Design of 3D-Printed Titanium Compliant Mechanisms

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Abstract

This paper describes 3D-printed titanium compliant mechanisms for aerospace applications. It is meant as a primer to help engineers design compliant, multi-axis, printed parts that exhibit high performance. Topics covered include brief introductions to both compliant mechanism design and 3D printing in titanium, material and geometry considerations for 3D printing, modeling techniques, and case studies of both successful and unsuccessful part geometries. Key findings include recommended flexure geometries, minimum thicknesses, and general design guidelines for compliant printed parts that may not be obvious to the first time designer.

Introduction

A compliant mechanism derives its motion from the deflection of its constituent members. Compliant mechanisms offer decreased part count, decreased complexity, lower weight, longer life, and lower cost. Since compliant mechanisms can be designed with no surface contact, wear and all its associated issues are eliminated. In many cases, bearings may be eliminated, along with their weight, complexity, and failure modes [1]. Preliminary work has shown the applicability of compliant mechanism technology to space applications [2]. Additionally, compliant mechanisms lend themselves to monolithic construction through additive manufacturing processes.

Advances in Electron Beam Melting (EBM) enable additive manufacturing (also referred to as rapid manufacturing) in a variety of metals, including alloys of Titanium. The EBM process is well documented [3] [4]. Case studies have shown that rapid manufacturing offers reduced costs when production volumes are low, many design iterations are to be explored, high geometric complexity is needed, or when new materials are to be explored [5] [6]. Additionally, material scrap rate can be significantly reduced by printing a near-net-shape part rather than machining it from solid billet [7]. Combining compliant mechanisms with rapid manufacturing techniques opens up interesting possibilities for creating compliant space mechanisms that have unprecedented performance.

Figure 1. A compliant titanium hinge produced with EBM. This hinge is capable of ±90° of motion. Images provided courtesy of Robert Fowler. [8]

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Rapid manufacturing processes have been used in multiple aerospace applications, including ductwork [5] [6] and a capacitor housing on the International Space Station [9]. These applications used selective laser sintered nylon parts, which established a basis for rapid manufacturing as a viable method for producing parts. Structural brackets [3], a shrouded cryogenic impeller [3] [10], and brackets for the Juno spacecraft [7] have also been manufactured in titanium using rapid manufacturing processes. While most parts built thus far have been structural members (brackets, etc.) or non-structural assemblies (ductwork and housings), in our work we use additive manufacturing to create monolithic mechanisms for aerospace applications. As part of that effort, it is desirable to know what to expect when printing slender geometries, and maximum allowable stresses in EBM-produced titanium parts.

Material Considerations

Porosity of EBM produced parts

EBM produced parts can achieve full density [11]. Wooten and Dennies claim that the fully dense region occurs in bulk parts about 1.25 mm (0.05 in) below the surface [3], but give no explanation of how this figure was arrived at. This depth is more than the thickness of many printed flexures. While the region near the surface may not be fully dense, Murr et al, mention that such micropores have no effect on short-term tensile properties [12]. However, surface roughness and micro-cracks contribute to reduced fatigue life. Because of the slender geometry, machining of flexures is often impractical, so surface porosity is difficult to eliminate and must be accounted for in the design. This surface porosity constitutes a major obstacle to high cycle fatigue life. Hot isostatic pressing (HIP) improves the fatigue life of EBM produced parts [13]. If HIP treatment is impractical, property data obtained from raw (not treated with HIP or finish machined) tensile samples are available [14].

Thickness Correction Factor

Early design work for a two-degree-of-freedom (2 DOF) pointing mechanism [15] required testing the fabrication and performance of cross-axis flexural pivots. These flexures have a number of good characteristics, including good stability and load carrying capacity [16]. The flexure was modeled in ANSYS to predict its torsional stiffness, which was compared to analytical solutions. Finally, the flexures were produced using EBM, and an example is shown in Figure 2, along with the pointing mechanism.

The torque and deflection characteristics of three printed flexures were found. The FE model significantly over-predicted (~30%) the stiffness of the printed. Because of high surface roughness, it was thought that perhaps not all of the thickness of the flexure contributes to its bending stiffness. Applying a correction factor of 0.83 to the thickness resulted in good agreement between the FEA and measured stiffness of the flexures. Later this correction factor was used to predict the overall stiffness of the pointing mechanism, again resulting in good agreement. Therefore, when using thin flexures, a thickness correction factor of 0.83 is recommended to accurately predict the torsional stiffness of printed flexures.

