Sensors and Actuators A 249 (2016) 284–293

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Metal additive manufacturing for microelectromechanical systems: Titanium alloy (Ti-6Al-4V)-based nanopositioning flexure fabricated by electron beam melting☆

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ARTICLE INFO

Article history:
Received 14 January 2016
Received in revised form 21 July 2016
Accepted 29 August 2016
Available online 31 August 2016

Keywords:
Electron beam additive manufacturing
Electron beam melting
Nanopositioning flexure
Ti-6Al-4V
Piezoelectric actuator
PID control

ABSTRACT

Three dimensional printing (3D printing) or additive manufacturing is a promising approach for construction of small-sized, complex structures in microelectromechanical systems (MEMS). This paper reports the design, fabrication and testing of an XY nanopositioning flexure made up of Titanium alloy (Ti-6Al-4V) created for the first time through electron beam melting (EBM), also known as electron beam additive manufacturing (EBAM). Titanium alloys present attractive characteristics including high biocompatibility, distinct strength and corrosion resistance. However, it has been difficult to machine titanium alloys through conventional processes. The use of additive manufacturing has enabled us to build a multi-dimensional nanopositioning flexure with amplified mechanical displacement and improved bandwidth contained in a compact structure.

We first characterized mechanical properties of EBM-printed Ti-6Al-4V cantilevers and compared the results with those of bulk metal cantilevers. Due to the porous surfaces, the printed cantilevers acted as a softer material with an averaged Young's modulus of 41 GPa when considering only the outermost dimensions. By introducing inner widths of 0.51–0.53 mm for the CAD-designed beam width of 0.7 mm, we calculated a Young's modulus of 90–120 GPa, which is comparable to 108–120 GPa reported in literature for bulk Ti-6Al-4V. With the completion of the initial characterization, fabrication of the flexure was then undergone and successfully carried out. Mechanical levers printed within the flexure amplified an actuation from a piezoelectric actuator by a factor of six to displace a positioning platform supported by the network of parallel supporting beams. The maximum displacement of 47.4 μm was obtained at the driving voltage of 150 V. The resonant frequencies measured for the x and y axes were almost identical 1854 Hz and 1858 Hz, respectively. A digital PID controller enabled laser-based dynamic positioning of the stage. For triangular sweeps at 16 Hz and 122 Hz, the positioning error was within 200 nm and 500 nm with time delays of 0.85 ms and 2.48 ms, respectively.

1. Introduction

1.1. Electron beam additive manufacturing

Manufacturing complex metal structures is one of the major challenges of developing advanced precision mechanical systems. For example, when medical implants are machined through conventional techniques, nearly 80% of input metal goes to waste [1]. Considering excessive costs of material/equipment and the lengthy manufacturing time, it becomes apparent that any intricately designed apparatus will be difficult to produce. Fabrication of precision machines and implants is greatly impacted by this as many of these designs must be extremely detailed and custom to the individual users.

Metal additive manufacturing, metal rapid manufacturing (RM), or metal 3D printing, is a technique that may offer a solution to problems associated with conventional machining. The method entails layer-based manufacturing where metal is deposited in a layer by layer fashion to construct the desired product. There are many different approaches to this type of manufacturing with one of the standard processes being Selective Laser Sintering (SLS) or Selective Laser Additive Manufacturing (SLAM). In SLS, a controlled laser beam in a closed chamber is aimed at specific locations on a bed of powder metal. In reaction to the laser, the targeted powder begins to bind layer by layer, forming a solid structure. During

☆ Selected paper from Transducers 2015 conference, June 21–25, 2015, Alaska, USA.

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http://dx.doi.org/10.1016/j.sna.2016.08.029
0924-4247/

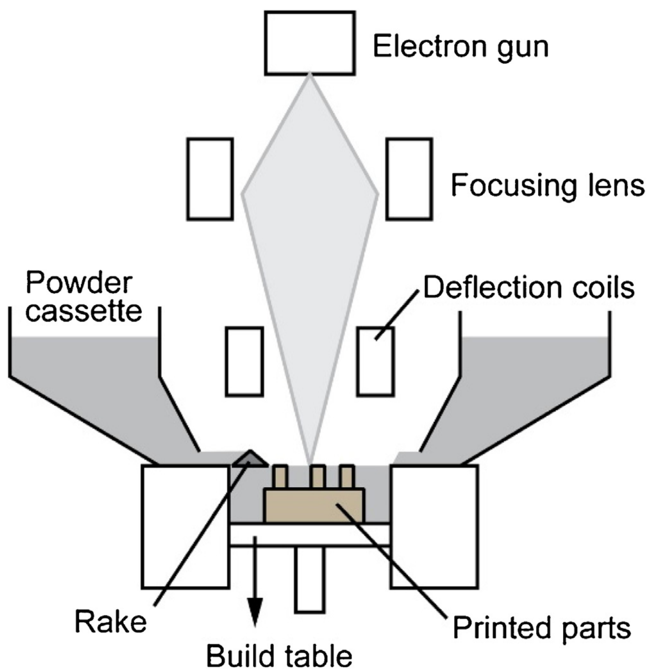

Fig. 1. The diagram of additive manufacturing based on Electron Beam Melting (adapted from [1]). The Focused electron beam in a vacuum chamber scans the titanium alloy powder layer by layer to directly "print" 3D parts.

