DETERMINATION OF ELASTIC MODULUS VALUE FOR SELECTIVELY LASER MELTED TITANIUM ALLOY MICRO-STRUT

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ABSTRACT

Experimental method in determination of elastic modulus (E value) for micro scale specimen can be a debated issue, in the aspect of reliability and robustness of the results. Attention shall be given to the limiting factors which influence the techniques and procedure, such as the sample's size, properties and geometries. It is also important to incorporate the microstructural effects toward producing a more understandable results. Analysis of tensile property for titanium alloy (Ti-6Al-4V) micro-struts manufactured from selective laser melting (SLM) rapid prototyping technology is presented in this paper. The result is found comparable to a standard value and will be used in future analysis of micro-lattice performance as core material in sandwich structure.

KEYWORDS*: Elastic modulus, compliance method, titanium alloy, micro-lattice, micro-struts*

1.0 INTRODUCTION

It has been reported in a survey of literature that a great variety of tensile specimens with different sizes and geometries have been used by different authors, primarily depending on the availability of material (Zhao *et.al.*, 2008). Study on size and geometrical effects on tensile test properties of non-standard specimens have been done in order to obtain a comparable result to the ASTM standard test (Sergueeva *et.al.*, 2009). While it is suggested in the standard (BS EN ISO 6892-1, 2009) that the application of extensometer is a necessary, a problem faced in testing a non-smooth specimen geometry requires solution of avoiding the equipment usage, and a direct testing method with the introduction of compliance correction during experimental analysis would be preferred.

In the previous research of micro-lattice structure manufactured from a rapid prototyping technology using selective laser melting (SLM) technique, tensile properties of individual micro-strut has been studied in order to evaluate the performance of stainless steel micro-lattice structure (Shen, 2009). By using an extensometer, elastic modulus value of around 50 GPa or only 26% of stainless steel bulk material's modulus has been determined. The low elastic modulus value was expected from the strain calculation of the extensometer, which was derived by using the crosshead displacement during the tensile test. However, a compliance correction using finite element analysis was then applied in order to achieve a value of 140 GPa or approximately 74% of the bulk material's value (Tsopanos *et.al*., 2009). Other important findings reported in the studies is that the mechanical properties of SLM micro-struts are strongly dependent on build angles and the manufacturing parameters such as laser power in Watts and laser exposure time in micro-seconds (Shen, 2009; Tsopanos *et.al*., 2009).

As compared to SLM stainless steel micro-lattice, it was reported that SLM titanium alloy micro-lattice has shown competitive specific strength properties with aluminium honeycomb as core material in sandwich construction (Mines *et.al*., 2009). Thus, further theoretical and experimental analysis is needed since there is a future prospect for the SLM titanium alloy micro-lattice structure. However, a more reliable method of determining the elastic modulus value is required rather than depending on the finite element analysis procedure. In current study, the elastic modulus of SLM titanium alloy micro-struts is being investigated, using basic experimental compliance correction methods as found in other's studies (Sergueeva *et.al*., 2009; Kalidindi *et.al*., 1997; Turek, 1993).

2.0 GOVERNING EQUATIONS AND LIMITATIONS

The fundamental concept behind compliance correction is based on the assumption that the specimen and testing fixture can be modeled as a system with two springs in series. When subjected to a same applied load, F, the total measured displacement can be taken as the sum of the displacements in the specimen and the loading system, as represented by Equation [1].

$$\delta_T = \delta_S + \delta_C \qquad [1]$$

δ_T is the total measured displacement, while δ_S is the specimen deformation and δ_C is the displacement in the loading system, i.e. the machine compliance. If both the specimen and the loading system are assumed as linear elastic springs, it can be shown that the apparent compliance, C_a (= δ_T/F), is related to the machine compliance, C_m(= δ_C/F), as given in Equation [2].