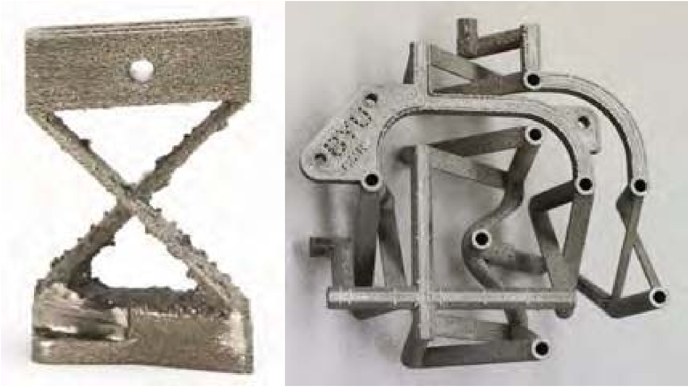

Figure 2. Cross-axis flexural pivot and 2 DOF pointing mechanism used to compare FEA and analytical models to measured stiffness.

Allowable Stress

Two grades of titanium powder are currently produced for use in EBM machines: Ti6Al4V and Ti6Al4V ELI (ELI is “extra low interstitials,” which improves ductility and fracture toughness of the alloy). These two alloys have slightly different strength characteristics, but Ti6Al4V has slightly higher strength [13]. Table 1 presents strength data from several sources. These data were gathered from samples prepared in different ways; some used highly polished samples while other samples are tested in the as-built condition, with no post-processing or heat treatment. Rafi et al, found a strong correlation between build orientation and strength [14], while the manufacturer data make no distinction between build orientations [13].

Table 1. Summary of strength data gathered from other sources. (*) indicates that sample underwent HIP process.

Material	S_y	S_{ut}	S_e	Notes
Ti6Al4V	950	1020	600*	Manufacturer data [13]
Ti6Al4V ELI	930	970	600*	Manufacturer data [13]
Ti6Al4V ELI	782	842	120	As-built vertical [14]
Ti6Al4V ELI	844	917	225	As-built horizontal [14]
Ti6Al4V ELI	869	928	325	Machined vertical [14]
Ti6Al4V ELI	899	978	300	Machined horizontal [14]

Geometry Constraints

Feature Geometry

Minimum wall or flexure thickness depends on feature orientation. A minimum thickness of 0.75 mm is recommended for flexures that have the thickness orthogonal or parallel to the build direction. If the flexure is built at other angles, 1.00 mm is recommended as the minimum thickness. If the flexure is built at some angle from the vertical, the larger dimension is recommended. Figure 3a illustrates this orientation dependence. The authors have had good success building flexures that rise at 45° from the horizontal when the flexures are 1.00-mm thick.

Figure 2. (a) - Flexures built at angles not orthogonal or parallel to build plate should be slightly thicker. (b) - Horizontal flexures build more successfully when supported by build plate as shown on the right.

Thermal Stresses and Part Warping

Because the build chamber is maintained at between 500°C and 700°C, most stresses are relieved during the part’s build cycle [11, 3], but some warping due to thermal stresses has been observed. Figure 4 shows a part where enough warping occurred that the part failed to build correctly. Although not fully understood, it is thought that this warping is due to stresses that occur when the molten metal solidifies but are subsequently relieved as the part is held at high temperature. Usually the part is bulky enough that these low stresses do not cause warping. For the geometry shown in Figure 4, the part was redesigned to have the flexures rest on the build plate (illustrated in Figure 3b). Supporting the flexures in this way eliminated the warping and allowed a successful build. It is postulated that other ways to avoid warping include better support of the cantilevered flexure from underneath (by having it connect to another portion of the part) or making it wider. In general, narrow, unsupported flexures are to be avoided.

Figure 3. Build failure due to warping of slender flexures.

Manufacturing Clearances

Clearances are important to ensure that the completed mechanism can move freely, without fusing sections that should move relative to one another. On a number of mechanisms with small (<2 mm) gaps, the final gap dimension was significantly less than was specified in the part file. Additionally, gaps must be wide enough that un-melted powder can be easily removed to allow motion in the mechanism. Experience with successful mechanisms suggests a minimum gap of 1.0 mm. The final gaps are less than the specified gap. In one instance, a gap as small as 0.66 mm was specified and the part successfully printed without fusing the two sections together; the measured clearance was 0.23 mm. These clearances were measured in the horizontal direction (parallel to the build plate). Vertical clearances should be specified larger, especially in areas where powder removal is difficult.

Powder and Support Removal

Another design consideration is that the geometry must allow for removal of un-melted powder and any support structure. Closed geometries should be avoided, or openings should be provided to allow access to loosen packed powder with hand tools or media blasting. In some cases this may not be possible, and post machining using special fixtures or tooling must be used. Figure 5 shows the tooling required to allow machining the inside of a particular feature. In another case example, a linear spring was printed that consisted of Belleville washers stacked end-to-end. The internal areas of the spring were inaccessible, but by using a press to compress the spring, enough powder was removed from between each washer segment to allow the spring to function as intended.

