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SiC particulate reinforced aluminum matrix composite coatings prepared by laser powder deposition

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A SiC particulate reinforced aluminum matrix composite coatings for wear resistance improvement were investigated. Laser powder deposition processing was optimized, the microstructure of the coatings was analyzed, and the wear resistance of the coatings was evaluated. Under optimized processing, a laser powder deposited coating is free of cracks and porosity. SiC particles were uniformly distributed in the coating and well bonded with the matrix. A laser powder deposited coating consists of α-Al, SiC, Al_4C_3, Si and Al_2O_3 phases. Due to formation of Al_4C_3 and Si phases and crystal grain refinement, the wear resistance of laser powder deposited coatings was increased 2.06-3.76 times that of the aluminum alloy substrate based on the high hardness and deformation resistance of the SiC particles.

Key words: Laser powder deposition, Silicon carbide, Particulate reinforcement, Aluminum alloy, Composite, Coating, Wear resistance.

Introduction

Aluminum alloys possess excellent properties such as low density, good plasticity and ductility, and good corrosion resistance. They find extensive applications in aeronautics, astronautics, automobile and high-speed train fields. However, low hardness and poor wear resistance results in their limited application in heavy-duty environments. So it is important to develop advanced processing and technology for the improvement of wear resistance.

Surface engineering technology has been applied to aluminum alloys for the purpose of improving wear resistance. Methods include electroplating, anodic oxidation, micro-arc oxidation, and thermal spraying [1-4]. However, electroplated layers readily crack and pollute the environment, a thermal spraying coating readily spalls off due to poor mechanical adhesion with the substrate and extensive porosity, the thickness of micro-arc and anode oxidation coatings are too thin for the heavy duty environments. This means that these methods have not been applied extensively in industry.

It has been proved that particulate reinforced aluminum matrix composites can improve considerably the strength and hardness of aluminum alloys. However, at the same time, the plasticity and ductility can be substantially reduced. This will severely affect the safety and reliability of components fabricated from Al metal matrix composites (MMCs).

Laser surface modification possess many advantages such as producing thick and dense coatings with solid bonding strength, low stress and distortion, and a refined microstructure. Laser remelting, cladding and alloying have been used to prepare Fe-Al, $MoSi_2$, and TiC coatings to improve the surface properties of aluminum alloys [5-8].

In this paper, a laser powder deposited SiC particulate reinforced A356 aluminum matrix composite coating was investigated. The deposition processing was optimized. The microstructure of the coating was analyzed. The wear resistance was evaluated and the wear mechanism was considered.

Experimental Details

The substrate material were A356 casting aluminum alloy plates with a size of 20×40×100 mm. Their chemical composition is given in Table 1. Before the processing experiments, the plates were polished and washed with acetone in order to remove grease, moisture and oxide scale. The deposited powders were Al-SiC mechanically mixed powders. SiC particles were added into aluminum powders at 10, 20 and 30% volume fractions in order to investigate the influence of SiC content on the wear resistance.

Table 1. Chemical composition of A356 casting aluminum alloy (wt.%)

Cu	Mg	Fe	Mn	Si	Al
<0.2	0.25-0.45	<0.2	<0.5	6.5-7.5	Bal.

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A PRC3000 high power CO_2 laser with a THPF-1 powder feeder and a THCN-3 coaxial nozzle was used for the laser powder deposition. The influence of laser processing on the shaping, quality, composition and microstructure was investigated by changing the laser power, scanning velocity, powder feeding rate, and beam diameter. The optimized processing parameters were as follows: laser power P=1.5 kW, scanning velocity V=4 mm/s, powder feeding rate Q=4.0 g/minute and beam diameter D=5 mm. Argon was used as the shield gas.

The wear experiments were conducted by a MPX-2000 sliding wear tester. The contact formation of friction couples was by pin on disc. The samples as the pins were cut from the coated specimens and their surfaces were ground mechanically. Disc samples were made from mild carbon steel with a quenched and tempered microstructure and a hardness of HRC58. Prior to the wear tests, the samples were washed in acetone to remove grease. The wear parameters were as following: normal pressure P=20 N, sliding speed of friction couple ω=370 rpm, wear time t=30 minute. For the purposes of comparison, the wear resistance of A356 and laser-remelted A356 alloy were also tested. The thickness variation of pins was used to evaluate the wear resistance of the materials.

