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SMALL-SCALE CHARACTERIZATION OF ADDITIVELY MANUFACTURED ALUMINUM ALLOYS THROUGH DEPTH-SENSING INDENTATION

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Abstract

Selective laser melting (SLM) can be considered as a suitable additive manufacturing method for printing complex-in-shape aluminum components. However, to adopt the SLM for mass production of aluminum components for automotive and aerospace applications, one needs to fully understand the correlations between the SLM parameters, produced microstructure, and local mechanical properties of the printed parts. In this paper, along with microstructural assessments (optical and scanning electron microscopy), small-scale properties of two additively manufactured aluminum alloys, AlSi10Mg and A205.0, were examined using an instrumented (depth-sensing) indentation testing technique. An instrumented indentation testing approach is a semi-destructive, reliable and convenient method which enables us to study the variations and distributions of the mechanical properties (*i.e.* hardness) as a function of distance from the build plate. The variations in properties are then compared in AlSi10Mg and A205.0 alloys and are correlated to the generated microstructures in the printed alloys.

Introduction

Aluminum alloys (Al) are the second most used metals in the industry which in some properties surpass the properties of conventionally used materials like steel in the industrial applications [1]. The aluminum alloys have wide range of applications in the automotive, aerospace, ship manufacturing, and several other industrial applications due to their recyclability, excellent strength, strength-to-weight ratio, and both electrical and thermal conductivities. The engineering parts which are made up of the aluminum alloys have been manufactured by using conventional mechanical processes that include molding, casting, and welding of the materials. However, these conventional manufacturing processes, due to the cooling process associated with these manufacturing processes, may not always provide desirable microstructure. Moreover, the costs of conventional tool-making processes are high and time consuming. The techniques of selective laser melting (SLM) have proven to be an effective solution to the manufacturing problems associated with the aluminum alloys.

SLM is one of the most commonly employed additive manufacturing processes of the aluminum alloys which has the capability to produce materials near to the full density [2]. The SLM process of the aluminum alloys does not require any additional steps like in the conventional mechanical manufacturing processes [2]. As well the SLM is cost-efficient and the material is easily molded and changed into a variety of complex shapes. Owing to these properties, the manufacturing process is gaining focus in the industrial and academic research works.

In any given additive manufacturing process, the SLM falls under the process of powder bed fusion [3]. In this process, the laser helps in inducing fusion within the particles of powder in every layer of the prescribed region. The previous layers are re-melted by the laser's high energy. This explains the reason as to why the SLM process is perfect for high-density and well-bonded metal parts like aluminum alloys. Lastly, depth-sensing indentation helps in determining the mechanical properties of different materials.

The method of depth-sensing indentation was introduced as an improvement of the measurement of conventional hardness. Today, the method is being widely employed to characterize and extract fundamental properties in different materials including metals and non-metals. During the depth-sensing indentation process, an indenter observing a constant loading rate or indentation rate penetrates the material's surface [3]. Often, during numerous measurements, the loading rate is kept constant. After the load reaches its maximum value, the indenter retracts back allowing the elastic recovery.

The objective of the current paper is to establish the correlations between microstructure, mechanical properties and print parameters in the as printed and heat treated Al alloys. This is achieved through depth sensing indentation testing approach. To do so, microstructural characterizations and micromechanical assessments (depth sending data) are combined to shed light on the effect of heat treatment and gradation of microstructure on the properties.

Experimental Procedure

Materials

Samples were produced from atomized powders whose compositions are given in Tables 1 & 2, using a SLM280 printer with two 400 watt lasers. Two samples were fabricated from each alloy then one pair underwent a T_6 heat treatment cycle. The heat treatment cycle consists of solutionizing treatment at 520 ℃, holding for 1 hr then quenching at cold water followed by artificial aging at 170 ℃ for 4 hrs (see Fig. 1).

