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Formation of metal matrix composite layer on aluminum alloy with TiC-Cu powder by laser surface alloying process

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Abstract

Thick hardened metal matrix composite (MMC) layer was formed to improve the wear resistance of a commercial Al–Mg alloy (A5083) plate by using laser surface alloying with Cu coated TiC powders in the size of between 20 and 40 μm. A continuous wave CO_2 laser beam (2100 W) was irradiated on the pre-placed TiC-Cu powder to melt them together with the substrate in argon atmosphere. The thickness of the MMC layer was approximately 1–2.5 mm. In the MMC layer, TiC particles were not dissolved and were uniformly distributed in the molten matrix. The matrix structure of the MMC layer consisted of the mixture of the hypo-eutectic, eutectic and hyper-eutectic structures with primary θ ($CuAl_2$) phase and the lump like Cu_9Al_4 compound and corresponded to the binary Al–Cu system. The hardness of the MMC layer increased with increasing Cu content and the volume fraction of TiC particle, and reached approximately HV600 in maximum. The wear resistance of the MMC layer was evaluated by the Ogoshi type wear test as an abrasive wear test with a rotating counter roller. The wear rate decreased to one-sixth of that of the substrate. The wear resistance of the MMC layer was much better than the Cu alloyed layer without TiC powder and austenite stainless steel SUS304.

Keywords: Laser beam; Aluminum alloy; Hardness; Wear resistance; Metal matrix composite

1. Introduction

Aluminum and its alloys have been extensively used in automobile machinery and other potential industries, owing to their low density, high specific strength, good electric and thermal conductivity and good workability. However, the surface properties of aluminum alloys, in particular hardness and tribological properties, are insufficient for recent requirements. In order to obtain superior wear resistance of their surface, some surface hardening treatment, such as a hard anodizing, electroplating and chemical plating have been applied. However, as the hardened layer made by these processes is a thin layer with several tens of micro millimeters, if high surface load will be applied on these layers, the thin hardened layer is easy to break by a deformation of aluminum alloy substrate [1,2]. Therefore, it is necessary to make a thick hardened layer in the order of millimeters [1,3].

Recently, laser surface alloying process [4,5] has been used to modify the surface of these alloys by melting the alloying materials such as Fe, Cu, Si and Ni etc. [6–9] together with the substrate. This process makes it easy to produce a thick hardened layer in a short time. The hardness of laser alloyed layer increases as increasing the content of alloying element [6–9]. In the case of using metal materials, however, excess alloying of element-induced cracks occured in alloyed layer when the hardness exceeded HV350 [7,8].

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On the other hand, the formation of a surface metal matrix composite (MMC) becomes possible by injecting the hard particles such as some ceramic particles of SiC [10,11], TiC [12] and WC [12]. Generally, ceramic materials have high-energy absorption for the laser beam. Due to the aluminum matrix being soft, it will be required to increase the amount of ceramic particles in MMC layers for increasing hardness and the wear resistance of aluminum alloy surface. However, it is difficult to produce high volume fraction of ceramic particles in MMC layers within a short time during laser irradiation. Then, it will be expected to increase the hardness and the wear resistance of MMC layers by adding both ceramic particles and alloying element. Liechti et al. [13] carried out the formation of SiC particle dispersed MMC layers by alloying SiC particles together with Al-12% Si powder on the Al–Si–Mg alloy substrate by the laser alloying process, but SiC particles partially reacted with the melted aluminum alloy, and the wear resistance of that MMC layer was not studied. TiC particles will be not dissolved in melted aluminum alloy [14].

Therefore, the aim of the present work is to produce in a thick hardened MMC layer in the order of millimeters to improve the wear resistance of aluminum alloy surface with TiC particles and Cu by the laser alloying process. The aluminum matrix alloyed Cu will be expected to produce a hardness of approximately HV350 in maximum [8]. The effects of volume fraction of TiC, Cu content and the traveling speed of laser beam on microstructure, hardness and wear resistance of MMC layers were examined.

