7. Near Net Shape Processing

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

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Net shape processing methods offer both cost and performance advantages over the fabrication of titanium alloy components from conventional ingot metallurgy. While many net shape processing methods are well established in niche markets, the emergence of additive manufacturing in the titanium aerospace market offers the potential for revolutionary advances in cost reduction and performance enhancement. From an affordability perspective, net shape processing can limit the need for cost intensive thermomechanical post processing operations. This is especially important for titanium alloys that are relatively difficult to handle at elevated temperatures, and challenging to mechanically work into useful shapes. Net shape processing also limits or eliminates the need for costly machining operations, which can account for a significant fraction of the overall production cost, especially in the aerospace market. Beyond affordability, net shape manufacturing can also provide a means for creating novel alloy compositions and microstructures through non-equilibrium solidification, solid-state consolidation, and gradient compositions. This paper reviews the broad capabilities for net shape processing of titanium alloy structures and offers a detailed assessment of additive manufacturing techniques for the low cost fabrication of advanced titanium components.

Keywords: *Titanium (Ti), net shape, additive manufacturing*

1. Introduction

Titanium alloys are often reserved for demanding applications where the need for exceptional performance outweighs the high cost burden. This is particularly true in aerospace applications where the various structural materials available have drastically different cost profiles. Compared to aluminum, the costs associated with refining titanium are approximately five times higher. The costs to further form and fabricate the refined metal into a useful product add an additional factor of 10 to the overallcost[1]. The performance demands for choosing titanium over aluminum (or other structural alloys) must be high in order to justify this extreme cost burden.

In the aerospace market, waste and inefficiency are common in the structural materials value stream. The common metric for measuring process inefficiencies is the buy-to-fly (BTF) ratio. This is simply a measure of the cumulative waste generated through all the processing steps for a given part. Buy-to-fly ratios can exceed 100 : 1, however, on average, they are around 15 : 1. For the Lockheed Martin F-22, an airplane with 40% titanium by weight, the average BTF for titanium structure was approximately 11 : 1[2]. In direct terms this means that roughly 92% of the titanium purchased for the program (50,000 kg per vehicle) was turned into waste. Clearly there is a need for robust net shape processing methods that can improve the material utilization rate. For large titanium-intensive programs with high volume production runs, even incremental improvements towards near net shape processing can translate into millions of dollars of programs savings and lead to a significantly reduced waste stream.

2. Established Net Shape Processing Methods

Many net shape manufacturing fabrication options are currently available for titanium alloys. Some of these methods directly yield parts that require little or no additional post processing. Minimizing the labor and material waste associated with these post processing steps is key to reducing the overall cost for a given structure. These efficiency gains, however, must be achieved without any loss in overall material quality or inspectability. The slow pace of adoption of net shape methods for titanium illustrates what a challenging endeavor this is.

2.1 Casting

Castings offer an excellent combination of shape complexity and size capability. Exceptionally intricate, very large shapes have been successfully fabricated in titanium using casting techniques[3]. Castings generally fall into two main categories: lost-wax investment and graphite mold (rammed or machined). Graphite mold methods offer the advantage of a sand casting-like approach using cope and drag molds and simple (e.g. wooden) patterns[4]. The investment method holds an advantage in part complexity as there is no parting line in the mold and associated draft issues which can limit geometric precision. For aerospace applications, investment casting has historically been the preferred method.

The Lockheed Martin F-22 program embarked upon an ambitious plan to introduce investment castings as a large percentage of the structural weight of titanium in the aircraft. Early in the program, over 60 titanium castings with a combined weight of 590 kg were scheduled to be incorporated on the airframe[2]. Most of these castings were ultimately put on the production airplane representing a significant shift towards closer-to-net methods. While this shift did improve the titanium manufacturing efficiency on the program, it still generated significant waste. The early analysis for the

F-22 program showed a buy-to-fly ratio of about 7 to 1 (pour weight to finished titanium weight). While the excess material is largely in gates and risers and relatively cost effective to remove, these numbers demonstrate that the casting process is not without its own inefficiencies.

