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ScienceDirect

Scripta Materialia 96 (2015) 25–28

Scripta MATERIALIA

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Rapid fabrication of Al-based bulk-form nanocomposites with novel reinforcement and enhanced performance by selective laser melting

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Received 7 October 2014; accepted 12 October 2014
Available online 30 October 2014

A novel ring-structured nanoscale TiC reinforcement with a regular distribution was tailored along the grain boundaries of the matrix by selective laser melting (SLM) to produce TiC/AlSi10 Mg nanocomposite parts. Relative to the SLM-processed unreinforced AlSi10 Mg part, the TiC/AlSi10 Mg nanocomposite part with the novel reinforcement architecture exhibited elevated microhardness (188.3 $HV_{0.1}$) and tensile strength (486 MPa) without a reduction in elongation (10.9%), due to the combined effects of grain refinement and grain boundary strengthening caused by the ring-structured nanoscale TiC reinforcement.

Keywords: Laser treatment; Powder consolidation; Metal matrix composites (MMCs); Nanocomposite; Selective laser melting (SLM)

As outstanding high-performance lightweight materials, aluminum matrix composites (AMCs) reinforced with harder and stiffer ceramic particles are widely used in aerospace, aircraft and automotive applications because of their excellent properties, such as high specific stiffness, high specific strength and excellent wear resistance [1–4]. Normally, the improvement in the mechanical properties of AMCs is mainly determined by the particle size and distribution state of the reinforcement [5]. It has been found that decreasing the reinforcement particle size from the relatively large micrometer level to the considerably finer nanometer scale can lead to the simultaneous enhancement of the strength and ductility of AMCs [6,7]. Such novel materials are defined as nanocomposites [8]. Currently, several manufacturing techniques are used to produce nanoparticle-reinforced AMCs, including mechanical alloying [9,10], powder metallurgy [11,12], stir-casting [6,7], etc. The aim of these methods is generally to obtain a uniform distribution of nanoscale reinforcing phase in the matrix in order to enhance the reinforcement effect. Differently, some previous research work has revealed that the mechanical properties of metal matrix composites (MMCs) can be further improved by tailoring the distribution of reinforcement on a microscopic level [13,14]. However, previous research efforts have mainly been focused on controlling microstructures of MMCs reinforced with microsized ceramic particles. For ultrafine nanoscale ceramic reinforcement, it is much more difficult to tailor the distribution during MMC preparation: the uncontrolled agglomeration of nanoparticles due to the considerably large van der Waals attractive forces tends to cause significant microstructural inhomogeneity. Very little previous work has been reported on the processing of nanocomposites with novel reinforcement microstructure.

Selective laser melting (SLM) is regarded as a promising additive manufacturing technique due to its flexibility in producing complex shaped parts directly from loose powder [15–17]. SLM provides new technological opportunities for fabricating high-performance MMCs parts with unique microstructures, because of the extremely rapid melting/solidification induced by non-equilibrium laser scanning [18–21]. Very recently, work has been carried out that testifies to the possibility of processing Fe-matrix and Ti-matrix nanocomposites using SLM [16,17]. However, there are no previous reports on SLM processing of Al-based nanocomposite parts with tailored microstructure and performance. This work on SLM of bulk-form TiC/AlSi10 Mg nanocomposites thus concentrates on the above issue. The nanoscale TiC is selected as reinforcement based on its good wettability and thermodynamic stability within the molten aluminum. This work focused on the

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http://dx.doi.org/10.1016/j.scriptamat.2014.10.011
1359-6462/

influence of SLM processing parameters on microstructural evolution and mechanical properties (especially tensile strength and elongation) of SLM-processed Al-based nanocomposites. A process–microstructure–performance relationship was established to enable the successful production of AMC parts with tailored reinforcement architecture and improved mechanical performance.

99.0% purity TiC nanopowder with a non-spherical shape and a mean particle size of 50 nm, and 99.7% purity AlSi10 Mg powder with a spherical shape and an average particle diameter of 30 μm were used. The TiC and AlSi10 Mg powder system consisting of 3 wt.% TiC were mechanically mixed in a Fritsch Pulverisette 4 vario-planetary mill, using a ball-to-powder weight ratio of 1:1, a rotation speed of the main disk of 200 rpm, and a mixing duration of 4 h.

The SLM system consisted mainly of an IPG YLR-200-SM ytterbium fiber laser with a power of ~200 W and a spot size of 70 μm, an automatic powder spreading device, an inert argon gas protection system, and a computer system for process control. Based on a series of preliminary experiments, the following SLM parameters were optimized: scan speed $(v) = 200\ \mathrm{mm\ s^{-1}}$, scan line hatch spacing $(h) = 50\ \mu\mathrm{m}$, and powder layer thickness $(d) = 50\ \mu\mathrm{m}$. In order to change the processing conditions during experiments, various laser powers (P) of 80, 100, 120 and 140 W were set by the SLM control program. Four different "volumetric laser energy densities" (E) of 160, 200, 240 and 280 J mm^{-3}, which were defined by $E = \frac{P}{vhd}$ [22], were used to assess the laser energy input to the powder layer being processed.

