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Microstructure, Mechanical,, and Fatigue Properties of a Laser Powder Bed Fused Al-Cu-Mg-Ag-Ti-B (A205) Alloy

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Abstract

This paper aims at assessing the effect of heat treatment on fatigue behavior of a novel laser-powder-bed-fusion (L-PBF) fabricated Al-Cu-Mg-Ag-Ti-B alloy, known as A205. To this end, L-PBF samples were heat-treated including (i) stress-relieving, and (ii) T7 stabilizing over-aging. Upon printing and post-heat treatments, advanced microstructural characterizations, mechanical property measurements and force-controlled fatigue performance studies were conducted on the samples, systematically. The findings in this paper present useful information for the selection of appropriate heat treatment conditions, to facilitate control of the fatigue behavior in the L-PBF A205 material, which is of great significance for their high-demanding applications in aerospace sectors.

Keywords: A205; Al-Cu-Mg-Ag-TiB_2; laser powder bed fusion; fatigue; T7 aging.

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Introduction

The grain refinement of Al by titanium diboride particles, TiB_2, is a common practice [1, 2]. This is because of high elastic modulus and hardness, as well as high melting point and outstanding thermal stability of the TiB_2 [3, 4]. Besides, TiB_2 particles do not react with Al, therefore brittle reaction products are not formed at the reinforcement–matrix interface.

Among various TiB_2-reinforced Al composites, Al-Cu-Mg-Ag-TiB_2, known as A205 is an Al-Cu-Mg-Ag composite reinforced with nanosized TiB_2 particles and is considered a great high-strength and high-temperature heat treatable casting alloy [5, 6]. Essentially, the A205 alloy is a modified version of the A201 alloy, with the solidification process having been changed by the inclusion of TiB_2 and hyperperitectic Ti to such a degree that the castability of Al–Cu based alloys has greatly enhanced. Mg and Ag elements contribute directly to the strengthening of the alloy by forming Mg-Ag co-clusters upon aging heat treatment. The TiB_2 particles also pin the grain boundaries and act as nucleation sites for the generation of dislocations (and new grains) and therefore act as grain refiner and improve the strengthening of the alloy [7].

The available literature on fatigue of Al-Cu matrix composites (reinforced with TiB_2 nanoparticles) is on conventionally fabricated (cast and/or wrought) materials. Being a newly developed powder for the additive manufacturing process, the fatigue of L-PBF A205 and effect of post heat treatment (stress-relieving vs T7 heat treated) have never been studied before. Though there are multiple studies on the processability of A205 [8, 9], microstructure [10, 11], mechanical properties (bulk scale and micromechanics) [12, 13], corrosion [14], and time-dependent plastic deformation [15] of the L-PBF A205, there exists a tangible lack of knowledge and published literature on fatigue performance of L-PBF material. To this end, the goal of the research is to fundamentally assess and develop the correlation between microstructure, post-L-PBF heat treatment, and fatigue performance of the alloy for the very first time. We tend to fill the scientific gap in understanding the controlling mechanisms of fatigue failure of the newly developed laser powder bed fused (L-PBF) A205 alloy and to understand the contribution of post-printing heat treatment. As such, this alloy is a family of aerospace-approved A20X for printing flight-critical components, it is of utmost importance to fundamentally quantify the correlation between mechanical properties and fatigue performance of the material and to assess the microstructural evolution and L-PBF induced defects (e.g. gas porosity).

Experimental procedure

A 350 W EOS M290 machine was used to print the A205 test specimens. Hatch distance, scan speed, layer thickness, and laser spot size were set at 0.05-0.10 mm, 1000-2000 mm/s, 50 μm, and 80 μm, respectively. Upon printing and removing the printed parts from the build plate, the materials were divided into two sets for post-fabrication heat treatment (HT): one set was stress relieved and the other set was T7 aged. The stress relief heat treatment was conducted at 300°C for two hours in a Techne FB-08 Series Precision Fluidized Bath of alumina particles (for better control of the temperature consistency). The T7 (solutionizing and over-aging) heat treatment is a multistage cycle process. The solution heat treatment segment is a six-stage process as follows:

1. Place parts in a cold oven.
2. Ramp to 505°C for a minimum of 100 minutes.
3. Hold at 505°C for 2 hours (minimum).
4. Ramp to 530°C without delay.
5. Hold at 530°C for 4 hours (minimum).
6. Quench in 20-25% glycol (polymer) solution with a maximum quench delay of 15 s.