Another issue that has limited the advancement of titanium castings into the aerospace market is the legacy application of casting factors in design load calculations. These casting factors reduce the design minimum strength values in order to compensate for defects within the part. These defects are generally categorized as inclusions (such as ceramic mold material) or voids (such as porosity)[5]. Improvement in solidification modeling, inspection methods, and the use of hot isostatic pressing have greatly improved casting quality. In 2008 Tital was approved by Airbus Germany to produce titanium castings for the A380 program with a casting factor of 1.0[6]. While this is a notable achievement for strength-limited structure, for fatigue-limited structure minimum flaw sizes still dictate part design. And the higher propensity for flaws in castings generally requires larger minimum flaw size criteria relative to wrought products. Continued improvement in casting quality, primarily as it relates to defects, will be required before titanium castings can compete on a large scale with fracture critical wrought and forged material.

2.2 Powder Metallurgy

Various traditional powder metallurgy (P/M) methods are available for producing complex net shape titanium parts[7-9]. Generally these methods excel at producing small, high volume parts and are capable of very complex geometries. In general, the consolidation methods available are:

- Cold press (uniaxial or isostatic) + vacuum sinter
- Vacuum hot press (uniaxial or isostatic)
- Metal injection molding (MIM) + vacuum sinter

These methods can employ either prealloyed or blended elemental powder feedstock. The atomization process for producing prealloyed powders is an expensive and hazardous batch process that adds significant cost to the overall process. Elemental blends are more cost effective as they often use sponge fines blended with master alloy powders at the desired final alloy ratio. This method also enables the incorporation of novel alloying additions that can result in new compositions with unique properties[10].

The main processing challenges for P/M titanium processes are shrinkage/distortion, residual porosity, and binder contamination. While challenging, these limitations can all be overcome through the use of proper design strategy and careful selection of consolidation method. Beyond the intrinsic limitations of the process, the single biggest factor limiting the growth of the titanium P/M field is the cost of the powder materials. Recently much attention has been given to the field of "low cost titanium" and multiple approaches have been funded world-wide in an attempt to reduce the cost of refining titanium metal[11]. The advantage to the P/M industry is that many of these processes directly yield prealloyed powder or agglomerate. If one or more of these methods succeeds in producing industrial-scale quantities of low cost titanium powder, the titanium P/M industry will surely benefit.

2.3 Precision Forging

Forging can be considered a near net shape technique depending on the size and shape of the part being formed, though the need to remove alpha case formed during forging prevents it from being truly net shape. For large titanium aerospace structures, however, forging is generally not considered a near net shape method due to the large amount of excess material that must be removed after the forging process. For closed die forgings, the processes are characterized (in increasing order of net shape fidelity) as blocker, conventional, high definition, and precision, with precision requiring little or no post process machining[12]. For aerospace structures, precision forgings are generally not an option due to geometric constraints (deep, stiffened pocket design with thin gage walls).

A published example from the Boeing 757 program illustrates the efficiency gains possible through progression to a closer-to-net shape forging approach [*ibid.*]. The progression from blocker to conventional to high definition reduces the buy-to-fly ratio from 5:1 to 4:1 to 3.2:1. While this represents a 35% reduction in overall material usage is still only utilizes 30% of the starting weight of the forging (with 70% being turned into waste through machining). Further improvements that yield a closer-to-net forged shape could be achieved with certain ideal geometries, however, production volumes and the economic "break even" point must be considered. Due to the difficult hot working characteristics of titanium, the push to a closer-to-net shape equates to increased steps and/or die sets which leads to increased non-recurring cost. Furthermore, early part designs are often intentionally low in fidelity in order to allow for design changes after the forging dies have been produced. Combined, these factors require a large volume production run and an incremental approach towards closer-to-net shape in order fornear-net shape forgings to be a viable production method.

2.4 Linear Friction Welding

Linear friction welding is a very specific category of net shape processing. The frictional heating associated with the relative motion of two components under pressure results in a clean, metallurgically sound bond[13]. This method has primarily been used in aero engine applications for the fabrication of bladed disks (blisks). The high capital equipment costs and very specific geometric constraints have limited the usefulness of this method beyond engine components. Additionally, the current largest weld demonstrated in titanium is 100 cm^2 which further limits the size and scale of candidate parts[14].

