STRUCTURE AND PROPERTIES OF ADDITIVELY MANUFACTURED WE43 MAGNESIUM ALLOY

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Abstract

The experiment described in this article deals with the comparison of structures and mechanical properties of the Mg-4Y-3RE-0.5Zr (WE43) magnesium alloy produced by three different methods. A technique of additive manufacturing, selective laser melting (SLM), is compared with two conventional manufacturing techniques, casting and extrusion. Microstructures and chemical composition of present phases were studied using scanning electron microscopy (SEM) and energy dispersive X-ray spectrometry (EDS). Mechanical properties were compared based on hardness measurement, compression test and three-point flexural test. Significant differences were found between the microstructures of WE43 alloy produced by different production processes. Measurements of mechanical properties showed similar mechanical properties of additively manufactured samples with as-cast samples

Keywords: Magnesium alloy, casting, extrusion, 3D printing, mechanical properties, microstructure

1. INTRODUCTION

Magnesium alloys are ones of the most used alloys due to its low density and good mechanical strength, especially in the automotive and aerospace industries. The mostly used Mg alloys contain Al and Zn as essential alloying elements. The main drawback of the Mg-Al-Zn alloys (AZ types) is a low mechanical stability at elevated temperatures above 150 °C. To overcome this drawback, Mg-RE alloys have been developed which are able to withstand temperatures up to 250 °C and more. In these alloys, stable Mg-RE precipitates are formed that hinder dislocation motion at higher temperatures [1,2]. Mg-4Y-3RE-0.5Zr alloy, known as WE43, was chosen for this experiment. This alloy is known for it's a good thermal stability, high strength, good corrosion resistance and biocompatibility [3].

Additive manufacturing (also known as 3D printing) is a modern method of producing structurally complex parts that are almost impossible to produce by conventional means [4]. One method of 3D printing is Selective Laser Melting (SLM) where atomized powders are consolidated by the action of a laser beam. A powder is deposited onto a working plate to form a layer, several tens of micrometers thin. The powder layer is then selectively scanned by in each cycle, the working plate is lowered down by one-layer thickness and a new powder layer is deposited [1,5,6]. Due to high energy directed to a small volume of material, very high temperature gradients and so cooling rates arise, resulting in very fine-grained microstructures. Cooling speed can reach values up to 10^3-10^6 °C/s [7,8].

Due to the fact that 3D printing of magnesium alloys is a relatively new process, this paper is focused on describing the microstructure and mechanical properties of the SLM WE43 alloy, and comparison with well-known processes of casting and extrusion.

2. EXPERIMENTAL SETUP

2.1. Specimens preparation

The subject of this work is a 3D printed WE43 magnesium alloy produced by the selective laser melting (SLM) technology. The same alloy produced conventionally, by casting and extrusion, served as a reference material. All compared materials were of the same composition Mg-4Y-3RE-0.5Zr. The 3D printed material was produced by an SLM Solution 280^{HL} (SLM solutions AG) machine equipped with 400 W ytterbium fiber laser, in cooperation with Brno University of Technology. All parameters of the SLM process are shown in **Table 1**. The samples were printed from a fine gas-atomized powder (30-60 µm, Luxfer Mel Technologies) in the form of blocks 80 mm x 10 mm x 2 mm in size. The longest side was parallel to the working plate. Scanning strategy were stripes, with the change of scanning direction by 67° each layer.

The cast material was purchased from an industrial manufacturer in the form of an ingot. Further, as-cast ingots were cut into cylinders of 30 mm in diameter and 60 mm in length and subjected to a hot-extrusion. The extrusion was carried out at 400 °C, with an extrusion rate of 2 mm/s and extrusion ratio of 16. The resulting extruded rod had a diameter of 7.5 mm.

Table 1 SLM parameters

Laser power	225 W	**Atmosphere**	Argon
Scanning speed	450 mm/s	**Overpressure**	1.2-2 kPa
Hatching distance	90 µm	**Oxygen level**	0.1-0.3 %
Layer thickness	50 µm	**Built plate temp.**	120 °C

a. Microstructure characterization

For microstructural characterization, a we used a standard metallographic procedure consisting of grinding on SiC papers, polishing on diamond pastes and final polishing on silica suspension Etosil E. Microstructures were observed using a light metallographic microscope OLYMPUS PME 3 and a TESCAN VEGA-3 LMU scanning electron microscope (SEM) equipped with energy-dispersive X-ray spectroscopy (EDS) analyzer Oxford instruments INCA 350.

b. Mechanical properties

The mechanical properties were compared based on hardness measurement, compression tests and three-point flexural tests. Hardness was measured by the Vickers method using a Future-Tech FM-700 microhardness tester with a load of 100 g at a dwell of 10 s. Three-point bending tests and compression tests were performed with the LabTest 5.250SP1-VM universal loading machine. Three measurements were done for each material. For bending, beam test specimens (3 mm x 5 mm x 18 mm) were used, placed on two supports and the force was applied to the testing body midway between the supports (three-point bending). For compression tests specimens (7 mm x 7 mm x 7 mm) were used.