Table 1: Chemical composition of the AlSi10Mg powder (weight %)

Al	Si	Mg	Others
88.3	11.2	0.48	0.02

Table 2: Chemical composition of the A205.0 powder (weight %)

Al	Cu	Ti	Others
91.01	6.4	1.68	0.91

Nanoindentation

Mechanical properties were measured with the nanoindentation experiments that involved using the Berkovich tip in obtaining the hardness and the Young's modulus. During the experiments, the load-displacement curves were obtained. These curves were then further analyzed to calculate various properties. In this process, a trapezoidal shaped loading and unloading was applied with the maximum force of 50 mN. A KLA Tencor G200 Nano Indenter was utilized for the experiments. The experimental schedule included loading the sample to a maximum load of

50 mN at a strain rate of 0.05 /s. There was a hold period at the maximum load for 2 seconds followed by the unloading. 25 indents were conducted on the samples with spacing between each indent of 400 μm. The 25 indents were on the YZ plane where it is starts near substrate and proceeds to the top.

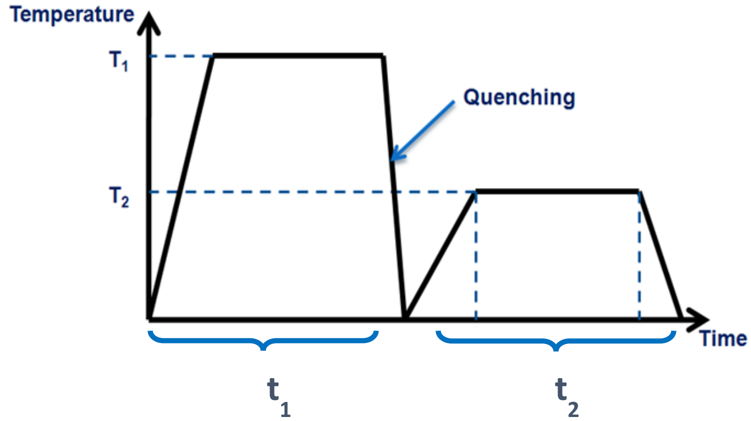

Fig. 1. Heat Treatment solution for both alloys: T_1 is 520 ℃, T_2 is 170 ℃, t_1 is 1hr and t_2 is 4hr.

Results and Discussion

Figure 2 shows the optical microcopy images of the AlSi10Mg material used in this study, before and after heat treatment. Figure 2(a) shows the as-built AlSi10Mg which contains the melt pool core and the boundaries. Upon conducting the T_6 heat treatment, the Si fibers/needles in the as printed material are converted to round (spheroidized) particles distributed evenly within the Al matrix as shown in Fig. 2(b). These features are visible in the SEM images given later in the paper.

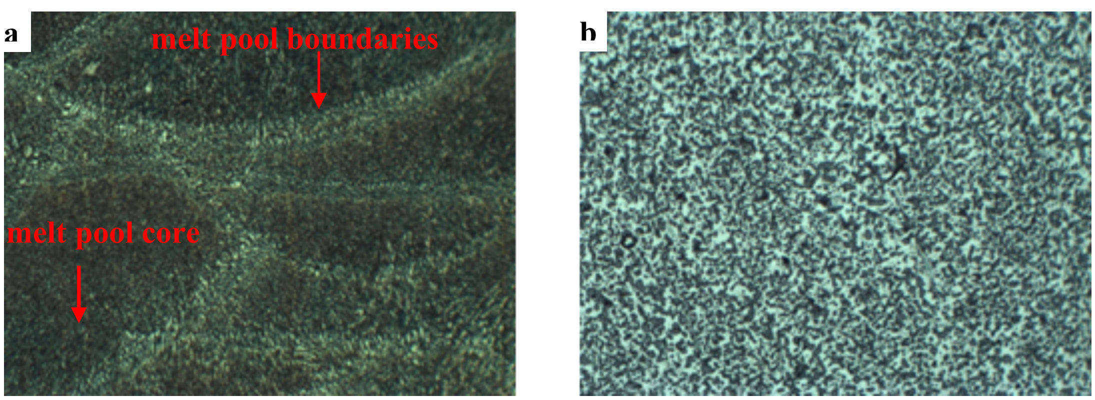

Fig 2. Micrographs of the as-built and heat-treated SLM AlSi10Mg specimens, (a) as printed (b) heat treated.

Figure 3 shows an SEM micrograph showing the spheroidized Si particles in the heat-treated sample. The Spheroidization of Si is due to atomic diffusion that occur on fragmentation of Si fibers that result in the spherical particles coarsening [4, 5].

