Ti-6Al-4V Helical Spring Manufacturing via SLM: Effect of Geometry on Shear Modulus

Mohamed A. E. Saleh, and Adham E. Ragab

Abstract— **Selective Laser Melting (SLM) is an additive layer manufacturing technique that is towards free form solid The effect of component geometry on part performance measured in shear modulus is studied. Ti-6Al-4V functional parts were produced using Selective Laser Melting (SLM). The parts were designed as helical springs with the same dimensions except for the pitch that was used as a geometry factor. Springs with four different pitches were produced and tested to measure their spring constant, and hence their shear modulus. One way ANOVA statistical analysis was used to estimate the significance of differences among different pitches. It was found that the differences are significant, and the geometry has a major effect on the produced mechanical properties.**

Index Terms— **SLM/SLS, Ti-6Al-4V, mechanical properties, geometry**

I. INTRODUCTION

Additive manufacturing (AM) – also called Additive Layer Manufacturing, layer manufacturing or 3D printing, is a set of advanced manufacturing techniques that have been used for around two decades in prototyping [1], [2]. Recently, researchers and manufacturers took these techniques to a new domain by utilizing them in producing functional or end user components [2]. Their goal is to take advantage of the AM in real world industry in order to attain several benefits include single part lot, minimizing material and energy usage, reducing waste, shortening time to market and attaining design freedom of components geometries [2], [3].

Selective Laser Melting (SLM) is one of the AM fabrication techniques that can be used to produce geometrically complicated components in materials including, stainless steels, Aluminum, Nickel, Cobalt-Chrome and Titanium based alloys [4], [5]. In SLM, high power laser beam is used to fully melt metal powders, of very fine grain size, and utilize the melt to build a 3D part, layer by layer, following a CAD model [2], [5].

Mechanical properties of SLM made components were always questionable compared to parts made in conventional manner. Many researchers tackled this topic in order to uncover, and solve, the expected problems in this regard [2], [4], [6], [7].

One of the common alloys used in AM processes is the Ti-6Al-4V. This alloy is very promising in biomedical industry for metallic implants. It is widely used in replacing hip joints, knee joints, and bone plates [8]. This interest in the alloy for medical needs is a consequence of its unique properties such as, corrosion resistance, biocompatibility and light weight [5], [8], [9]. Ti-6Al-4V is also used extensively in several industries: aerospace due to its stability at high temperatures [10], chemical industry due to its high corrosion resistance [11].

Mechanical properties of SLM, Ti-6Al-4V, produced components was a subject of extensive research during the last decade [1], [2], [4], [6]- [9]. The non-homogeneous microstructure of products, due to the layer-wise building methodology, affects the part’s mechanical properties [12], [13]. This may result in properties that are quietly different from standards. Heat treatment might eliminate, or reduce, the side effects of microstructure non homogeneity [13]. An important factor that would affect the microstructure of SLM Ti-6Al-4V components is the part geometry. This paper focuses on the effect of design geometry of a functional component on the resulted shear modulus as an example of mechanical properties.

II. EXPERIMENTAL PROCEDURE

The selection of end products that share the same working function and vary in shape geometry is not that easy. In contrary, the greater part of functional components usually has complicated geometries that are not possible to test in a standard fashion. Generally, to test mechanical properties, parts of simple geometry are needed to allow for standard test. Here comes the selection of helical springs. The basic function of a spring is to store mechanical energy as it is initially elastically deformed and then recoup this energy at a later time as the spring recoils. Therefore, one of the functional parts that can be tested for an important mechanical property is helical spring. A well known formula relating spring function to its material properties; shear modulus, is established as given in equation 1 [14].

$$F = \frac{d^4 * \delta_c G}{8D^3} \qquad \text{equation 1 [14]}$$

Where F is the compressive force, δc is the displacement of one spring coil, D is the coil center to center diameter, d is the wire diameter and G is the shear modulus of the material of which the spring is constructed. δc can be calculated as δs/Nc, where δs is the total spring deflection

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and Nc is the number of effective coils in the spring. This equation could be modified as shown in equation 2 to estimate the shear modulus directly from the spring constant K =F/ δs.

$$G = \frac{8D^3 K\, N_c}{d^4} \qquad \text{equation 2}$$

Thus, helical springs with same length L, diameters D and d but various Nc should return the same G if they have the same material. In this study, helical cylindrical springs of round wire with open ends ground were produced using SLM. The used system is EOSINT M 280 produced by Electro Optical Systems. The system is equipped with 400 watts solid state laser and argon protected atmosphere. The springs were surface finished using blasting after manufacturing. The springs were produced by the help of EOS company.