Table 1
Static analysis of EBM printed samples.

Sample	*l* (mm)	*h* (mm)	*w* (mm)	*k* (N/m)	*E* (Gpa)
Aluminum	15.5	3.0	0.80	7250	70
Steel	15.8	3.1	0.70	15600	231
Titanium	15.7	3.1	0.80	11100	108

this time, the chamber is continuously flushed by argon in order to minimize nitrogen and oxygen pick-up [2].

Electron beam melting (EBM), also known as electron beam additive manufacturing (EBAM), is a novel approach to additive manufacturing for fabrication of complex metal components. Following a CAD 3D model, an electron beam from a welding gun is controlled by deflection coils and is focused onto a bed of metal powder. The powder reacts to the electron beam by melting together and another powder layer is then added by two powder cassettes. The new powder is evenly distributed over the entire surface via a powder rake and the process continues in a layer by layer fashion until the part reaches the final design [1]. A schematic displaying all components of the EBM system can been seen in Fig. 1. Using these rapid prototyping techniques, short lead-times can be obtained and design changes can be easily incorporated. By omitting extensive machining, material costs and scrap can be reduced, leading to a lower environmental impact with a good economic balance [3]

1.2. Titanium alloy (Ti-6Al-4V) for mechanical systems

Titanium (Ti) alloys are becoming increasingly considered in mechanical system design due to their demonstrated success in numerous industries such as automotive, aerospace and medical [4]. The most commonly used alloy is Ti-6Al-4V which contains 6% aluminum and 4% vanadium [5]. There are many material properties that make it advantageous for such a wide range of applications. For example, Ti alloys have a low material density, strong mechanical properties [5], a high resistance to corrosion [6], and high biocompatibility [7]. These factors, in particular, make the material ideal for biomedical applications and withstanding harsh environments [8]. It is clear that there is considerable value in using Ti alloys for many types of designs, however, there are still challenges to overcome in the actual fabrication process. The high strength and low modulus of elasticity make Ti alloys a more difficult material to modify in general. Though it is still possible to machine, the tools being used also tend to wear away much faster than with other metals. This is attributed to Ti's high chemical reactivity which causes it to weld to the tools and the low thermal conductivity which leads to the tool interface temperature increasing. To prevent this rapid wearing, the entire process must be customized to the specific properties of the particular alloy being machined [9]. This takes both additional time and resources making customized machining a less than ideal solution.

The focused electron beam in the EBM allows for direct 3D printing of Ti-6Al-4V. Experimental products fabricated from Ti-6Al-4V powders through EBM have shown remarkable promise for custom designed components especially for medical implants [1]. It is possible to print implants with intricate porous structures to obtain an elastic modulus close to that of natural bones [10,11]. They are cost and time effective and there is a significant reduction in material waste. Basic mechanical characteristics of EBM-formed Ti-6Al-4V as a structural biomedical material have been discussed in [1,12]. Additive manufacturing is a promising approach to construct a small-sized, complex three dimensional structures for micro-electromechanical systems (MEMS). In this paper, we design and fabricate a XY nanopositioning flexure made up of Titanium alloy (Ti-6Al-4V) created for the first time through EBM. Through the testing and analysis of the Ti-6Al-4V-based integrated micromechanical system, we demonstrate the advantages of using EBM for dynamic micromechanical applications. Firstly, we test basic static and dynamic mechanical characteristics of EBM-printed cantilevers as a basic building block to construct complex mechanical systems. This basic analysis is followed by the design, fabrication, and analysis of a piezoelectric actuated XY nanopositioning stage made up of Titanium alloy (Ti-6Al-4V), which has been fabricated through a 3D printing. The stage is compact and robust, and provides nanopositioning suitable for fast scanning as reported in [13,14]. Our unique design differs from the previous studies by two points: (1) titanium alloy is used as stage material which excels in mechanical dynamic properties and (2) the fabrication process i.e. EBM allows the formation of a complex framed structure. It reduces the mass of system resulting in the higher frequency and fast response of the system.

Table 2
Static analysis of EBM printed cantilevers.

Sample	Design (mm)	*l* (mm)	*h* (mm)	w_1 (mm)	w_0 (mm)	*k* (N/m)	E_1 (Gpa)	E_0 (Gpa)
#1	l = 15, w = 0.85, h = 3.0	$l_1 = 14.6$	3.1	0.79 ± 0.02	0.59	7420	60	145
		$l_2 = 7.0$				55200	50	119
#2	l = 15, w = 0.70, h = 3.0	$l_1 = 14.6$	3.1	0.73 ± 0.02	0.53	3910	40	105
		$l_2 = 7.4$				28100	38	99
#3	l = 15, w = 0.70, h = 3.0	$l_1 = 14.7$	3.1	0.71 ± 0.03	0.51	3890	45	120
		$l_2 = 8.4$				21200	45	122
#4	l = 20, w = 0.70, h = 3.0	$l_1 = 19.7$	3.1	0.75 ± 0.03	0.55	1530	36	91
		$l_2 = 10.2$				13200	43	109