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Laser fusion of aluminum-alumina composites obtained in the vortex layer apparatus

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Abstract. The current study is devoted to laser fusion of aluminum-matrix composites with 3 wt. % of alumina obtained in the vortex layer apparatus. The mixing parameters and the distribution of alumina in the composite structure were studied. Three parameters of laser fusion for plate synthesis were used. The finest results were achieved using a volumetric energy density of 24 J/mm^3 with 370 W laser power. The maximum mechanical properties of the samples synthesized by the optimal parameters were: UTS = 384 ± 5 MPa; E_f = 0.54 ± 0.1 %.

1. Introduction

Metal matrix composites are widely used in aerospace, defense, and automotive industries due to their high strength and excellent wear resistance. Recently, aluminum-based composites have been increasingly used among composites with a metal matrix due to their combination of lightweight and high mechanical characteristics [1]. To date, many scientific groups have investigated a wide range of reinforcements for aluminum-matrix composites, such as SiC, AlN, TiC, TiB_2, and others. However, in comparison with other reinforcing additives, Al_2O_3 particles can improve both the mechanical and high-temperature properties of aluminum products without forming any undesirable phases [2,3]. An optimal set of mechanical properties can be achieved with evenly dispersed small Al_2O_3 particles in the metal matrix. Based on this, this study was aimed to form Al–Al_2O_3 composite materials in a vortex layer apparatus with efficient mixing of powders. The prepared powders were subjected to laser fusion followed by the characterization of the resulting composites.

2. Materials and Methods

Silumin and alumina powders were the initial materials for producing aluminum–alumina composites. The silumin contained ~ 86.5 % Al and ~ 11.0 % Si and included small additives of Mg, Mn, Fe, and Ti [4]. The average particle size of the silumin powder was 43 μm. Alumina obtained from aluminum chloride was used as reinforcement [5]. Alumina contained more than 99.0% Al_2O_3 and corresponded to the α-modification of alumina. The alumina used was pre-grounded in a ball mill and carefully classified using a sieve with a hole diameter of 64 μm. The average particle size of the alumina was 20 μm.

Mixing of powders was performed in a classical vortex layer apparatus, a similar scheme of which is discussed in detail in [6]. Mixing was carried out by ferromagnetic steel bodies managed by a high-power electromagnetic field. The ferromagnetic bodies had a cylindrical shape with a height of 1.3 cm. The ratio of the mass of the mixture to the mass of the ferromagnetic bodies was 2 to 1. The powders

were mixed for 60 seconds. The speed of rotation of the magnetic field in the working chamber did not exceed 3000 rpm.

Laser fusion of aluminum-alumina composites was performed on an SLM Solutions 280 HL 3D printer. The synthesized samples were square plates with a thickness of 3 mm and a side length of 25 mm. The thickness of the initial powder layer was 80 μm for each plate. The volumetric energy density (VED, J/mm^3) was used as an optimization parameter [7]. The VED was calculated using the equation (1)

$$VED = P / (V \cdot h \cdot t) \quad (1)$$

where *P* is the laser power (W), *V* is the scan speed (mm/s), *h* is the hatch spacing (mm), and *t* is the layer thickness (mm).

For all modes, the VED was about 24 J/mm^3, but the parameters P and V varied: P = 370 W was used for Mode #1, 200 W for Mode #2, and 100 W for Mode #3.

Scanning electron microscope (SEM) images of the powders and the synthesized samples were obtained using a Tescan Vega 3 SEM with an element mapping attachment. The analysis of porosity of the synthesized samples was performed using a Carl Zeiss Axio Observer A1M optical microscope (OM). Tensile tests were performed on an Instron 5969 testing machine at room temperature with a crosshead speed of 0.5 mm/min.

3. Results and Discussion

For the study, a mixture of aluminum powder with 3 wt.% of alumina was prepared in a vortex layer apparatus. As can be seen in Figure 1c, the vortex layer apparatus allowed a thorough mixing of powders, as well as subjected to the grinding of alumina. The initial alumina powder (see Figure 1b) contained particles up to 30 μm in size, while after mixing the powders, the alumina particle size was 1-3 μm on average. However, as can be seen from the elemental distribution map (see Figure 1d), there are areas of alumina accumulation in the powder mixture that reach 20-25 μm in size. The size and shape of silumin particles did not change after mixing in the vortex layer apparatus. The distribution of alumina in the mixture was fairly uniform, which indicates the effectiveness of using the vortex layer apparatus to produce powder composites.

