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Microstructure and mechanical properties of Ti-2Al alloyed with Mo formed in laser additive manufacture

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A series of Ti-2Al-*y*Mo ($y = 2,5,7,9,12$) alloy samples were produced from blended elemental Ti, Al and Mo powders using the laser solid forming technology. The influence of the β stabilizer Mo on the morphology of the grains, the size and the distribution of the α laths, the Vickers hardness and the tensile properties of Ti-2Al-*y*Mo alloys were explored under designated laser processing parameters. It was found that the microstructure in Ti-2Al-5Mo, Ti-2Al-7Mo, Ti-2Al-9Mo, and Ti-2Al-12Mo deposited layers were composed of irregular columnar grains that grow epitaxially, with some small equiaxed grains in the upper region, while that of the Ti-2Al-2Mo alloy was composed of large columnar grains. The grain size decreased, while the thickness of equiaxed grains layer increased with increasing Mo content. This indicates a tendency towards columnar-to-equiaxed transition with increasing Mo. The dominant β grains form a basketweave microstructure composed of primary α laths, secondary α laths and retained β phase. It was also observed that with increasing Mo content, both the size of primary α laths and secondary α laths decreased significantly, while the number of secondary α laths increased sharply, and the Ti-2Al-12Mo is also constituted of α phase and β phase. The Young's modulus of Ti-2Al-7Mo, Ti-2Al-9Mo, and Ti-2Al-12Mo were basically the same within experimental error. Tensile testing of the specimens showed that Ti-2Al-7Mo exhibits a good combination of strength and elongation to failure. As a result, this material can be considered suitable as a viable feedstock for laser additive manufacturing.

1. Introduction

Laser solid forming (LSF) are also known as directed energy deposition (DED) [1], direct metal deposition (DMD) [2], laser melting deposition (LMD) [3] or laser metal deposition (LMD) [4,5]. It is a rapidly developing additive manufacturing technology that can be used to fabricate near-net shape metallic components. It is typically used to manufacture or repair high value engineering components directly from CAD models. During LSF, a laser beam traverses across a metallic substrate to create a moving melt pool, into which the feedstock powder is delivered through a nozzle. The melt pool solidifies to form a deposit that is welded to the substrate, and the required geometry is then built up in layer-by-layer. This technique can significantly reduce the time between the initial concept design and the creation of the finished part. More importantly, the LSF process allows the flexibility to deposit a blend of elemental powders and create an alloy in the process since the powders can be injected into the melt pool synchronously. This is a highly desirable capability since it will lay the foundations for the integrative control of composition, microstructure, and the mechanical properties of high value metal parts. It could also be used to investigate new alloy systems and, create functional structures

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and innovative materials [6,7].

Titanium alloys have been extensively used in additive manufacturing, largely due to its favorable response to a broad range of processing parameters. Alloying elements in titanium alloys can be generally classified as α or β stabilizers. β stabilizers result in stability of the β phase at lower temperatures [8]. In fact, most of the titanium alloys, including certain α alloys, commercially pure (unalloyed) titanium and all the α+β and β alloys contain β stabilizing elements. Recently, some interesting work has been carried out to synthesize the novel titanium alloys by using laser additive manufacturing from blended elemental powders. Mendoza et al. [9] deposited a compositionally graded Ti-xW ($0 \leq x \leq 30$) specimen using laser engineered net shaping (LENS) technology, and explored the grain-refinement effect of tungsten on laser additive manufacturing of Ti-based alloys. A significant reduction in the grain size was observed with addition of up to 23 wt% W. Vrancken et al. [10] studied the solidification, microstructure, mechanical properties and response to heat treatment of selective laser melting (SLM) parts produced using a mixture of Ti6Al4V-ELI powder with 10 wt% Mo powder, and found that the tensile properties of this novel alloy were equal to or better than conventional β titanium alloys. Li et al. [11] designed a novel titanium alloy Ti-6Al-2V-1.5Mo-0.5Zr-0.3Si and prepared the alloy samples by laser additive manufacturing from blended elemental powders. The as-deposited structure, composition, microhardness and room temperature tensile properties were also studied. Fischer et al. [12] manufactured Ti-26 at.% Nb alloy from Ti powder and Nb powder by directly melting a mixture of non-spherical elemental powders under the laser beam, and the influences of the process parameters on homogeneity, compactness and elastic properties of the alloy were investigated. Sing et al. [13] deposited titanium-tantalum alloy parts via selective laser melting with a mixture of commercially pure titanium and tantalum powders as the feedstock. They then determined the microstructure and mechanical properties of the subsequent samples, including elastic modulus, ultimate tensile strength, yield strength, and microhardness. Yan et al. [14] prepared Ti-6Al-4V from Ti, Al, and V elemental powder blends using the direct laser deposition (DLD), and investigated the effects of the laser transverse speed and laser power on the initial fabrication of the deposits' microstructure and Vickers hardness.