$$C_a = C_m + (1/EA)L \qquad [2]$$

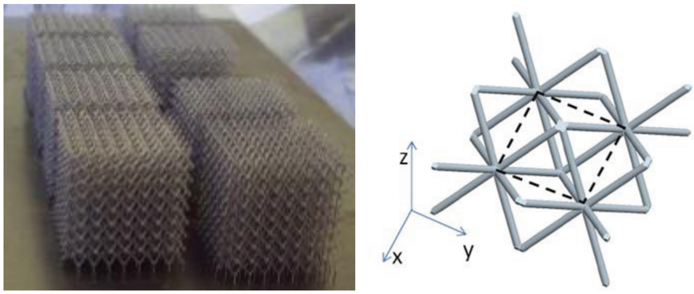
E is the elastic modulus of the tested specimen while *A* and *L* are the cross-sectional area and the length of the specimen, respectively. As suggested in a withdrawn but still reliable standard (ASTM D 3379-75), C_m is the zero gauge length intercept on a plot of C_a versus *L* for a given material, and the corrected elastic modulus, *E*, of the material can be extracted from the slope of this plot, or calculated from Equation [3], where E_u is the uncorrected elastic modulus of the tested material.

$$E = \frac{(L/A)}{(C_a - C_m)} = \frac{(E_u C_a)}{(C_a - C_m)} \qquad [3]$$

However, for a more accurate compliance factor, Equation [2] can be modified as shown in Equation [4], with C_m is the zero gauge length intercept on a plot of C_a versus L/D^2, where *D* is the diameter of the specimen (Li and Langley, 1985).

$$C_a = C_m + (4/\pi E)(L/D^2) \qquad [4]$$

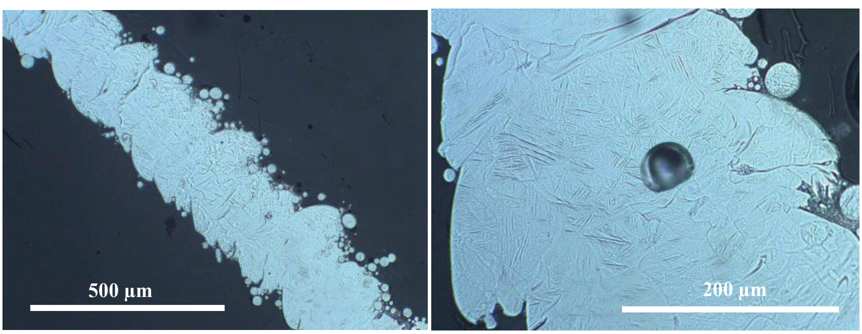
In this study, by considering the very low elastic modulus value obtained in previous research of stainless steel micro-strut specimen (Shen, 2009), attention is decided to be given to the variation of geometry, microstructure and post-failure surface area examination of the strut specimen. For current titanium alloy micro-strut specimen, the manufacturing parameter has been set as 200 W laser power and 1000 μs laser exposure time. Another aspect to be considered is that the strut specimen with 35° build angle is being used, as this build angle represents the real angle position of each strut in body centred cubic (BCC) architechture of micro-lattice structure as illustrated in FIGURE 1. Different results may be obtained if a 0° build angle of micro-strut specimen is being used in the determination of elastic modulus of titanium alloy. However, the 0° build angle strut could only be produced as long as 23 mm due to manufacturing limit, and this is not a suitable length to be used as a specimen in this study.



(a) (b)

FIGURE 1 (a) Micro-lattice blocks; (b) BCC architechture of unit-cell micro-lattice structure (source: Tsopanos *et.al*., 2009)

Optical microscope image as in FIGURE 2(a) shows a cross-sectioned part of 35° build angle titanium alloy micro-strut specimen. Although it is assumed that the strut is in cylindrical shape, it can be seen that the geometry of the strut is not really uniform throughout the specimen. It is also noted in FIGURE 2(b) that the micro-strut specimen has a microstructure similar with cast α-β titanium alloy (Polmear, 2006).