3. RESULTS AND DISCUSSION

3.1. Microstructure

The microstructures of the WE43 alloy are shown in **Figure 1**. The microstructure of as-cast alloy (**Figure 1A**) is composed of α-Mg dendrites and eutectics predominantly formed by α-Mg + β-$Mg_{14}Nd_2Y$ phase. The average thickness of dendritic branches achieves almost 50 µm. The microstructure of the sample after the extrusion is shown in **Figure 1B**. The eutectic network was broken by the extrusion so that the intermetallic phase fragmented into very fine particles arranged in parallel in the direction of extrusion can be observed. Also, recrystallization and grain refinement took place. **Figures 1C** and **1D** show the microstructure produced by SLM. The SLM material has extremely fine microstructure, with very fine dendrites of α-Mg and interdendritic network enriched in the alloying elements. The dendritic structure can only be observed at high magnification (**Figure 1D**). Due to the high affinity of magnesium to oxygen, oxide shells are abundant in the microstructure. These oxides shells can prevent the powder particles from a complete fusion. Therefore, original particles of the powder randomly distributed in the material can be found (**Figure 1C**).

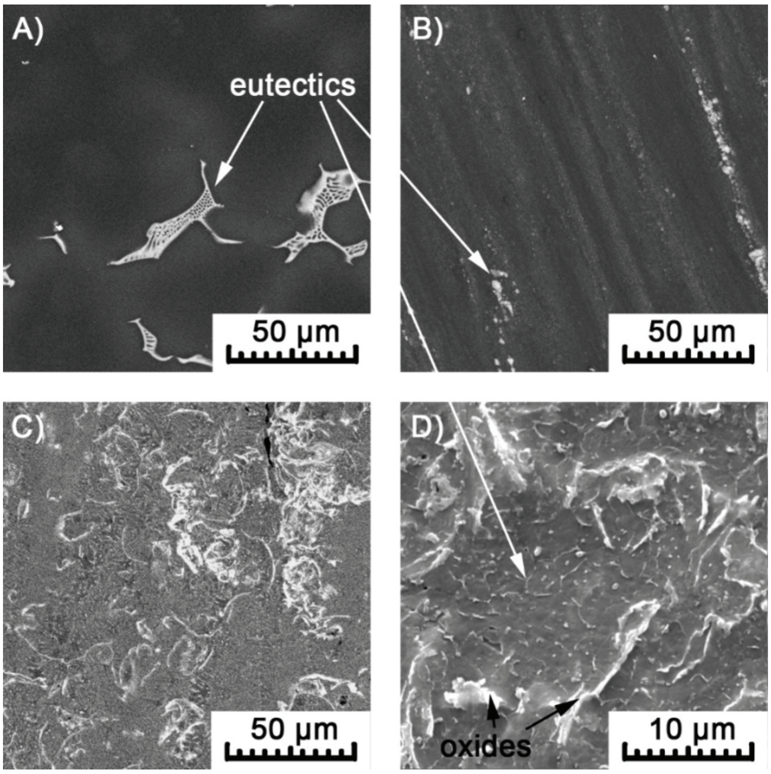

Figure 1 Microstructures of the WE43 alloy: A) as-cast, B) hot-extruded, C, D) 3D printed by SLM

3.2. Mechanical properties

Despite significantly finer microstructure, 3D printed WE43 alloy did not show unambiguously the best mechanical behavior. Due to improper consolidation (presence of porosity) and high amount of oxides, the flexural strength remained comparable to the as-cast material (see curves in **Figure 2**, values in **Table 2**). Hot extruded samples performed the best thanks to the recrystallization, grain refinement, fragmentation of eutectics and lack of porosity. Only under compression, where internal defects play significantly lower effect, the fine 3D printed structure manifested. The 3D printed samples reached ultimate strength of 441 MPa, about 100 MPa more than the as-cast samples and 38 MPa more than the extruded samples. The representative stress-strain curves are compared in **Figure 3**.