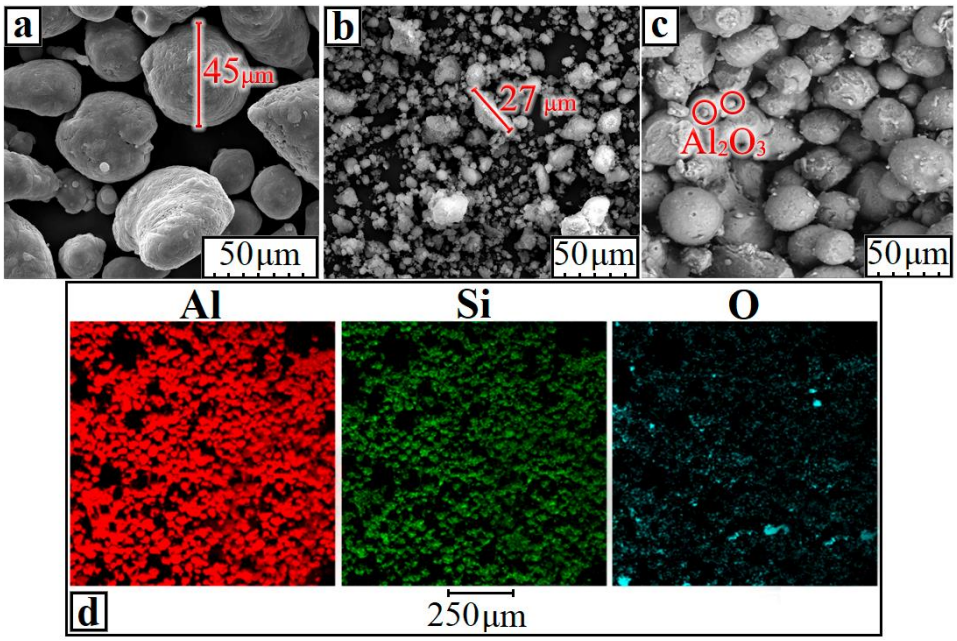

Figure 1. SEM images of powders: silumin powder (a); alumina powder (b); silumin and alumina powder mixture (c); element mapping of silumin and alumina powder mixture (d).

Images of synthesized samples obtained using optical microscopy are shown in Figure 2. All samples had a noticeable pore content, and the samples synthesized in Modes #2 and #3 had distinct areas of insufficient fusion of the composite material. The microstructure of the samples fused in Modes #2 and #3 indicated the choice of an incorrect laser fusion mode. The lowest porosity (0.3±0.02 %) was observed in the plate synthesized according to Mode #1.

The SEM image of the synthesized sample using Mode #1 is shown in Figure 2d. As can be seen from Figure 2, during the laser fusion, alumina was evenly distributed over the surface of the aluminum alloy, and areas of alumina accumulation were no longer observed. Probably, due to the brittleness of the used α-Al_2O_3, it was crushed by mechanical mixing with ferromagnetic steel bodies, and the areas of alumina accumulation in Figure 1d are caused by sticking with partially fused aluminum particles.