(a) (b)

FIGURE 2 (a) Cross-sectioned part of 35° build angle, 200 W laser power, 1000 μs laser exposure time of titanium alloy micro-strut specimen; (b) Microstructure of micro-strut similar to cast α-β titanium alloy Ti:6Al:4V

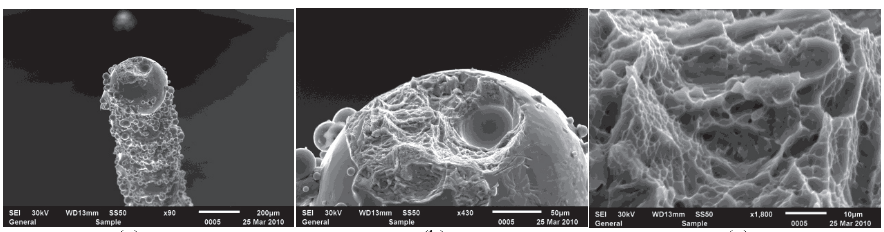
On the other hand, scanning electron microscope (SEM) images in FIGURE 3 show fractured surface of titanium alloy micro-struts. It can be seen that the welded area (fractured area) is not the same with the apparent cross-sectional area of the micro-strut specimen. Another finding is that, although the specimen has not experienced a noticeable ductile extension, it is noted that ductile fracture has occurred at the fractured surface, as indicated by ductile dimples in FIGURE 3(c).

Therefore, in the determination of elastic modulus for the titanium alloy micro-strut, an important assumption is introduced in the analysis, where the cross-sectional diameter of cylindrical specimen is taken only as two-third of the measured diameter, by taking into consideration that the welded area is not covering all of the cross-sectional area (apparent area). A better definition of cross-sectional area, A, is the welded area of the micro-strut, with diameter approximately two-third of the measured diameter, D, as derived in Equation [5].

$$A = \frac{\pi}{4}\left(\frac{2}{3}D\right)^2 = \frac{\pi D^2}{9} \qquad [5]$$

With the new definition of area, Equation [3] can be re-written and as shown in Equation [6].

$$C_a = C_m + (9/\pi E)(L/D^2) \qquad [6]$$



(a) (b) (c)

FIGURE 3 (a),(b) Fractured area of titanium alloy micro-strut is not the same with the apparent cross-sectional area; (c) Ductile dimples at fractured surface

3.0 EXPERIMENTAL PROCEDURE

Cylindrical shape micro-struts of titanium alloy Ti:6Al:4V have been manufactured from the selective laser melting (SLM) process (MCP Realizer II machine), at 200 W laser power and 1000 μs laser exposure time. This produced an average of 0.37 mm measured diameter, D, of micro-strut with 35° build angle (measured by using micrometer). The length of the manufactured specimen is approximately 43 mm, limited by the SLM manufacturing space capability.

The tensile tests were conducted on a small bench top servo-hydraulic testing machine (Instron 3342 machine), with 500 N load cell. Loading velocity of 0.1 mm/minute was applied throughout the test, without the application of extensometer for strain measurement. The strain was derived directly from the crosshead displacement and the compliance correction method as described earlier is being used. Limited by the manufactured specimen length, only five different gauge lengths, *L*, were tested, which are 5 mm, 8 mm, 10 mm, 22 mm and 30 mm, with three repeat tests for each gauge length. FIGURE 4 (a) to (e) show the arrangement of the machine for the tensile tests of different gauge lengths, without the application of extensometer. The faces of the test machine grips had been glued with 240 grit emery paper which minimized the slippage effect of the micro-strut during the test.


(a) (b) (c) (d) (e)

FIGURE 4 Micro-strut tensile test at different gauge lengths; (a) 5 mm; (b) 8 mm; (c) 10 mm; (d) 22 mm; (e) 30 mm

4.0 RESULTS AND DISCUSSIONS

Throughout the analysis, the welded area definition for cross sectional area as been described in Equation [5] is being used. TABLE 1 tabulates the average values of elastic modulus for titanium alloy micro-struts at different gauge lengths, before and after the application of compliance correction.

TABLE 1 Elastic modulus of titanium alloy micro-struts at different gauge lengths, before and after compliance correction

Gauge Length (L, mm)	Diameter (apparent) (D, mm)	Area (welded) (A, mm^2)	Compliance factor (apparent) (C_a, mm/N)	Uncorrected elastic modulus (E_u, GPa)	Corrected elastic modulus (E, GPa)
30	0.374	0.04884	0.0107	59.9	99.0
22	0.379	0.05006	0.0089	53.4	101.1
10	0.375	0.04918	0.0064	37.9	113.2
8	0.371	0.04814	0.0062	30.7	96.2
5	0.374	0.04883	0.0055	21.5	101.6

As mentioned in Equation [6], the machine compliance, C_m is the zero gauge length intercept on a plot of apparent compliance, C_a versus gauge length over square of diameter, L/D^2 . Therefore, as shown in FIGURE 5, the value of machine compliance, C_m in this study is found as 0.0042 mm/N. The obtained value of C_m is being used in Equation [3], to determine the corrected elastic modulus value for each gauge length with the respective apparent compliance, C_a. The list of corrected elastic modulus value is as mentioned in earlier TABLE 1.