2. Materials used and experimental methods

2.1. Materials used

The substrate sample was a commercial Al–Mg alloy (JIS A5083) of $50 \times 100 \times 10$ mm^3 plate. The alloying materials were composite TiC powders of which surface were electro-deposited by Cu charger. Cu content of composite powder was 10, 30, 50 and 60 mass%, which was changed by controlling the Cu thickness. Powder size was from 30 to 42 μm.

2.2. Laser alloying process

These alloying powders were pre-placed on the surface of substrate by using an acrylic binder and dried on a hot plate. The amount of pre-placed powder was 285 mg/cm^2. The multi mode continuous wave CO_2 laser beam with a maximum power of 2500 W was used for laser surface alloying. The specimen was set on a copper plate which was cooled with water in the gas shielding box. The laser beam was defocused at a distance of 50 mm up on the specimen and irradiated on the specimen with oscillating perpendicular to the traveling direction of the specimen with an oscillating frequency of 10 Hz and an amplitude of 5 mm. The laser beam power was set at 2100 W. The alloying powders were melted together with the surface of substrate by a laser beam. Argon gas flowed to shield the melted area through the laser nozzle at 15 l/min and into shielding box at 20 l/min. The traveling speed of specimen (v) was selected from 80 to 1000 mm/min. Microstructural examination of the MMC layers was carried out using optical microscopy, SEM, EDX, EPMA and XRD. The hardness distributions of MMC layers were measured using the Vickers hardness tester. The wear resistance of the MMC layer was evaluated by the Ogoshi type wear test, as an abrasive wear test with a rotating counter roller made SUJ2 at a rotating speed of 4.36 m/s, applying a load of 20.6 N and sliding distance of 100 m.

3. Results and discussion

3.1. Effect of laser processing conditions on the formation of MMC layer

Fig. 1 shows the typical surface appearance and the cross-section macrostructure of MMC layers at $v = 300$ mm/min with TiC-60 mass% Cu powder. This layer has a smooth surface and a good adhesion with the substrate. The surface morphology of MMC layers was classified into three types, namely, smooth, rough and flaking surfaces. A good layer with a smooth, surface shown in Fig. 1, was obtained at a of traveling speed of 200–400 mm/min and Cu content of 50 and 60 mass%. A rough layer was observed at less than approximately 200 mm/min with Cu content more 30 mass%. Some bump-like compounds were formed on the surface of this layer. In the flaking surface type, the surface of MMC layer was partially flaked during laser processing. A flaking layer was observed at a higher traveling speed than that of forming the smooth and rough surface layers because the substrate was not melted sufficiently.

Effect of traveling speed on the thickness of MMC layers is shown in Fig. 2. The thickness of MMC layers decreased with an increase in traveling speed due to the decrease in the heat input from the laser beam. The thickness of the MMC layers with good surface appearance was approximately 1.5 mm at the traveling speed of 200–400 mm/min.

3.2. Microstructure of MMC layers

TiC particles were well embedded and uniformly distributed in the Cu-alloyed matrix of the optimum

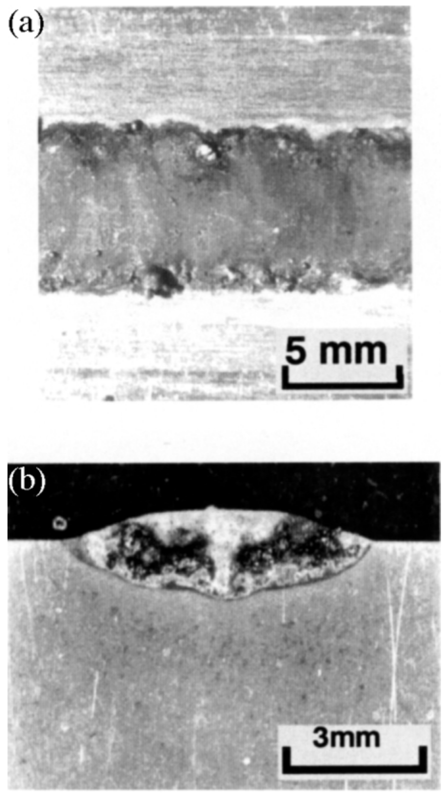

Fig. 1. Typical surface appearance (a) and macrostructure (b) of MMC layer.