Specimens for metallographic examinations were prepared according to standard procedures, and etched with a solution containing HF (2 ml), HCl (3 ml), HNO_3 (5 ml) and distilled water (190 ml) for 10 s. High-resolution study of the ultrafine nanostructures of SLM-processed nanocomposite samples was performed by field emission scanning electron microscopy (FE-SEM) using a Hitachi S-4800 at 5 kV. Phase identification was performed by X-ray diffraction (XRD) using a Bruker D8 Advance diffractometer with Cu K_α radiation at 40 kV and 40 mA, using a continuous scan mode at 4° min^{-1}. The Vickers hardness was measured using a MicroMet 5101 microhardness tester at a load of 0.1 kg and an indentation time of 20 s. The SLM-processed samples were cut using a spark-erosion wire cutting machine to prepare standard specimens for tensile tests, according to the standard GB/T228–2010. The tensile direction was parallel to the SLM-processed layers. Uniaxial tensile tests were performed at room temperature with a SANS CMT5105 universal testing machine at a strain rate of $1 \times 10^{-4}\ \mathrm{s^{-1}}$. The ultimate tensile strength and elongation were determined from the stress–strain curves.

The characteristic phases and microstructures of the SLM-processed TiC/AlSi10 Mg nanocomposite parts are illustrated in Figs. 1 and 2, showing the different morphologies and distributions of the reinforcement at various laser energy densities (E). As revealed in the XRD pattern of an SLM-processed part (Fig. 1e), strong diffraction peaks corresponding to Al_9Si (JCPDS Card No. 65-8554), as the matrix phase, and stoichiometric TiC (JCPDS Card No. 65-8805), as the reinforcing phase, were identified. Energy-dispersive X-ray spectroscopy (EDX) spot scan analysis was also performed on the matrix (Point 1, Fig. 1c) and the reinforcement (Point 2) to identify quantitatively the chemical compositions of different phases, with the detailed results depicted in Table 1. It was clear that the matrix was rich in Al element, with a small amount of Si, Mg, Ti and C elements dissolved inside it. The reinforcement was mainly composed of Ti and C elements with an atomic ratio very close to 1:1. The combination of XRD and EDX results revealed the formation of TiC-reinforced Al–Si–Mg-based nanocomposites after SLM.

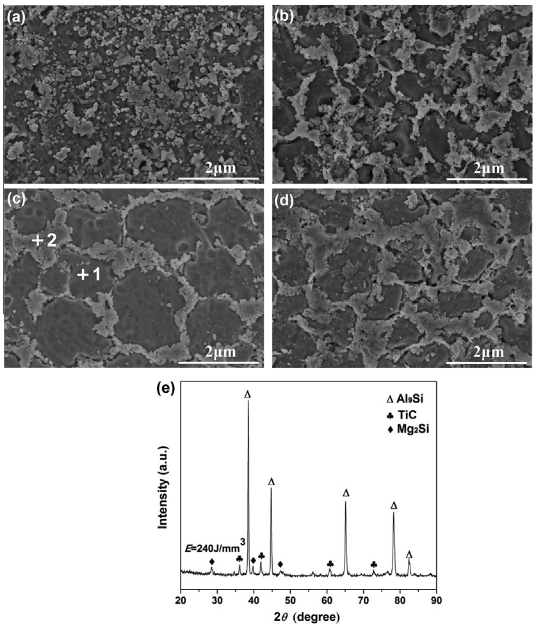

Figure 1. FE-SEM images showing typical microstructures of SLM-processed TiC/AlSi10 Mg nanocomposites at various laser energy densities (E): (a) $E = 160$ J mm^{-3}; (b) $E = 200$ J mm^{-3}; (c) $E = 240$ J mm^{-3}; (d) $E = 280$ J mm^{-3}. XRD spectra showing the constituent phases of SLM-processed Al-based nanocomposites (e).

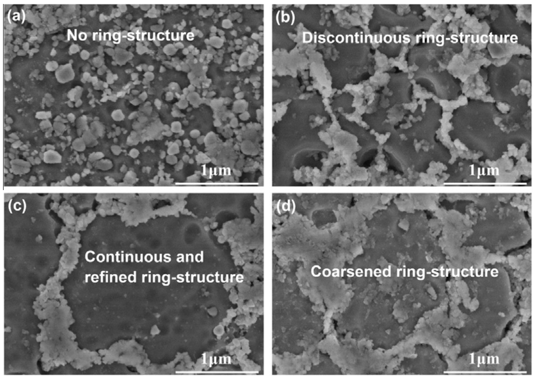

Figure 2. High-magnification FE-SEM images showing dispersion morphologies of nanoscale TiC reinforcement in SLM-processed TiC/AlSi10 Mg nanocomposites at different laser energy densities (E): (a) $E = 160$ J mm^{-3}; (b) $E = 200$ J mm^{-3}; (c) $E = 240$ J mm^{-3}; (d) $E = 280$ J mm^{-3}.

The applied laser energy densities (E) significantly influenced the microstructural development of TiC-reinforcing phase during the SLM process. At a relatively low E of 160 J mm^{-3}, the TiC nanoparticles showed a high tendency to aggregate into inhomogeneous clusters, with some large agglomerates of TiC reinforcement formed in the matrix (Fig. 1a). High-magnification FE-SEM analysis revealed that the TiC reinforcement showed an initial particulate morphology after SLM, having a disordered distribution within the matrix (Fig. 2a). With the increase of E to 200 J mm^{-3}, the TiC reinforcement started to have a