Figure 4. The 2 DOF pointer mechanism in fixture for removal of powder and supports from inside a split-tube flexure.

Summary

The following checklist can be used for designing compliant mechanisms for EBM manufacturing:

- ☐ Select minimum thickness for desired flexure orientation (0.75 mm for horizontal or vertical flexures and 1.0 mm for other angles)
- ☐ Find flexure length sufficient to bring stress into allowable range, subject to deflection and thickness
- ☐ Select flexure width to support applied loads without requiring excessive actuation torque
- ☐ Ensure minimum gap width is observed (1.0 mm)
- ☐ Ensure horizontal flexures are supported at both ends
- ☐ Ensure that geometry allows powder removal
- ☐ If post-machining is necessary, provide geometry for fixturing
- ☐ Orient part so that every feature is built up from build plate or supported in some way

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References

[1] L. Howell, Compliant Mechanisms, John Wiley Sons, Inc, 2001.

[2] R. M. Fowler, L. L. Howell and S. P. Magleby, "Compliant space mechanisms: a new frontier for compliant mechanisms," *Mechanical Sciences,* vol. 2, pp. 205-215, 2011.

[3] J. Wooten and D. P. Dennies, *Electron Beam Melting Manufacturing for Production Hardware, Paper number 08AMT-0061,* SAE International, 2008.

[4] L. E. Murr, S. M. Gaytan, D. A. Ramirez, E. Martinez, J. Hernandez, K. N. Amato, P. W. Shindo, F. R. Medina and R. B. Wicker, "Metal Fabrication by Additive Manufacturing Using Laser and Electron Beam Melting Technologies," *Journal of Materials Science & Technology,* vol. 28, pp. 1-14, 2012.

[5] B. Fox, "Rapid Manufacture in the Aeronautical Industry," in *Rapid Manufacturing: An Industrial Revolution for the Digital Age*, N. Hopkinson, R. Hague and P. Dickens, Eds., Chichester, West Sussex: John Wiley & Sons, Ltd, 2006, pp. 221-231.

[6] J. Wooten, "Aeronautical Case Studies Using Rapid Manufacturing," in *Rapid Manufacturing: An Industrial Revolution for the Digittal Age*, Chichester, John Wiley & Sons, Ltd, 2006, pp. 233-239.

[7] S. Rawal, J. Brantley and N. Karabudak, "Additive manufacturing of Ti-6Al-4V alloy components for spacecraft applications," in *Recent Advances in Space Technologies (RAST), 2013 6th International Conference on*, 2013.

[8] R. M. Fowler, "Investigation of Compliant Space Mechanisms with Application to the Design of a Large-Displacement Monolithic Compliant Rotational Hinge," Harold B Lee Library, Provo, 2012.

[9] R. Spielman, "Space Applications," in *Rapid Manufacturing: An Industrial Revolution for the Digital Age*, Chichester, John Wiley & Sons, Ltd, 2006, pp. 241-248.

[10] J. Halchak, J. Wooten and B. McEnerney, "Layer Build of Titanium Alloy Components for Complex-Geometry Rocket Engine," 2005. [Online]. Available: http://www.calraminc.com/newsletters/Impeller_Paper.pdf. [Accessed 10 October 2013].

[11] Arcam, AB, "EBM® Electron Beam Melting - in the forefront of Additive Manufacturing," [Online]. Available: http://www.arcam.com/technology/electron-beam-melting/. [Accessed 17 October 2013].

[12] L. E. Murr, S. M. Gaytan, A. Ceylan, E. Martinez, J. L. Martinez, D. H. Hernandez, B. I. Machado, D. A. Ramirez, F. Medina, S. Collins and R. B. Wicker, "Characterization of titanium aluminide alloy components fabricated by additive manufacturing using electron beam melting," *Acta Materiala,* vol. 28, no. 5, pp. 1887-1894, 2010.

[13] Arcam AB, "EBM-Built Materials - way beyond average," Arcam AB, [Online]. Available: http://www.arcam.com/technology/electron-beam-melting/materials/. [Accessed 20 September 2013].

[14] K. H. Rafi, N. V. Karthik, T. L. Starr and B. E. Stucker, "Mechanical property evaluation of Ti-6Al-4V parts made using Electron Beam Melting".

[15] E. G. Merriam, J. E. Jones, S. P. Magleby and L. L. Howell, "Monolithic 2 DOF Fully Compliant Space Pointing Mechanism," *Mechanical Sciences,* vol. 4, pp. 381-390, 2013.

[16] B. D. Jensen and L. L. Howell, "The modeling of cross-axis flexural pivots," *Mechanism and machine theory,* vol. 37, no. 5, pp. 461-476, 2002.