Boeing has recently been exploring the possibility of using linear friction welding to join titanium[15]. By adding small blocks of material to a simple geometry (such as a plate) using linear friction welding, a three dimensional tailored blank can be created that approximates the final shape of the part. This allows plate segments to be joined into a shape that would otherwise require forging to make. This near net shape approach can save raw material and processing cost even though final machining is still required. For ideal shapes, this is a useful near net shape approach.

3. Additive Manufacturing Methods

Additive manufacturing (AM) is a collection of technologies that has matured rapidly over the past 15 years. In general, additive manufacturing can be classified as fabrication techniques that utilize a feedstock material and some form of automated motion control to systematically deposit material into a three dimensional form. These techniques can be described by their consolidation method (either fusion or solid state) and by their feedstock material (either powder or wire/tape). Figure 1 shows a detailed breakdown of current metallic additive manufacturing technologies.

	FUSION			SOLID STATE	
	High Energy Beam		Arc	Ultrasonic	Cold Consolidation
	Laser	Electron			
WIRE	†RLMwD	EBF³/Sciaky	†SMD †IFF	Solidica †EWI-VHP	
POWDER FEED	LENS †Accufusion POM-Trumpf		†MER		Inovati CGT Obninsk CenterLine
POWDER BED	EOS 3D Systems MCP/MTT Phenix Systems Prometal Concept Laser fcubic	Arcam			

Figure 1. The current metallic additive manufacturing landscape broken down by heat source and feedstock material. Technologies marked with † indicate that a commercial system is not yet available though significant research work is being conducted in that area

3.1 Fusion-Based Methods

Fusion-based methods are by far the most common techniques for metallic additive manufacturing. As can be seen in Figure 1, the majority of commercially available systems utilize a laser heat source and a powder feedstock. These methods share a common ability to create very intricate, high resolution parts on a relatively small scale. Deposition rates are generally 50 to 100 g per hour for titanium and parts can be created net or very near to net shape[16].

The laser/powder method can be further segmented into powder feed or powder bed processes. In the powder feed process the powder is delivered to the molten pool by a delivery nozzle and a carrier gas. The laser and powder delivery nozzles are typically translated with respect to the substrate surface. With sufficient motion control axes, fully three dimensional shapes can be produced including unsupported overhanging features. Powder efficiency (i. e. how much powder actually gets melted in the pool) can range from 5% up to beyond 90%. The excess powder can potentially be reused though the reactivity of titanium must be considered when excessive handling is necessary.

The other laser/powder methods utilize a bed of powder and a stationary heat source. The laser is deflected over the over the powder bed surface and melts/fuses the powder together one layer at a time. After each layer is fused, a new layer of powder is spread across the top surface and the melting process is repeated. While the layers in this approach are all deposited normal to the initial substrate plane, a fully three dimensional shape is possible through the addition of built-in support feature and the support of the unfused powder surrounding the part. Finishing the part requires removal of support features and any adhered surface particles. As with the powder feed approaches, the unused powder can be recycled and reused though contamination is concern here as well.

For electron beam-based methods, there are fewer options available. One of the primary advantages electron beam-based methods have over the laser methods is the ability to deposit a broader range of alloy materials. The laser coupling interaction with highly reflective materials (e. g. aluminum) is quite poor depending on the wavelength of the laser source. This is not an issue with electron beam heat sources. The electron beam/powder process commercialized by Arcam AB Mölndal, Sweden, is very similar to the laser/powder bed processes in that the heat source is fixed and deflected over a powder bed in order to fuse each layer. The major difference in this method compared to the laser methods is that the processing chamber is under vacuum. The deposition rates are somewhat higher than the laser-based processes (300g per hour for titanium)[17] but the trade off is less resolution and a rougher surface finish.

The other electron beam method is the EBF^3 process commercialized by Sciaky, Inc. , Chicago, Illinois, USA. This system utilizes a very large vacuum processing chamber with translating table and/or electron gun and the wire feedstock is fed directly into the molten pool. The primary advantage of this system is its ability to deposit at very high rates (5 to 10 kg per hour) and make very large parts. These advantages make this method the most attractive for producing large primary structure for aerospace applications. Currently Lockheed Martin is pursing a pilot implementation effort on the F-35 program for the replacement of large (up to 3 meter long) titanium forgings[18]. Further details will be discussed in the Affordability section.