Table 2 Comparison table of mechanical properties of WE43 alloy produced by different methods

	Casting	Hot extrusion	3D printing
HV0.1	97	132	86
Flexural strength (MPa)	221	398	219
Ultimate compressive strength (MPa)	341	403	441

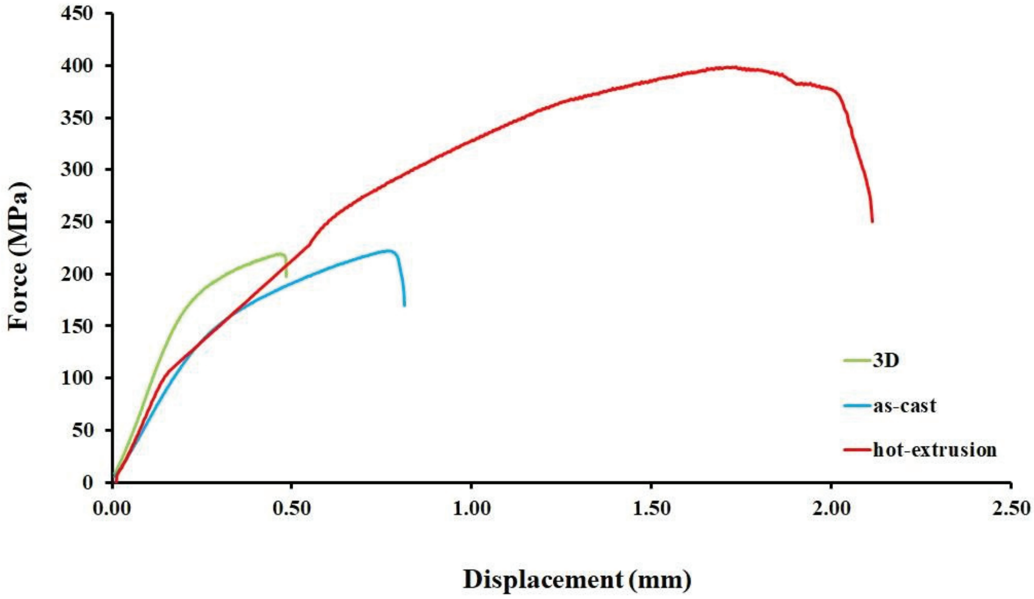

Figure 2 Three-point bending load-dispalcement curve

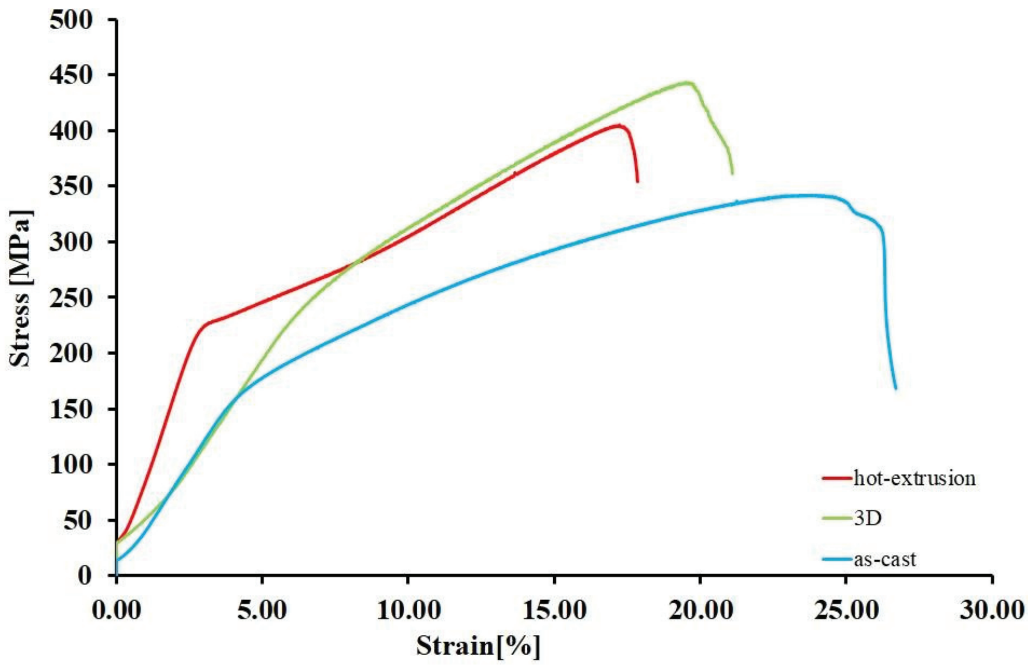

Figure 3 Compression stress-strain curves

4. CONCLUSION

Based on the comparison of the microstructure and mechanical tests carried out for 3D printed (SLM), as-cast and hot-extruded WE43 alloy, the following conclusions can be drawn. Microstructure differs significantly according to the production process. Extremely fine microstructure of the 3D printed material can be attributed to very high cooling rates during SLM. However, non-ideal processing atmosphere in SLM with oxygen residues yields in the presence of oxides and imperfect consolidation. As a result, the 3D printed WE43 alloy performs similarly to the as-cast material, worse that the hot-extruded material. Only under compression, the 3D printed alloy surpassed the hot-extruded alloy by 38 MPa.

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