As a result of the Si Spheroidization, due to the removal of sharp tips and terminals of the Si blades, the material softens [6]. To clearly observe this, the nano-hardness values were recorded for both as-built and heat-treated samples of the AlSi10Mg alloy. Figure 4 shows the nano-hardness values in (GPa) for YZ plane, from one side of the surface to the other, in the as-printed and heat-treated materials. There is a dramatic drop in the hardness values of the heat treated alloy (average value for as-built is 2.71±0.12 GPa whereas the heat treated one shows 1.56±0.11 GPa). This is directly resulted from change in the morphology of Si in the microstructure due to the heat treatment and corresponding spheroidization.

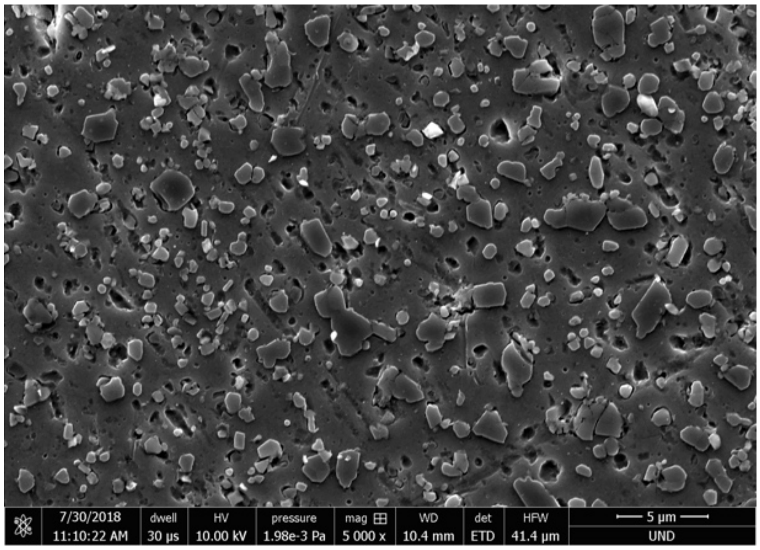

Fig. 3. Spheroidized Si particles in the heat treated sample (AlSi10Mg).

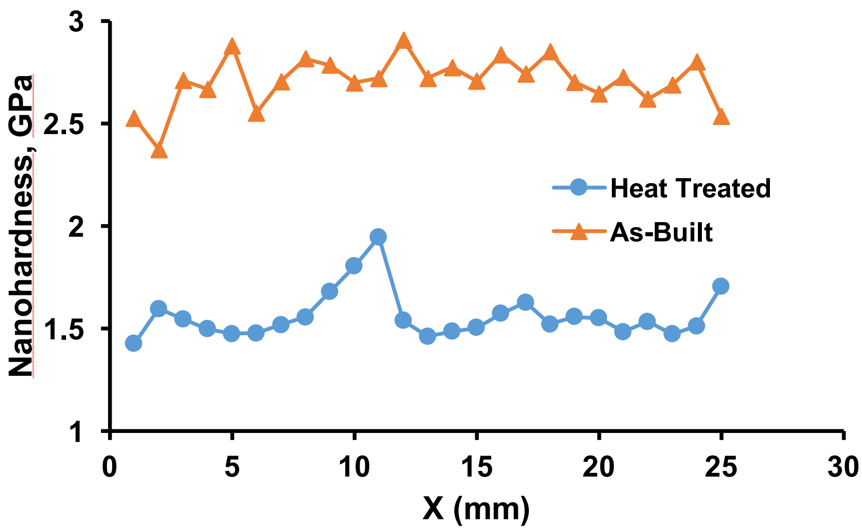

Fig. 4. Nano-Hardness measurement for AlSi10Mg (Nano-indentation on YZ plan).

Figure 5 shows the SEM images of the A205.0 alloy before and after heat treatment. A growth in both grain size and the Ti particles due to Ostwald ripening are clear from Fig. 5b. Indeed, energy dispersive x-ray spectrometry "EDS" confirms these particles are Ti-rich phases in the microstructure which slightly grow upon heat treatment. Upon conducting the nano-indentation tests, a drop in hardness values is observed when comparing the as-built and heat treated samples. From Fig. 6, YZ plan average value for as built is 2.81±0.14 GPa whereas heat treated is 1.95±0.15 GPa. This can be attributed to both grain and Ti-rich particles growth.