After completion of the solution treatment, the final T7 artificial aging was conducted on the specimens, soaking at 190°C for 4-6 hours, followed by cooling to ambient temperature.

Upon stress relieving and T7 aging, samples were polished following standard metallographic procedure for microstructural assessment, starting from 400 up to 4000 grits of sandpapers. The SEM (Scanning Electron Microscope) was conducted by a Hitachi S-4800 field emission SEM. Keyence VHX-600 Digital Microscope was utilized for OM (Optical Microscopy) characterization with a magnification range of 20x-2000x.

Force-controlled fully reversed fatigue tests (R= -1) according to ASTM E606 [16] standard was conducted at room temperature. A sinusoidal waveform was applied until failure or up to 10^7 reversals as a run-out test in this study. For all 18 tests no cyclic stress hardening or softening was observed here. All fatigue tests were performed at force-controlled mode.

To assess the mechanical properties of the test materials, room temperature indentation testing employing an iMicro Nanoindenter platform equipped with a self-similar pyramidal indenter (Berkovich) was used.

Results

Microstructural Analysis: Figure 1 shows the SEM images (Figures. 1a & 1b) of the A205 alloys (stress-relieved and T7 HT) microstructures along with grain size distribution (Figures. 1c & 1d). A fine microstructure of randomly oriented equiaxed grains (grain size of 1.5 ± 0.5 mm and 3.5 ± 1.6 mm in stress-relieved and T7 materials, respectively) is observed. The unique fine-grained microstructure is due to the presence of thermally stable TiB_2 particles that pin the grain boundaries and also act as heterogeneous nucleation sites for new grains.

