Journal of Manufacturing Processes 32 (2018) 606–614

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Pulsed laser remelting of A384 aluminum, part I: Measuring homogeneity and wear resistance

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ARTICLE INFO

Article history:
Received 16 September 2017
Received in revised form 5 February 2018
Accepted 6 March 2018

Keywords:
Aluminum
Laser
Remelting
Homogeneity
Hardness
Wear resistance

ABSTRACT

The objective of this study is to understand how pulsed laser remelting of aluminum alloy A384 redistributes its surface compositions, and affects its hardness and wear resistance. As a result of each laser pulse, the material experiences rapid heating (melting) and cooling (solidification), which can change the microstructure and degree of chemical homogeneity significantly. These changes in microstructure would manifest themselves as changes in mechanical properties. The proeutectic silicon precipitates found in as-cast A384 melt and disperse into the aluminum matrix during pulsed laser remelting, and do not have sufficient time to grow into large precipitates due to the rapid cooling rate. The result is a more homogeneous surface. The homogeneity is investigated by scanning electron microscope/energy dispersive spectroscopy and two-dimensional power spectral density analysis. Nanoindentation and wear tests at micro- and meso-length scales are applied to identify the effect of element redistribution on hardness and wear resistance. Compared to the base material, the hardness of the pulsed laser remelted surface becomes more uniform, which is an expected consequence of elemental homogenization. The remelted surface exhibits a higher hardness compared with the matrix of the base material, and homogenization is found to improve the wear resistance at both the micro- and meso-length scale.

1. Introduction

Aluminum-silicon (Al-Si) casting alloys form a major group of engineering materials due to their high specific strength [1], die filling capacity[2], excellent corrosion resistance [3], and lightweight [4]. In many applications, Al-Si alloys undergo cyclic loading and sliding against mating surfaces [5] that make it essential to have adequate wear resistance.

Traditional methods that improve the mechanical properties and wear resistance of aluminum (Al) alloys have been investigated thoroughly, such as applying reinforcement particles to substrate material [6–9], spray depositing [10] or friction stir processing [11]. Long et al. [6] investigated the wear behavior of hypereutectic Al-Si alloys with different Si percentages and with silicon carbide (SiC) whisker dispersions. They found that the wear loss was inversely proportional to the size and proportional to the spacing of Si particles, and the SiC whiskers prevented the slip of Si particles and led to better wear resistance in this material. Some researchers used copper-matrix material to confirm that the particles dispersed in the matrix could prevent wear by pinning the grains [12]. Lim et al. [10] fabricated Al alloy A390 by hot spray-depositing and compared the mechanical properties to conventionally-cast alloys. The spray-deposited alloys were found to have a higher micro-hardness and better wear resistance due to the refinement of the uniformly distributed, nearly equiaxed, and small silicon-rich secondary phases. Previous work has shown that the interfacial strength at the particle/base material interface contributed to the enhancement of wear resistance [9]. Lasa and Rodriguez-Ibabe [13] studied the wear behavior of five Al-Si alloys with different Si percentages, and found that a fine, homogeneous microstructure and small spacing between the primary silicon (Si) precipitates improved the wear resistance of Al-Si alloys.

As small, well-dispersed reinforcement particles have been found to improve the wear resistance of Al-Si alloys, the method

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https://doi.org/10.1016/j.jmapro.2018.03.004
1526-6125/

Table 1
Composition percentage (wt%) of Al alloy A384 investigated in this study [23].

Si	Cu	Fe	Zn	Others (Mn, Ni, Sn, Mg, *etc*)	Al
10.5–12.0	3.0–4.5	<1.3	<1.0	<1.95	Balance

to achieve such phases within the microstructure has been another area of interest. Yamagata et al. [14] investigated the Al-Si alloy cooled at different cooling rates ranging from 4.9 to 82.9 °C/s and demonstrated that the cooling rates influenced the equivalent diameter of primary Si in hypereutectic die casting Al alloys. They found that increased cooling rates resulted in smaller primary Si. Suarez et al. [15] studied the microstructure of Al-Si-X alloys cooling at different cooling rates ranging from 0.95 to 190 °C/s. Their results showed that Al-Si-X alloys cooled at higher rates formed smaller particles and had a more uniform distribution of Si-rich phases. If the proeutectic Si in die casting Al alloys can be formed as small particles and dispersed more uniformly in the Al matrix by thermal processing, the Si particles can be viewed as a reinforcement phase that may improve the mechanical properties of the alloy.