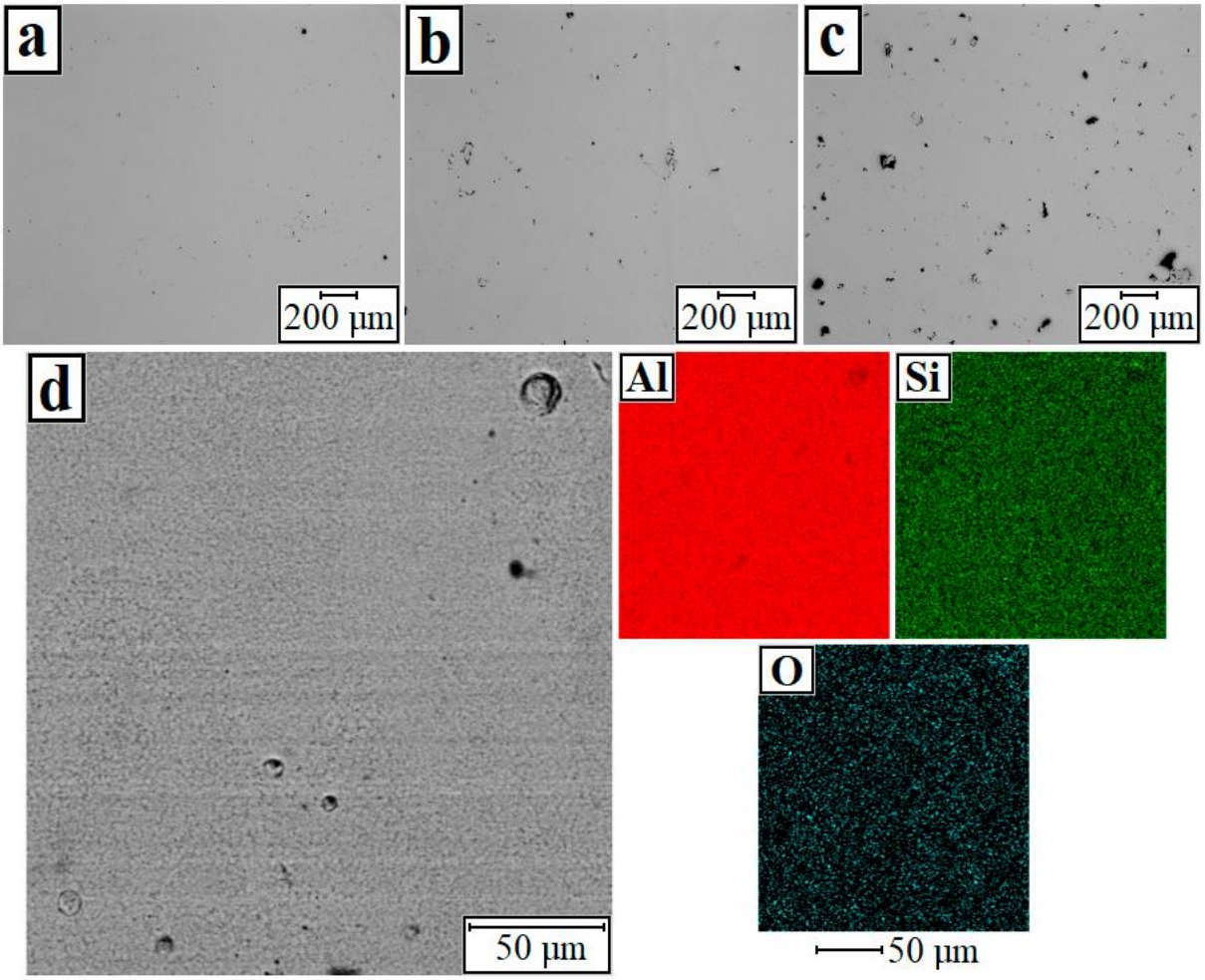

Figure 2. OM and SEM images of the synthesized samples using Mode #1 (a, d), Mode #2 (b) and Mode #3 (c).

The mechanical properties of the synthesized plates are presented in Table 1. The lowest ultimate tensile strength (UTS) was observed with Mode #3, which is explained by insufficient heat input of the laser beam energy and only partial melt of the aluminum matrix.

During the laser fusion process, the composite powder formed a molten pool. α–Al_2O_3 as a reinforcement, practically was not subjected to melting in comparison with silumin. Due to their small size, alumina particles were distributed in the molten pool as a suspended substance, which increased the viscosity of the melt. Despite the same VED value, the formation mechanism of the molten pool in each sample was different. At a low laser power value, the composite material did not have time to

completely melt. The melt viscosity was too high for the effective wetting of the composite particles and previous molten layers, which led to the formation of internal defects [8]. As can be seen from Table 1, the strength of the samples increased with an increase in laser power.

Table 1. The mechanical properties of the synthesized objects.

Laser fusion mode	State	UTS (MPa)	E_f (%)
Mode #1 (P = 370 W)	as processed	384 ± 5	0.54 ± 0.1
Mode #2 (P = 200 W)	as processed	241 ± 4	0.25 ± 0.1
Mode #3 (P = 100 W)	as processed	150 ± 9	0.33 ± 0.1

However, for all samples, UTS was noticeably less than for samples synthesized from a classic aluminum alloy for additive manufacturing ($AlSi_{10}Mg$, state: as processed, UTS = 430 MPa) [9]. Also, the elongation of all synthesized samples did not exceed 0.54%. This indicates a high content of Al_2O_3 in the samples, which increased their brittleness. Despite the uniform distribution of alumina in the samples, its high content caused insufficient laser fusion of the composite material, which reduced the bonding strength between the reinforcement and the matrix. According to the obtained results, further research will be concentrated on a lower content of alumina in Al–Al_2O_3 composites obtained by the vortex layer apparatus.

4. Conclusions

In this paper, the process of aluminum–alumina composites formation in a vortex layer apparatus and subsequent laser fusion was considered. Composite materials obtained in the vortex layer apparatus were characterized by a uniform distribution of alumina in the matrix. Three laser fusion modes were tested, the most effective being Mode #1, which was performed at VED = 24 J/mm^3 and P = 370 W. The sample synthesized using Mode #1 had the following mechanical properties: UTS = 384 ± 5 MPa; E_f = 0.54 ± 0.1 %. The obtained results indicated a too high content of alumina for the used laser fusion modes, causing high porosity of the synthesized samples. According to the results, further research using a smaller amount of Al_2O_3 in the composite is planned.

5. Funding

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