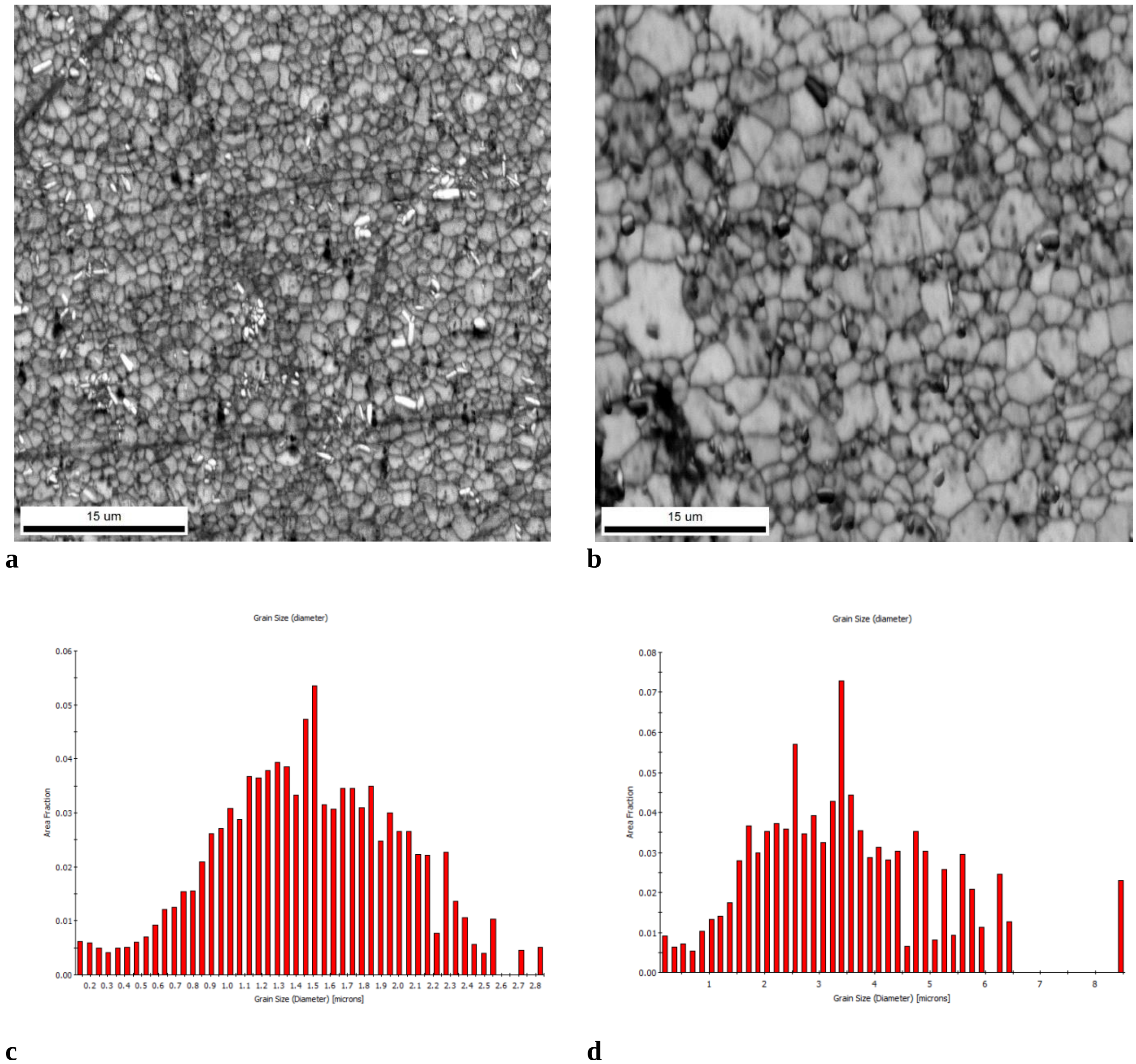
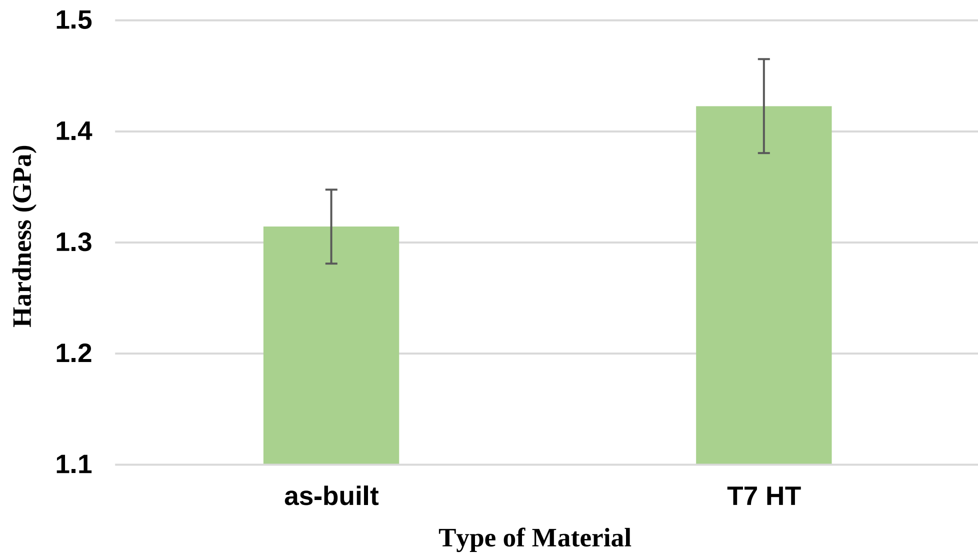


Figure 1: SEM micrograph of a) stress-relieved, b) T7 HT, c,d) grain size distribution of the stress-relieved and T7 HT materials, respectively.

Hardenss and Young's modulous: Indentation tests performed on both categories of samples. Reduced modulus (Er), also called indentation modulus and Micro Hardness test data were obtained. Results are plotted for stress-relieved and T7 HT samples in Figure 2. As it has been manifested in the plot, after applying T7 HT the reduced modulus of the samples has been reduced but hardness has increased. Reduced modulus from indentation tests can be used for the calculation of elastic modulus.