3. 2 Solid-State Methods

Solid-state methods for producing net shape titanium components are also available. The consolidation method is either through ultrasonic joining of flat tape or high velocity impact of powder/particulate material. Solidica, Inc. of Ann Arbor, Michigan, USA, has commercialized an additive manufacturing system that can deposit flat tape material in an additive fashion that also incorporates integrated machining for true net shape capability. The solid state nature of this process give it certain advantages over fusion-based methods, however, power limitations inherent to the system restricts the ability to process high strength materials like titanium. Edison Welding Institute, Columbus, Ohio, USA, is currently working to increase the power capability of the ultrasonic consolidation method with the goal of applying it to a wider range of alloy systems, including titanium[19].

Powder-based solid-state consolidation (also known broadly as cold spray) is a method where powder particles are accelerated to a very high velocity and impacted against a substrate. The high velocity impact joins the individual particles together in a manner similar to other high strain rate joining methods (e. g. explosive bonding). This is an effective method for generating cladding-like feature but is less successful at generating fully three dimensional structures. Other issues associated with contamination (oxygen absorption) and porosity have also presented challenges to this technique when using titanium alloys[20].

3. 3 Affordability Advantages

Cost savings is one of the primary advantages additive manufacturing has over conventional methods for producing titanium structure. The cost to refine titanium combined with the cost to process it into a useful shape is very much a limiting factor in expanding its use inside and particularly outside the aerospace market. There are, however, specific criteria that help determine the applicability of AM to a given structure and the possible cost savings relative to conventional processing techniques.

The two key considerations for choosing a specific AM method are resolution and deposition rate, which are generally inversely related. In order to achieve a truly net shape structure, a high fidelity, low deposition rate method must be chosen. Conversely, in order to build large structures in an economically reasonable amount of time, a coarse method with high deposition rate must be chosen. For aerospace structures, a secondary consideration relates to surface finish. Most titanium structure in air vehicle applications is deemed fracture critical and thus the surface finish must be tightly controlled in order to reduce the potential for surface crack nucleation. Thus, most surfaces require a machined or chemical milled surface finish. This requirement can often time negate the benefits of a closer-to-net shape process as an appropriate amount of cover material must be incorporated into the part such that all surfaces can be machined to the proper dimensions with the proper surface finish. As the excess cover material is reduced, it becomes increasingly difficult to fixture the part for machining such that the deposited pre-form yields the desired finished structure. Finding the right balance between sufficient cover material for ease of machining and minimum cover material for reduced machining cost is critical.

The economic advantage for small, high production run titanium parts has already been demonstrated in the medical device market[21]. For the larger parts and lower production volumes typical of the aerospace market, AM methods become less competitive against conventional methods such as closed-die forging. An extensive business case analysis was conducted by Lockheed Martin for the F-35 program examining potential cost savings possible by replacing forged titanium parts with electron beam/wire AM parts. A relative cost summary for a particular F-35 structure is shown in Figure 2[18]. These cost estimates compare the baseline forged method with the proposed AM approach on a unit recurring flyaway cost basis. The total forged cost (shaping plus machining plus material) has been normalized to one for ease of comparison. While the shaping cost is drastically reduced in switching to an AM approach, the largest overall cost savings is reflected in the reduced material usage. The reduced waste offered by net shape processing methods is key to improving affordability.