MMC layer. A Cu layer coated on the surface of TiC dissolved into the matrix and formed the typical four matrix structures corresponding to a binary Al–Cu alloy system as shown in Fig. 3a,b,c for the hypo-eutectic, the lamellar eutectic and the hyper-eutectic structures which contained a hardened primary θ ($CuAl_2$) phase, respectively. The hypo-eutectic and the eutectic structures were easily produced at less than $v = 200$ mm/min with TiC-30, 50 and 60 mass% Cu powders due to sufficient dilution of the substrate. Fig. 3d shows the lump-like Cu_9Al_4 compound which was identified by using EPMA and XRD analysis. The crack occurred in this structure. There was no evidence showing the reaction between TiC and molten aluminum and formation of aluminum carbide. It is noticed that the TiC particles were not dissolved in the liquid aluminum alloy matrix during laser processing as Ayers previously reported [14].

3.3. Hardness of MMC layers

Fig. 4 shows the hardness distribution in the cross-section of the MMC layers at the traveling speed from 100 to 400 mm/min. At lower than the traveling speed of 300 mm/min, the hardness of the bottom side of the MMC layers were HV400–600, higher than that of the top side. The hardness in the topside of these layers increased from HV100 to HV300 increasing the traveling speed. It is noticed that the hardness depended on the matrix structure of MMC layer. Namely, the matrix structure of the bottom side consisted of hyper-eutectic structure and a small lump-like Cu_9Al_4 compound as shown in Fig. 4 which shows higher hardness than hypo-eutectic and eutectic structures. The matrix structure of the topside at the traveling speed of 100 mm/min was the mixture of hypo-eutectic and eutectic structures. Moreover, at the traveling speed of 400 mm/min, the hardness of the MMC layer excepting surface zone was approximately HV550–750 due to lump-like Cu_9Al_4 compounds and the hyper-eutectic structure. Fig. 5 shows the relation between Cu content analyzed by EDX and the hardness for the matrix of MMC layers. The hardness increased as increasing Cu content and reached approximately HV400 at 50 mass% Cu in the hyper-eutectic structure. Moreover, the hardness of the structure with Cu_9Al_4 compound increased to HV600 at 60 mass% Cu. However, the crack occurred at a hardness, which exceeded HV500 with this structure. A similar relationship as shown in this figure with the triangle mark (△) was obtained in our previous study on laser alloying of Al–Mg alloy (A5052) with Cu powder [8]. In this case, the hardness of the crack that occurred was HV350 lower than that of MMC layer.

On the other hand, it is well known that the hardness of MMC layer depends on the volume fraction of ceramic particle [15]. Fig. 6 shows that the relation between the volume fraction of TiC particles and the hardness of MMC layers consisted with the hyper-eutectic matrix structure. Until 20 vol% TiC, the effect of TiC volume on hardness is considered to be small. As increasing volume fraction of TiC, the hardness of MMC layers increased and reached HV500 at 40 vol% TiC. However, in this study, it was difficult to form the MMC layer exceeding 40 vol% TiC.

3.4. Wear resistance of MMC layers

The wear resistance of the MMC layer was evaluated

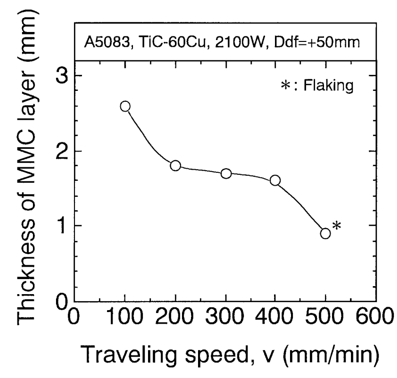

Fig. 2. Effect of traveling speed on thickness of MMC layer with TiC-60Cu powder.