By referring to other studies on titanium alloy (Sergueeva, 2009), 110 GPa can be accepted as the elastic modulus value of Ti:6Al:4V material. In this study, the average elastic modulus value determined from all gauge lengths is approximately 102 GPa, which is very close to the accepted value, with only about 7% error. FIGURE 6 compares the corrected elastic modulus with the accepted value of 110 GPa, while FIGURE 7 shows the example of corrected stress versus strain curve for 22 mm gauge length micro-strut specimen.

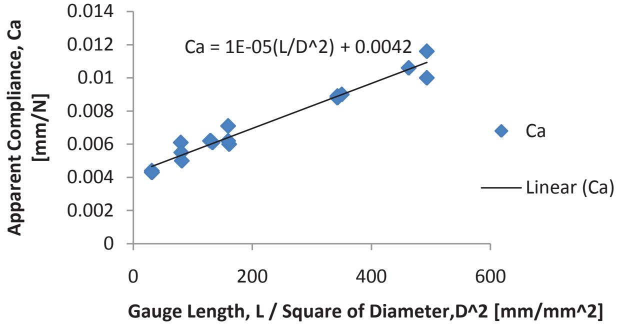


FIGURE 5 Plot of of C_a versus L/D^2 for micro-strut tensile test of titanium alloy

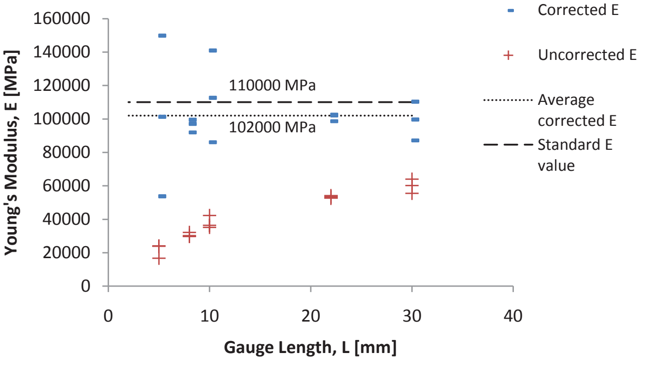


FIGURE 6 Comparison of the corrected elastic modulus values with the accepted value

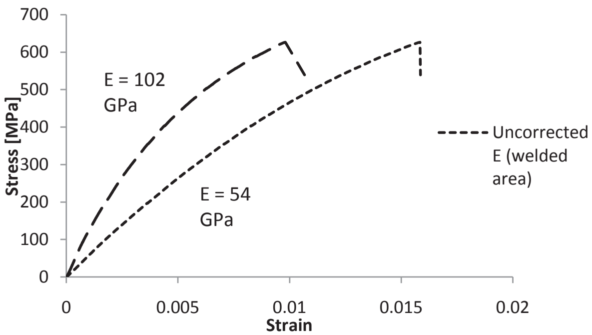


FIGURE 7 Comparison of corrected and uncorrected stress versus strain curve for 22 mm gauge length titanium alloy micro-strut specimen.

From the good result of elastic modulus value, it is recommended that the tensile test study of micro-strut specimen shall incorporate the variation of geometry, microstructure and post-failure surface area examination of the strut specimen. A major factor that contributes to the result is by introducing the new definition for cross-sectional area as an approximation of the welded area observed from the fractured surface examination.

5.0 CONCLUSION

In this study, it is found that direct tensile testing method with the introduction of compliance correction during experimental analysis at different gauge lengths would be preferred for micro-strut analysis, rather than using the extensometer with fixed gauge length. However, it should be noticed that the cross sectional area depends on the welded area observed from the fractured surface, which is different from the apparent measured area of the specimen.

6.0 ACKNOWLEDGEMENT

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