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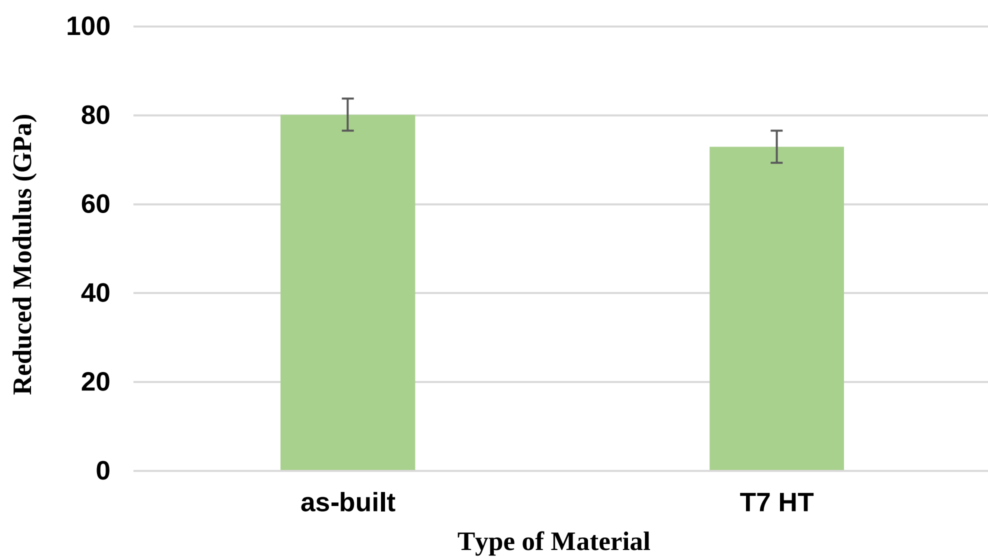


b

Figure 2. a) Micro-Hardness b) and Reduced Modulus test results for stress-relieved and T7 HT samples

Fatigue (S-N) data: The stress-life plot of the stress-relieved and T7 HT samples are shown in Figure 3. As it has been manifested in the plot, fatigue life of the specimens has been increased after applying T7 HT.

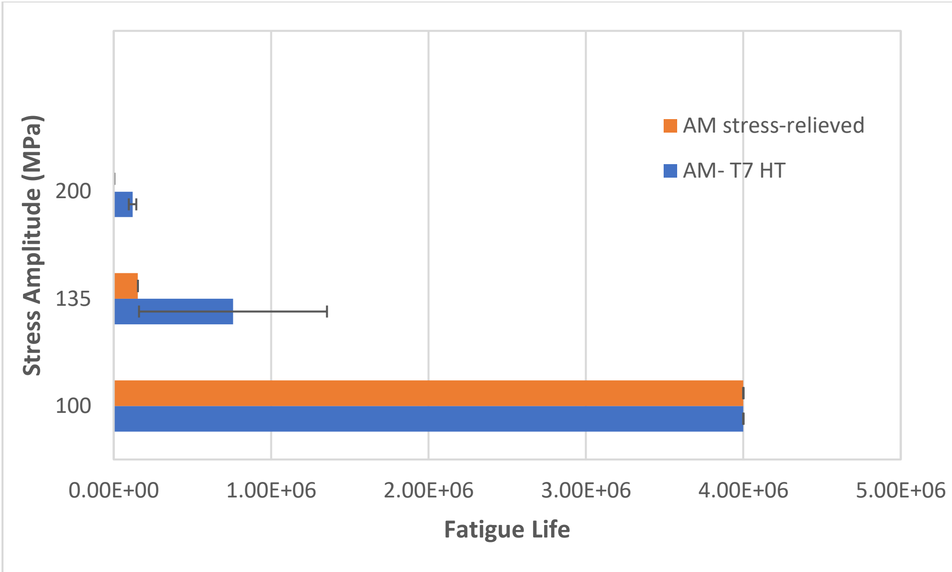
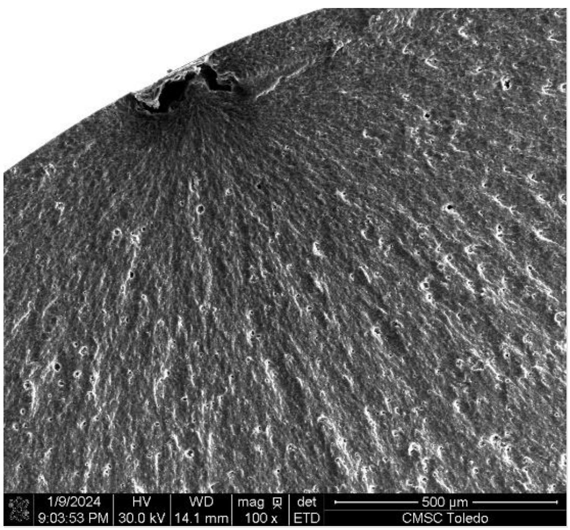


Figure 3. Fatigue strength vs Fatigue life plot for stress-relieved and T7 HT samples

Fractography images: Extensive SEM fractography studies were conducted on specimens for better understanding of fatigue procedure of T7 and stress-relieved materials. Figure 4, displays fracture surfaces of T7 heat treated and stress-relieved specimens at different magnifications, respectively. Cracks mostly initiated from the pores and inclusions near the surface of the samples.



