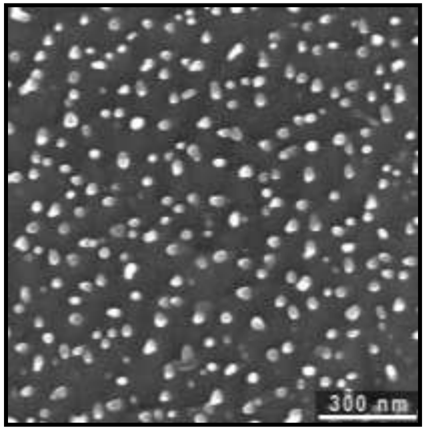


Photo credit: R. Banerjee, University of North Texas

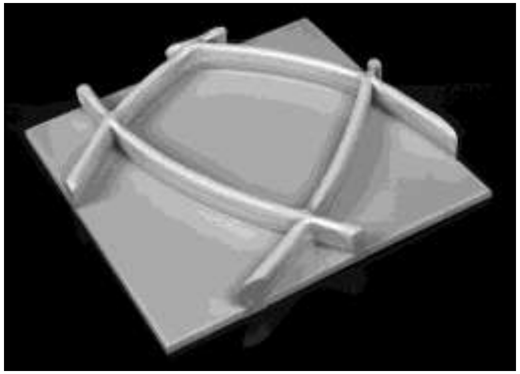


C.A. Brice, Proceedings of 11th World Conf. on Titanium (2007).

Novel Structures

Additive manufacturing enables the creation of novel structural shapes/configurations

- Unitized structure for reduces part count
- Curvilinear stiffened structure for optimized load paths, tailored acoustic transmission, etc.
- Lower density structures – periodic truss structures, random foam, etc.
- Conformal cooling channels, conduit, etc.
- Shapes *impossible* to build through conventional methods



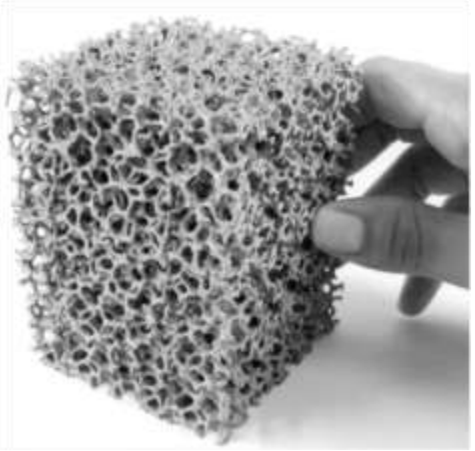


Photo credit: Frank Medina, University of Texas–El Paso

Photo credit: Arcam AB: www.arcam.com

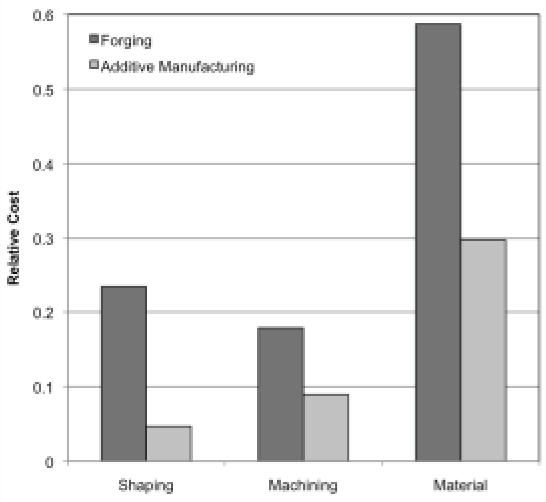
Cost Advantages

Significant cost savings possible through additive manufacturing

- Reduces/eliminates tooling requirements
- Fabrication directly from 3D CAD file
  - allows for rapid creation and rapid modification when necessary
- Reduces/eliminates finishing (e.g. machining)
  - significant savings from reduced material buy *and* reduced machining

Candidate structural titanium airframe part for pilot implementation (Lockheed Martin F-35 Program)

- Replaces die forging
- Large-scale electron beam/wire method (EBF^3)
- Significantly reduces "buy-to-fly" ratio
- Estimated 30% to 60% cost savings



Adapted from Brice et al, Presented at AeroMat 2010 Conf. & Expo. (2010).

Limitations

For aerospace applications, the single biggest limitation is the lack of extensive statistical data for design

- A, B, or S-Basis design allowable values
- Component static/dynamic full-scale test articles
  - expensive and time consuming
  - not necessarily transferrable across processes
- Effects of defects & probability of detection

Other issues

- Capital equipment cost
- Feedstock cost
- Deposition rates
- Surface finish
- Residual stress & distortion

Conclusions

Titanium net shape processing methods can deliver significant cost and time savings when compared to conventional processing methods

- Affordability and environmentally responsible manufacturing demands will require adoption of net shape methods

Additive manufacturing is a net shape enabling family of processes that can further improve cost and lead time while delivering unique performance characteristics

- Reduced waste (lower buy-to-fly ratio)
- Reduced post processing
- Novel materials and structural concepts