Previous studies reported that the microstructures of LSF processed titanium alloys are markedly different from those observed in wrought supply. This clearly suggests that the chemical composition of the current generation of materials are not optimized for LSF. Moreover, our current understanding of the influence of β stabilizers on the microstructure of LSF titanium alloys is quite limited.

Ti-Al-X ternary system alloys exhibit an excellent combination of mechanical properties and processability, and are widely used in the aerospace, petrochemical, and biomedical industries. Mo and V are the most commonly used β phase stable elements of titanium. Due to the low cost and low toxicity of Mo, new titanium alloys of Ti-2Al-yMo (y = 2,5,7,9,12) were deposited by LSF in this study, which forms the foundation for developing and improving new titanium alloys to fabricate orthopedic biomaterials. This is consistent with the drive in research activities towards optimizing materials' design for laser additive manufacturing processes.

2. Experimental method

2.1. Materials

Commercially pure Ti powder, with particles size range of 100–150 μm, commercially pure Al powder, with particles size range of 50–250 μm, and commercially pure Mo powder with particles sizes of 75–125 μm were used in this study. The purity of the elemental powders was measured to be higher than 99.5 wt%. The Mo additions selected for this study were 2, 5, 7, 9, 12 wt%. Prior to the experiments, the elemental powder particles were mixed proportionally according to the designated compositions and were

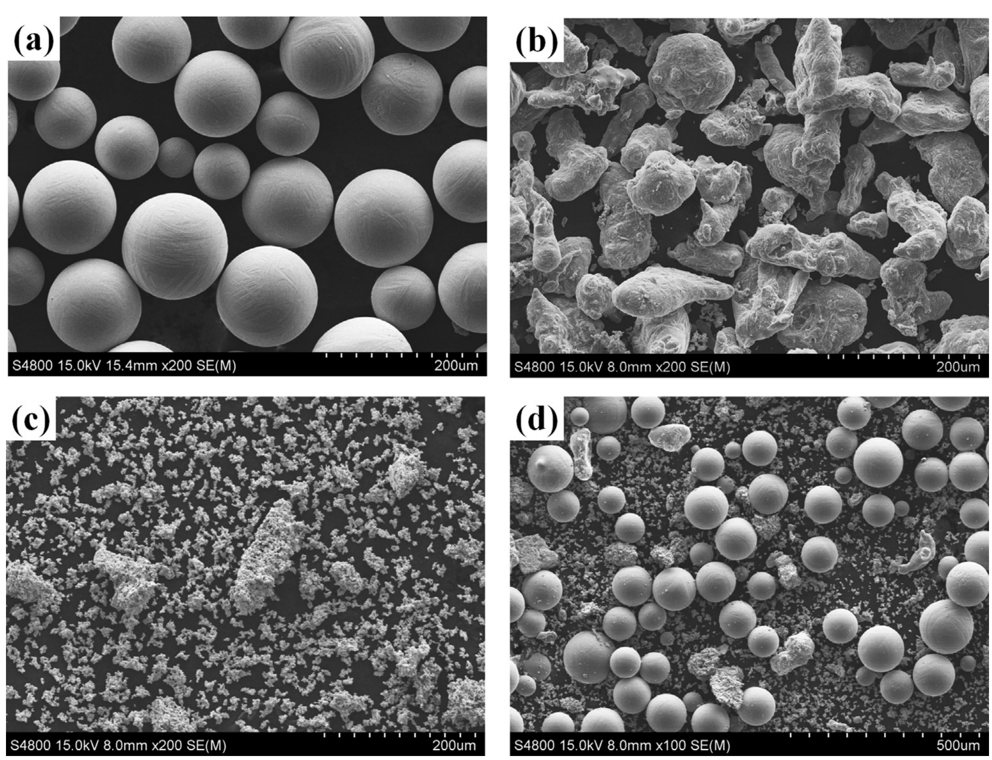

Fig. 1. Micrographs showing the morphologies of the elemental powders: (a) Ti, (b) Al, (c) Mo, (d) blended Ti-2Al-12Mo powder particles.