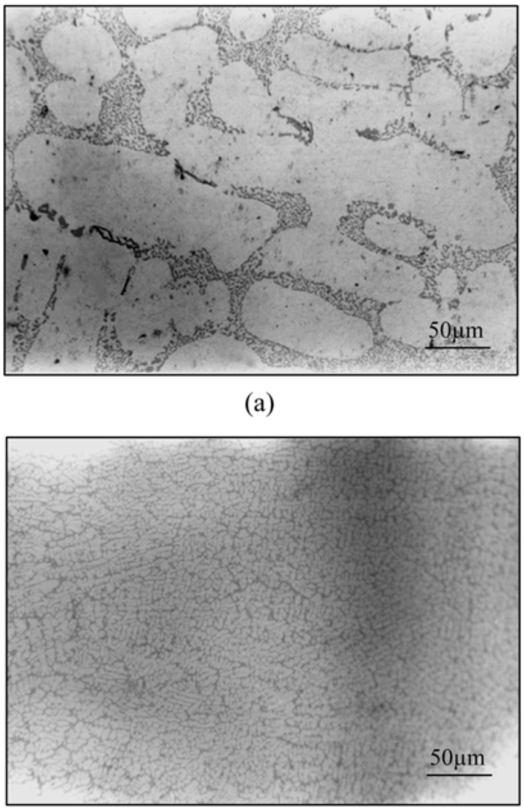
Metallgraphic samples were prepared for the observation of the microstructure of the laser deposited coatings. The specimens were etched with an HF acid water solution in 5% volume ratio. The microstructure and wear morphology of laser powder deposited coatings were observed and analyzed by a Neophot21 optical metallgraphic microscope (OM) and a JEOL6410 scanning electron microscope (SEM). The chemical compositions were analyzed with a Link ISIS energy dispersive X-ray spectrometer (EDAX).

Results

The original and laser-remelted microstructure of A356

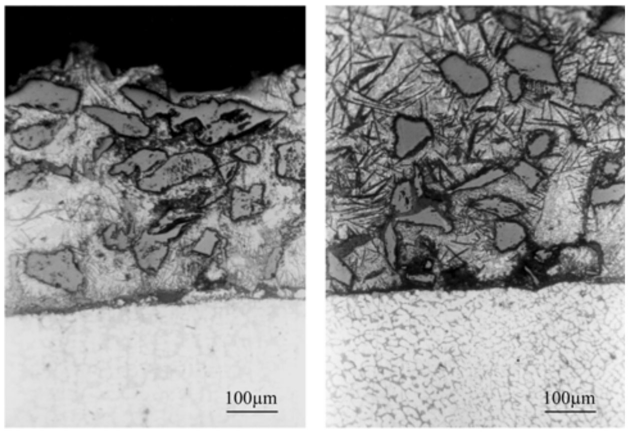
The original microstructure of the A356 as cast is shown in Fig. 1(a). It consists of dendritic α solid solution plus (α+Si) distributed between the dendrites. The original microstructure is very coarse.

The laser-remelted microstructure of A356 is given in Fig. 1(b). It can be established that the remelted layer constituents are the same as in the original microstructure. However, the laser-remelted microstructure was remarkably refined and distributed more uniformly. This results from rapid heating and cooling by the laser processing.



(b)

Fig. 1. (a) Original microstructure of A356 as cast; (b) microstructure of laser-remelted layer (optical microscope (OM) images).



(a) (b)

Fig. 2. Microstructure of laser powder deposited coating (a) low magnification morphology; (b) morphology at the junction between the coating and substrate (OM images).

Microstructure of laser powder deposited Al-20SiC coating

Figure 2 is the microstructure of the laser powder deposited Al-20SiC coating. It can be seen that the deposited coating is dense and free of cracks and porosity. The SiC particles are uniformly distributed and well bonded with the matrix. In addition, because of the loss of aluminum powder, the SiC volume ratio in the deposited coating is more than in the as mixed powder.

Figure 2(b) shows the microstructure at the interface of the laser deposited coating with the matrix. There are many needle-shape phases with different orientations in the matrix between the SiC particles. Similar phases were also found in other investigations. In general, they are considered to be Al_4C_3 phases caused by the melting and dissolution of SiC particles at high temperature and the reaction of Al and C. Because of severe brittleness of Al_4C_3 and its needle-shape, the aluminum alloy matrix is severely weakened and has stress concentrations. So Al_4C_3 is a harmful phases to some extent and need to be controlled either in size or shape.