All parts were made of Ti-6Al-4V alloy powder, commercially named as “EOS Titanium Ti64”. This powder is optimized for processing on “EOSINT M” systems [15], with a particle size about 30 microns. The alloy composition is shown in Table 1 [15]. Modulus of elasticity of the alloy, as manufactured via SLM, is given as 110 ± 10 GPa [15]. The Poisson’s ratio ν equals 0.33 [16]. Shear modulus could be calculated using the well-known formula: E= 2G(1+ν), where E is the modulus of elasticity, to be 38 ± 3.8 GPa .

TABLE I CHEMICAL COMPOSITION OF EOS TITANIUM TI64 ALLOY [15]

Aluminium, Al, Wt.%	5.5 – 6.75
Vanadium, V, Wt.%	3.5 – 4.5
Carbon, C, ppm	<800
Iron, Fe, ppm	<3000
Oxygen, O, ppm	<2000
Nitrogen, N, ppm	<500
Hydrogen, H, ppm	<150
Titanium, Ti	Balance

Twelve springs were produced in four different geometries, with three replicates each. The springs dimensions were the same except for the spring pitch, and hence the number of effective coils, that was used as a geometry factor. Table 2 shows the springs dimensions for the tested samples. The four springs samples are shown in Figure 1.

Fig. 1. Sample springs with four different pitches

TABLE II. SPRINGS DIMENSIONS

Spring Dimensions	Spring 1	Spring 2	Spring 3	Spring 4
Spring Height, L (mm)	42.04			
Coil center to center diameter, D, (mm)	22.14			
Wire diameter, d, (mm)	4.63			
Pitch (mm)	15.00	10.50	7.70	3.55
Number of effective coils, Nc	2	3	4	5

Compression tests were conducted to measure the spring constant of all springs in a complete randomized scheme. The load/displacement of the test was controlled through adjusting the displacement rate to be 5mm/min.

III. RESULTS AND DISCUSSION

Table 3 summarizes the values of spring constant measured for each spring. Relation between compressive load and compressive extension is illustrated in Figures 2-5 for springs 1-4 respectively. The results show that the springs of each category (pitch) act similarly with respect to the load/displacement relation. Also, the spring’s constants are within very tight range for the same size springs. The spring constant is inversely proportional to the number of effective coils as expected.

TABLE III. MEASURED SPRING CONSTANTS

Spring Sample	Spring Constant (N/mm)		
	Replicate 1	Replicate 2	Replicate 3
Spring 1	46.1	46.7	45.9
Spring 2	36.0	35.1	36.3
Spring 3	29.7	29.0	28.7
Spring 4	26.5	25.7	25.8