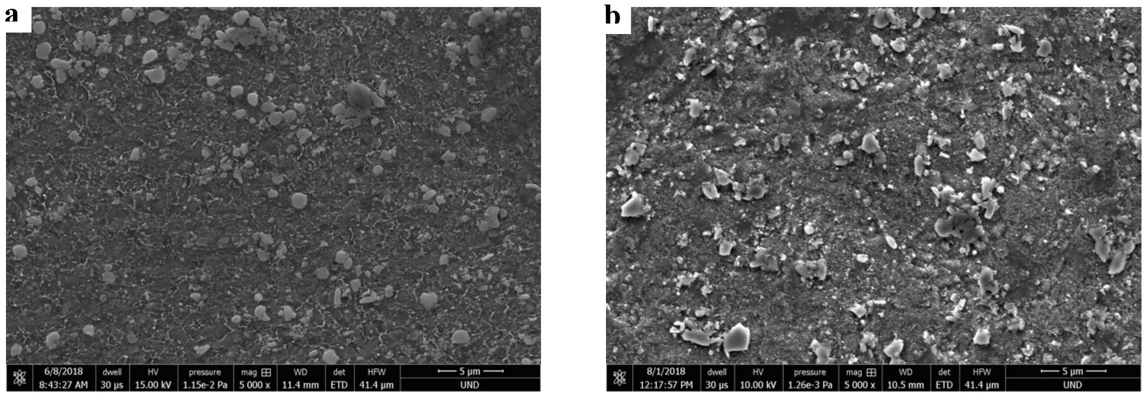

Fig 5. SEM of the as-built and heat-treated A205.0 specimen (a) as built, (b) heat treated.

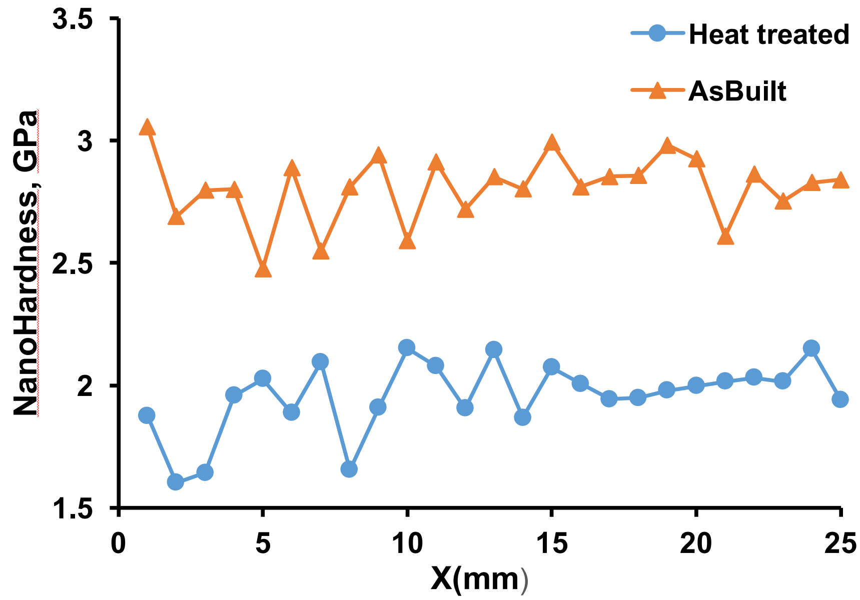

Fig 6. Nano-Hardness measurement of the as-built and heat treated A205.0 (YZ plane) alloy.

Conclusions

In this paper, preliminary results on microstructure/micromechanical characteristics of two commonly printed aluminum alloys, AlSi10Mg and Al-Cu-Ti in the as-printed and heat treated conditions, are presented. Microstructural assessments and nanoindentation testing approach were employed to establish the correlations. In particular, the effects of T_6 heat treatment on the microstructure and hardness properties of SLM AlSi10Mg and A205.0 were investigated in the present paper. Heat treatment at 520°C for 1 hour and then aging at 170°C for 4 hours brought a decrease of the nano-hardness values in both studied alloys. In the AlSi10Mg alloy, a decrease of the hardness by 42.4% in the YZ plane and in the A205.0 alloy a decrease by 30.6% is observed. These drops of hardness values are resulted from material softening due to grain growth, Ti-rich growth and Si-Spheroidization.

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