In order to further identify the constituents of the laser powder deposited coating, backscattered electron and compositional analysis were conducted by SEM and EDAX. Figure 3 is backscattered electron image of the deposited coating. From the EDAX analysis, it has been established that there are five phases in the matrix, a gray α-Al matrix, a white refined and particle-shaped Si, white net-shaped $Al_{4.5}FeSi$ and Al_8Fe_2Si, black needle-shaped Al_4C_3 and a few Al_2O_3 around the Al_4C_3. From Fig. 4, it can be established that as the SiC particle content increases, the content and shape of Al_4C_3 can be controlled.

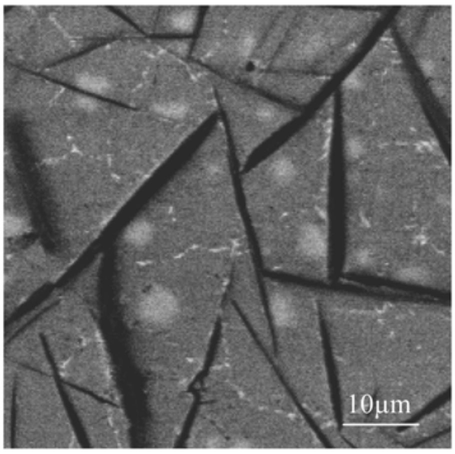
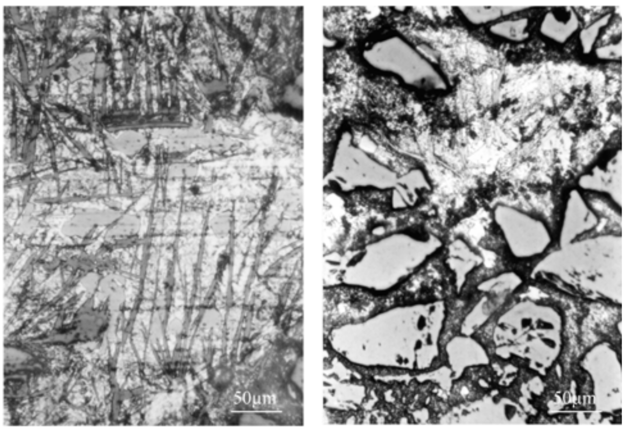


Fig. 3. Backscattered electron analysis of the refined structure of a laser powder deposited coating (scanning electron microscope (SEM) image).



(a) (b)

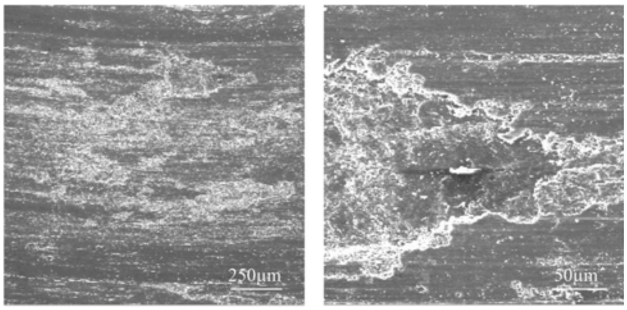
Fig. 4. Influence of SiC contents on the formation of Al_4C_3 (a) less SiC (b) more SiC (OM images).

Wear surface morphologies and wear resistances

The wear experiments were carried out on A356, laser-remelted layer and laser powder deposited coatings with the various volume fractions of SiC. Their relative wear resistances are given in Table 2. ΔH is the wear depth of pin samples and W^{-1} is the relative wear resistance that are defined as the reciprocal of the ratio of the wear depth of laser processed samples and the A356 raw material. The wear resistance of laser powder deposited coatings is much better than that of the substrate and the laser-remelted layer. With increased SiC contents, the wear resistance of laser powder deposited coatings is also enhanced. With increased SiC contents, they give 2.06-3.76 times the wear resistance of the A356 substrate.

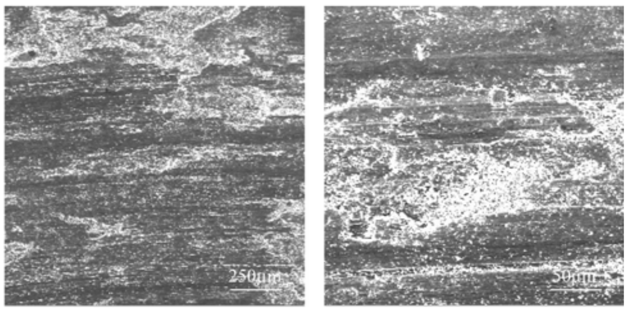
Table 2. Comparison of wear resitance of various materials and coatings