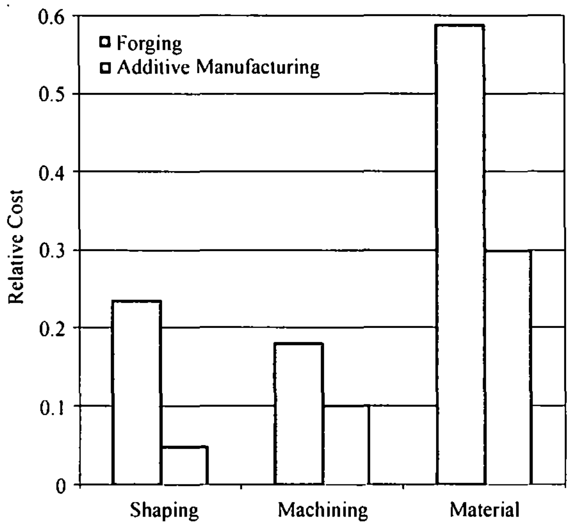


Figure 2. Relative cost breakdown for a candidate additive manufactured titanium large aero structure part. The sum of the forging cost is normalized to one. Adapted from[19]

3.4 Novel Materials

Additive manufacturing techniques have some fundamental processing characteristics that can be advantageous for creating novel materials and unique structural configurations. The incremental nature of the processes allows for much greater control of the microstructural features. For fusion-based processes, the molten volume is very small relative to ingot-based processes and thus the cooling rates can be quite high. The cooling rate generally depends on molten pool dimensions and the rates are in the 10^3 to 10^5℃ per second range. At these cooling rates, solubility limits can exceed equilibrium and phase transformations can be suppressed leading to the development of metastable microstructures. This leads to unique materials that are AM-specific that cannot be processed by other conventional methods.

A number of novel alloy compositions have been previously deposited in titanium. The reactivity of titanium combined with the rapid solidification inherent to the process can produce in-situ reactions with unique results. Oxide dispersion strengthening is possible through the incorporation of trace amounts of rare earth elements. The rare earth elements react with the oxygen present in the alloy and form an oxide dispersion. The rapid solidification of the process produces a well distributed network of nano-scale dispersoid particles. For compound-forming elements such as boron, a similar advantage can be achieved through the in-situ reaction with the titanium itself. Conventional ingot processing of similar compositions is possible though the microstructural scale and resultant properties are drastically different[22]. Figure 3(a) shows a laser/powder deposited Ti-B alloy with fine, nano-scale TiB precipitates. Again, the rapid solidification behavior is key to the microstructural development.

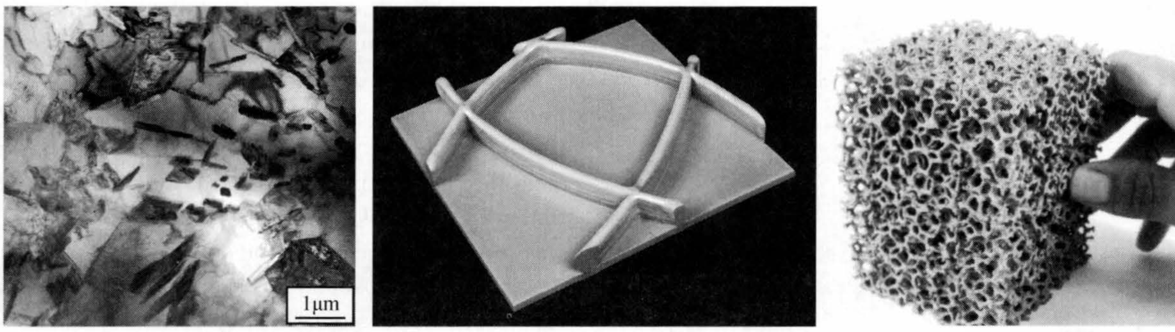
Additive manufacturing also offers the opportunity to create functionally graded compositions by varying the input chemistry during deposition[23-24]. This can be done through mixing of standard alloy composition or through the use of elemental blends of powders. Either way, this technique offers the possibility of continuously variable compositions. Conceptually, this technique could allow for customized alloy chemistry (and resultant properties) at any location in a given part. As is often the case in aerospace structures, the governing design criteria (e. g. strength, stiffness, durability, etc.) varies based on location within the part. By allowing the chemistry to change within a part in order to optimize the local structural performance, more efficient designs will be possible. This could lead to significant performance increases with an associated reduction in overall structural weight.

The solid-state AM techniques offer some unique advantages of their own. Layered combinations of typically incompatible alloys are possible with non-fusion processes. Selective reinforcement with fiber materials, embedded sensors for structural health monitoring, and complex conformal cooling channels in mold tooling are a few applications already demonstrate with these AM processes[25-27].