In this work, pulsed laser remelting is applied to an Al-Si casting alloy (A384) to study the change in the surface condition at small scales. Previous works [16,17] found that the remelting during pulsed laser processing decreases the surface roughness. The reduced roughness is beneficial for improving the wear resistance, especially reducing abrasive wear [18]. During processing, irradiation by a laser pulse will cause localized surface melting, solidification, and solid-state cooling before the next melt event (*i.e.*, laser pulse) [19]. The laser pulses used in this study are less than 100 μs and Al alloy A384 has a relatively high thermal diffusivity of 3.6×10^{-5} m^2/s [20], hence the melt zone will cool down rapidly (above 10^5 K/s). This process has been shown to result in a refinement in the microstructure of titanium and steel alloys [21,22]. If pulsed laser remelting refines, redistributes, and decreases the size of Si particles in an Al-Si alloy, a homogeneous surface layer with improved wear resistance may be realized.

Aluminum alloy A384, used as a die casting alloy due to its high fluidity, has a Si percentage of 10.5%–12.0% that precipitates out in the substrate during cooling as proeutectic Si and eutectic Si. This makes it a suitable material to explore the homogeneity and material properties before and after pulsed laser remelting. The effect of pulsed laser remelting on microstructure and material properties is studied by scanning electron microscope (SEM)/energy dispersive spectroscopy (EDS), 2D power spectral density analysis of surface maps collected by EDS, nanoindentation tests, and micro- and meso-length scale abrasive wear tests. The details of the material, laser processing, and experiments are given in Section 2, while Section 3 lists the findings on the elemental distribution, homogeneity, and the corresponding nanohardness, and scratch and wear properties.

2. Materials and methods

2.1. Materials

The elemental composition of the die casting alloy (A384) chosen for this investigation is shown in Table 1. The samples were prepared by mechanically grinding and polishing (Buehler MetaServ 250 Grinder-Polisher), with a final polishing step performed with 0.05 μm colloidal silica suspension. The root-mean-square (RMS) roughness of approximately 16 nm was obtained in a measurement area of 7 × 7 μm. The pulsed laser processing was then performed on the mechanically polished base material.

2.2. Pulsed laser processing

A 200 W, 1070 nm, fiber laser (SPI lasers, Model SP-200C-W-S6-A-B) was used for pulsed laser remelting, the laser system setup was shown in Fig. 1.

This is a continuous wave fiber laser that is pulsed by turning the pumping diodes on and off, hence the pulse power is the peak power during a pulse. In order to achieve a fluence high enough to melt the surface, a 30-μm-diameter laser spot was selected. The average power was set to 4 W, to avoid incomplete melting at low power or ablation at high power. The laser processing parameters are shown in Table 2.

2.3. Scanning electron microscope & energy dispersive spectroscopy

The surface chemistry and topography were characterized by SEM and EDS (LEO 1530 FESEM/EDS) on the base material, pulsed laser remelted surface, and the cross section of the remelted area. SEM images were obtained with an accelerating voltage of 3 kV while the EDS maps were obtained at an accelerating voltage of 15 kV.

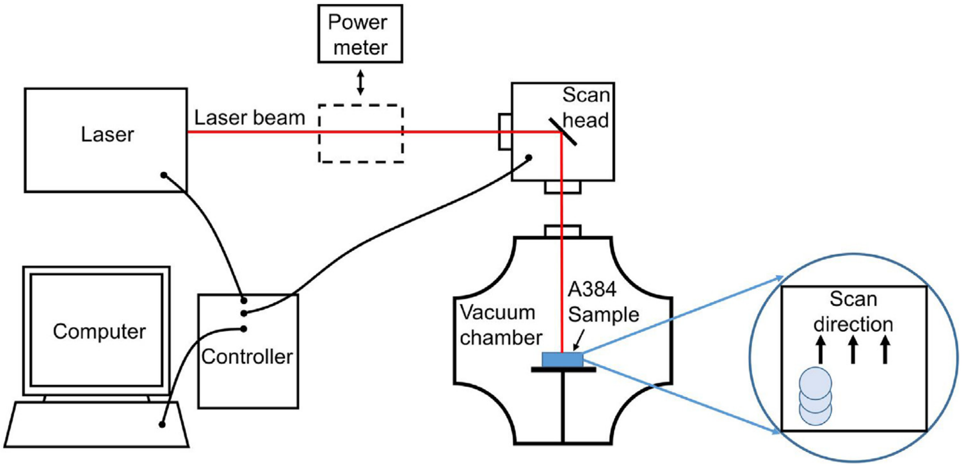

Fig. 1. Laser system setup.