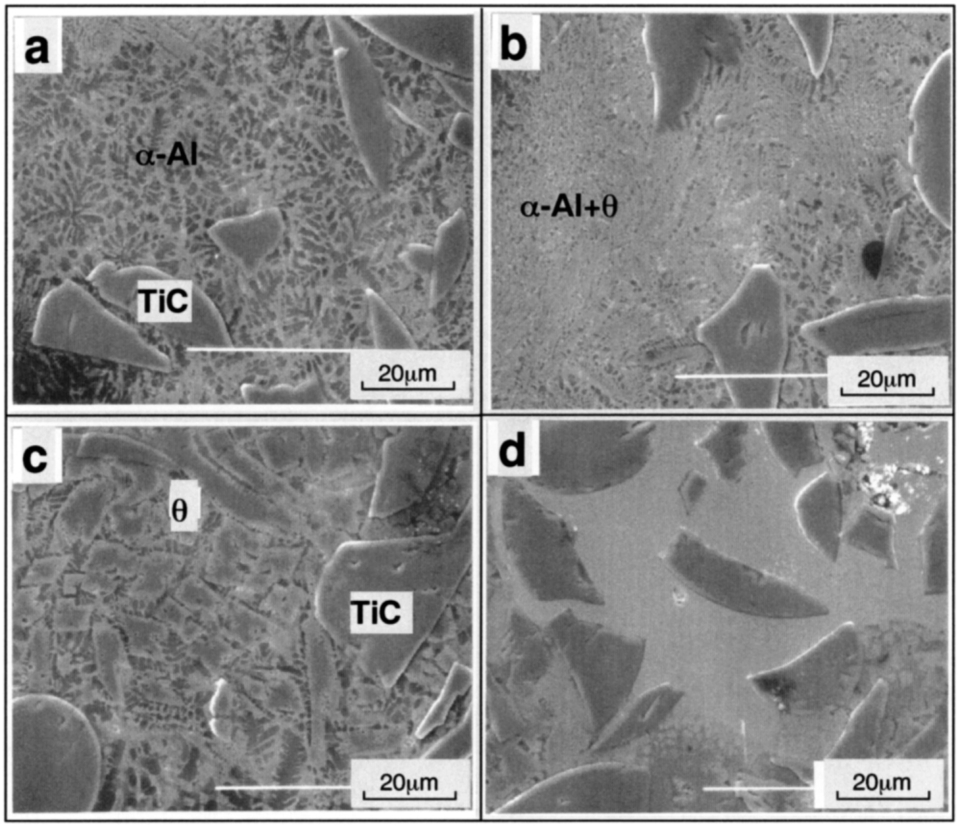

Fig. 3. Typical microstructures of MMC layer (a) Hypo-eutectic matrix structure, (b) lamellar eutectic matrix structure, (c) hyper-eutectic matrix structure which contained a primary θ ($CuAl_2$) phase and (d) lump-like Cu_9Al_4 compound structure.

by measuring the specific wear with the Ogoshi type abrasive wear test. The specific wear, W_s, means the wear loss in the units of contact pressure, contact area and sliding distance. Fig. 7 shows the relation between the surface hardness and the specific wear of the MMC layers. The solid mark indicated the W_s value and surface hardness of substrate. The W_s value of MMC layers decreased rapidly to a quarter of the base metal value with a slight increase in hardness up to HV200. Namely, the wear resistance of MMC layer was improved with an increase of its hardness. And, at more than HV200, the W_s decreased slightly increasing hard-