3.5 Novel Structures

In addition to materials advantages, there are structural design advantages to additive manufacturing as well. The ability to create freeform shapes without the need for expensive tooling is a major advantage of AM processing techniques. Rapid prototyping allows for quick proof-of-concept fabrication and gives structures designers the freedom to easily modify and refine a part design. For large structures that would typically be forged (and require forging tooling), this flexibility is tremendous benefit. Lead times for tooling intensive aero structures can spanmultiple years and this often creates a design constraint as the remainder of the vehicle is designed around these long-lead-time structures. The flexibility to create short-lead-time, tooling-free parts is very advantageous during the design integration phase of an air vehicle program.

The freeform fabrication capability of AM methods allows materials designers the ability to adopt a biologically inspired, organic design philosophy and create structures that cannot be fabricated any other way. The evolution of aero structural design practice has largely been influenced by the manufacturing processes available for fabricating and assembling structure. The current methodology of an orthogonal array of structural features is advantageous from a manufacturing standpoint, however, this is not always the most ideal design from a structural efficiency standpoint. Allowing the load path to determine the most effective structural design is possible if the capability to economically fabricate complex curvature, curvilinear stiffened structure is available. Demonstration of this concept is shown in Figure 3(b).



(a) (b) (c)

Figure 3. (a) Mircograph of laser/powder deposited Ti-B alloy showing nano-scale TiB precipitates [Photo courtesy P. Collins, University of North Texas], (b) Photograph showing notional curvilinear stiffened panel deposited using the electron beam/wire process. (c) Photograph showing random, reticulated foam structure deposited using electron beam/powder process [Photo courtesy F. Medina, University of Texas-El Paso]

Another organic design concept allowed by additive manufacturing is the ability to create functional density gradients in structures. These can be periodic arrangements of ligaments or they can be completely random foam-like structures. Figure 3(c) shows a photograph of a foam structure made using an AM process[28). These concepts can further optimize the structural efficiency of a part by reducing mass in areas where monolithic properties are unnecessary.

3.6 Limitations and Challenges

For all the potential benefits AM methods have to offer, there are still many limitations and challenges that stand in the way, especially for producing demanding aerospace structures. Qualification of new processes and materials is a costly and time consuming effort. In order to ensure consistency and repeatability in the process, a very large data set is necessary to establish design minimum properties. The true challenge with AM processes is that while they are all somewhat similar (such as the seven laser/powder bed methods shown in Figure 1), they are not identical. Thus, qualification data established on one system may not be applicable for another system. Finding a statistically rigorous way to pool data for similar processes is critical for advancing AM technologies into the aerospace market. Furthermore, rapid qualification procedures relying on computational materials design will be necessary to advance the new and novel materials that are available through AM.

Another serious limitation is the ability to design and analyze structures created with the freeform capabilities of AM. Current analysis techniques require fully solid, monolithic materials in order to accurately predict the stress field upon loading. The ability to create chemical and density gradients along with other novel constructs will be limited as long as there is no reliable method for conducting finite element analysis for stress state verification.

4. Conclusions

Titanium net shape processing methods can deliver significant cost and time savings when compared to conventional processing methods. The high cost to refine and fabricate titanium structures is a limiting factor in their expanded use. Affordability and environmentally responsible manufacturing demands will require a shift away from wasteful, inefficient processes toward improved methods. Adoption of net shape methods can help to improve the economics of titanium, lower waste, and allow it to better compete with other structural aerospace materials.

Additive manufacturing technologies have rapidly progressed in the past 15 years. These methods are broadly applicable to titanium alloys and can drastically reduce cost and lead times in aerospace structures. Additional benefits include the ability to create metastable alloys with unique properties and novel structural configuration with improved efficiency. The adoption of these technologies in the aerospace market will be paced by the high qualification burden necessary to introduce new materials and processes for fabricating flight articles. The increased need for aerospace titanium structure as B787, A380, and F-35 come into full production will likely provide some impetus for more rapid adoption of net shape processing capabilities.

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