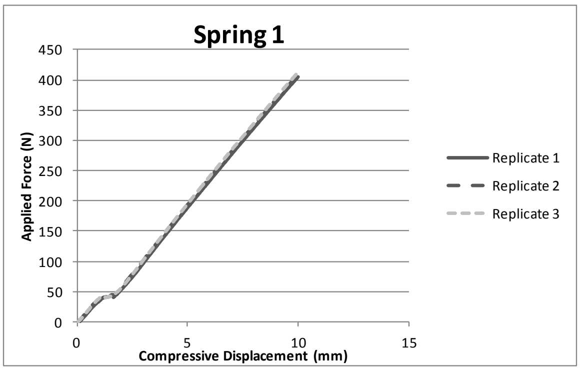

Fig. 2. Compressive load versus compressive extension for Spring 1

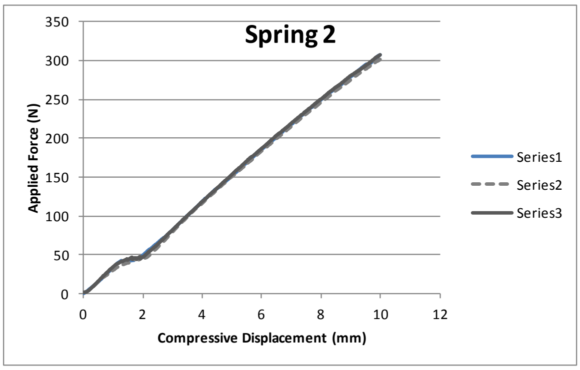

Fig. 3. Compressive load versus compressive extension for Spring 2

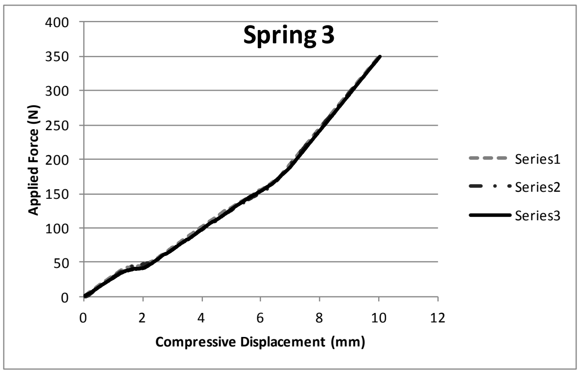

Fig. 4. Compressive load versus compressive extension for Spring 3

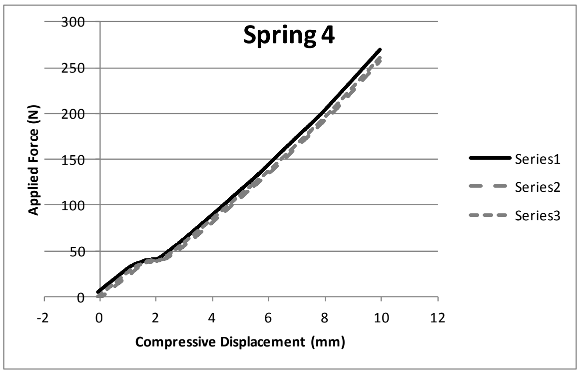

Fig. 5. Compressive load versus compressive extension for Spring 4

The loading curves of the four spring geometries are illustrated in Figure 6. All springs work as expected, except for spring 3 that acts differently, with the spring constant increases beyond expectations after compressing of about 7 mm. This trend occurred in the three replicates of this spring, which limits the probability of bad product. More study may be needed to understand the behavior of this spring.

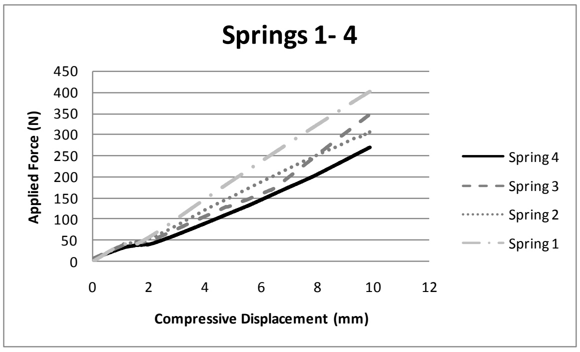

Fig. 6. Compressive load versus compressive extension for the four springs

Equation 2 was used to calculate the shear modulus of each spring. The results are illustrated in Table 4. One way ANOVA statistical analysis was used to evaluate the results. A significant effect of pitch size on the shear modulus of the spring material was detected with ($p < 0.001$). The results showed that the shear modulus ranges from 60 – 85% of the rated value (38 ± 3.8 GPa). Springs with smaller pitch size demonstrated closer shear modulus to the rated value.

TABLE IV. CALCULATED SPRING MATERIAL SHEAR MODULUS

Spring Sample	Shear modulus (GPa)		
	Replicate 1	Replicate 2	Replicate 3
Spring 1	22.3	22.6	22.2
Spring 2	26.1	25.5	26.3
Spring 3	28.7	28.1	27.7
Spring 4	32.1	31.1	31.2

IV. CONCLUSIONS

This research studied the effect of geometrical design of a functional component, produced using SLM layer additive technique, on one of its mechanical properties. Utilizing functional parts, in shape of helical springs, it was proved that the produced geometry made a difference in the material shear modulus. Twelve Helical springs of the same dimensions, except for the pitch, were produced on the same environments using “EOSINT M” systems and EOS Titanium Ti64 powder. The springs were tested for spring constant and hence, for shear modulus. The spring pitch was used as a geometry factor, with four pitches and three replicates each. The measured spring constants, for replicates of the same pitch size, were consistent with each other. The results have also illustrated differences between the material shear modulus calculated for different spring pitches. One way ANOVA demonstrated a significant difference amongst the four different pitches with $p < 0.001$. The research results show that the complicated geometry of functional components, produced by SLM, does have a significant effect on the Ti6Al4V mechanical properties.

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