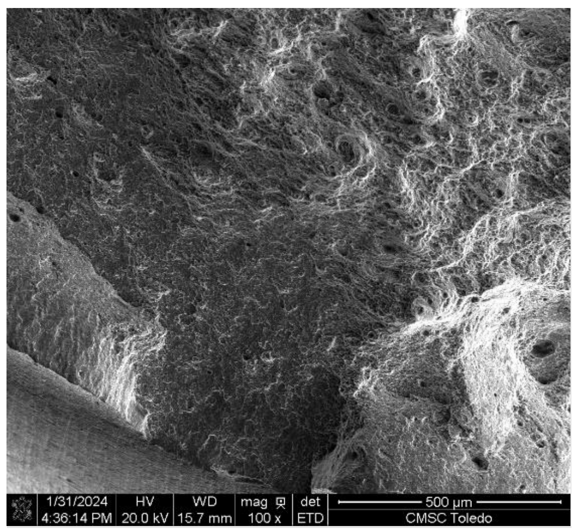


Figure 4. Surface fractography of additively manufactured samples

Discussion

In Al-Cu alloys there are variety of precipitates like θ, θ’, and θ’’ phases and they can highly impact the mechanical behavior of the material. To this end, there are some methods for improving the mechanical behavior via these precipitates, such as post heat treatment. T7 HT is the common post-processing HT for A205 alloy. In T7 HT, favorable θ’ and θ’’ phases are achieved by modifying the θ phases for assessing higher mechanical strength. Maximum strength can be achieved when secondary phases are appeared during the solidification and have been dispersed in base Al material evenly.

This HT also can enhance the strength of the A205 alloy. This concept was confirmed by the S-N curve in Figure 3. In this plot, we can see that T7 HT samples have higher fatigue lives compared to the stress relieved samples. One of the reasons is the dissolution of the segregated solute atoms in the Al matrix. This action will also improve the strength because of the higher interaction between nanoparticles which are evenly distributed. It is due to the prevention of dislocation movements in T7 heat-treated samples because they have higher Al_2Cu precipitates. Also, the strengthening behavior of the material improved since it caused the precipitation of Ω – Al2Cu and θ’ – Al_2Cu in the formation of thin plates since the Ω phase is the main factor for the strengthening of the material.

The fatigue behavior of the alloy mainly affected by the microstructure and existing defects in the fatigue specimens. Existence of the TiB_2 nanoparticles improve the toughness of the A205 Al alloys which is a combination of strength and ductility. The ductility of the material was enhanced due to the grain refinement. Distribution of nanoparticles over the samples was another significant factor for improving the ductility. TiB2 nanoparticles which are well dispersed through the material, can conduct grain boundary pinning structure which can hinder the growth of small cracks owing to the crystallographic misorientation around the cracks. Moreover, TiB_2 nanoparticles act as initiation sites for new grains which helps to shape refined grains. Crack growth can be diverged due to TiB_2 clusters within the matrix which supplies the ductility of the material. T7 post heat treatment on the L-PBF samples improved ductility and strength. Also, at various orientations it created thin plate like Al_2Cu precipitates within the grains.

Microhardness testing on both stress relieved and heat treated samples was conducted. Results showed that due to increase in density of Ω and θ’ precipitates, which formed along different habit planes and impeded the dislocation motion greatly, higher strength was observed for T7 heat treated samples, Figure 2 [17].

Conclusion

In this research, variety of advanced microstructural characterizations, micro hardness and conventionally fatigue tests were performed on stress relieved and T7 HT samples. It was observed that:

- Micro hardness results confirmed higher strength for T7 HT samples.
- Fatigue lives of the samples were improved after applying the T7 HT.

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