	Al	$Al_{remelted}$	Al-10SiC	Al-20SiC	Al-30SiC
$\Delta H/\times10^{-3}$ mm	222	162	108	89	59
W^{-1}	1	1.37	2.06	2.49	3.76



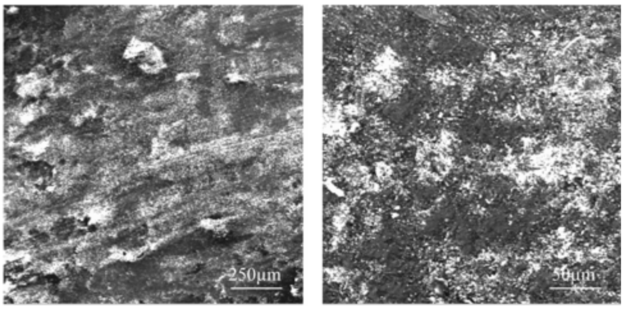
(a) (b)

Fig. 5. Wear surface morphologies of A356 substrate (a) low magnification; (b) high magnification (SEM images).



(a) (b)

Fig. 6. Wear surface morphologies of laser-remelted layer (a) low magnification; (b) high magnification (SEM images).



(a) (b)

Fig. 7. Wear surface morphologies of a laser powder deposited coating (a) low magnification; (b) high magnification (SEM images).

The wear morphologies of A356, laser-remelted layer and a laser powder deposited coating with 20 vol.% SiC are given in Fig. 5-7. It can be seen that the substrate and laser-remelted layer have severe plastic deformation and fatigue spallation. The laser powder deposited coating is only scraped slightly. The wear resistance improvement is due to the highly wear resistant SiC particles and the plastic deformation resistance of coating.

Discussion

The experiments indicate that due to poor wettability of SiC and the aluminum alloy, with a low laser power and large scanning velocity, it is very difficult for SiC particles to enter into the molten pool. A few SiC particles deposited in the molten pool readily spall off due to poor bonding with the substrate. This is because laser energy is mainly absorbed by the SiC; as a result, the energy absorbed by the substrate is so small that the aluminum melting temperature is too low. So an appropriate amount of aluminum powder was added to the SiC powder to give mixed powders. In addition, a higher laser power density was applied by adjusting the processing parameters to improve the wettability because a higher temperature of the molten aluminum favors a wettability improvement.

With SiC plus Al mixed powders, the energy absorbed by the SiC can reduced. Moreover, the energy can be compensated partly by the melting of the aluminum powder. So the wettability of SiC and Al can be improved.

These investigations show that there are several harmful phases including Al_4C_3, Al_2O_3, and Al-Fe-Si in the coating. Al_2O_3 inclusions mainly come from surface oxidation of aluminum melts. Al-Fe-Si phases mainly results from Fe elements in the raw materials. They have little influence because of low contents from protection and quality control of the raw materials.

Al_4C_3 phases are not only larger in content, but also needle-shaped. They cause intense disruption to the substrate and they have a considerable influence on the properties of the deposited coating. Their content and morphology must be strictly controlled. Methods of this control include (1) selecting a suitable laser energy density to reduce the melting temperature and restrain the melting and dissolution of SiC; (2) using a large scanning velocity to shorten molten pool time and weaken the reaction of SiC and Al; (3) increasing appropriately the amount of SiC to restrain the nucleation and growth of Al_4C_3.

Conclusions

Laser powder deposited SiC particulate reinforced aluminum matrix composite coatings were prepared and investigated. The following conclusions can be drawn.

(1) Laser powder deposited coatings are dense and free of porosity and cracks. These coatings have a solid metallurgical bonding with the substrate. In the coating SiC particles are homogeneously distributed and have an excellent bonding with the aluminum matrix.

(2) Laser powder deposited coatings consist of α-Al matrix, SiC reinforcement, needle-shaped Al_4C_3, particle-shaped Si and Al_2O_3. Al_4C_3 and Si are formed by a reaction between SiC and Al. Although the needle-shaped Al_4C_3 phases can serve to strengthen the matrix, it should be controlled because of brittleness. An increment of SiC content can restrain the formation of Al_4C_3 and promote refinement.

(3) The wear resistance of laser powder deposited coatings is much better than the substrate and a laser-remelted layer. With increased SiC content, the wear resistance is enhanced. They are 2.06-3.76 times that of the substrate. The wear mechanisms of the substrate and laser-remelted layer are severe plastic deformation and fatigue spallation. The wear mechanism of the laser powder deposited coating is slight scraping. The wear resistance improvement is mainly due to the highly wear resistant SiC particles and plastic deformation resistance of the coating.

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