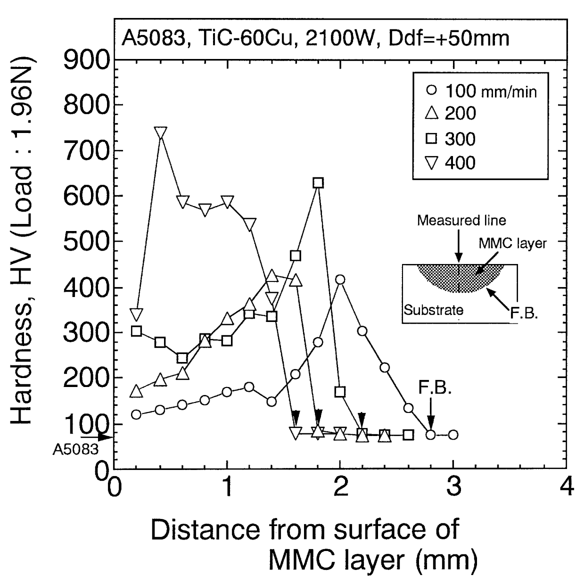

Fig. 4. Hardness profiles of MMC layers at the traveling speed of 100, 200, 300 and 400 mm/min.

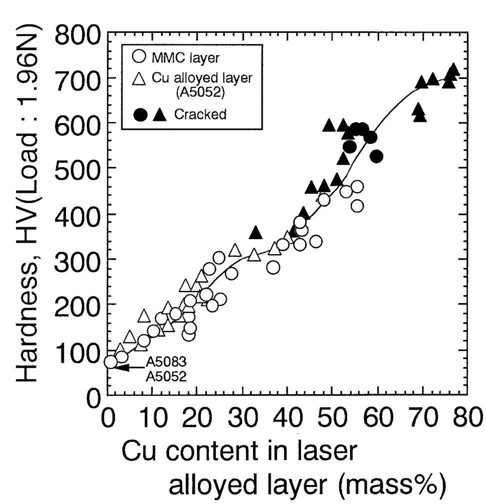

Fig. 5. Relation between Cu content and hardness for matrix of MMC layer and Cu alloyed layer without TiC, which was obtained in our previous study [8].

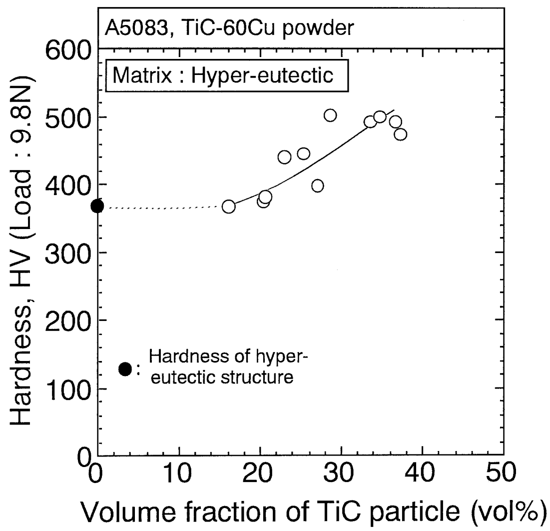

Fig. 6. Effect of volume fraction of TiC particle on the hardness of MMC layer consisted with the hyper-eutectic matrix structure.

ness. The W_s value of the Cu alloyed layer without TiC, which was obtained in our previous study [8], decreased gradually as increasing hardness as shown by a dotted line. As a result, it is noticed that the wear resistance of MMC layers was higher than that of the Cu alloyed layer due to the effect of containing TiC particles. Moreover, the wear resistance of MMC layers was much higher than that of austenite stainless steel SUS304 and is the same as that of carbon steel (0.5% C) S50C.

4. Conclusion

This study has examined the feasibility of producing a thick hardened MMC layer on the surface of Al–Mg alloy plate (A5083) with Cu coated TiC powders by CO_2 laser alloying process. The main conclusions that can be drawn from the results of this study are:

1. It was possible to form a thick MMC layer 1–2.5 mm in thickness. The thickness of the MMC layer decreased with an increase in the traveling speed of the specimen.
2. The MMC layer produced the TiC dispersed Al–Cu alloyed structure by melting both the alloying powder and the substrate. The microstructures of MMC layers consisted of the hypo-eutectic, the lameller eutectic, the hyper-eutectic contained primary θ ($CuAl_2$) phase and the lump-like Cu_9Al_4 compound.
3. The hardness of MMC layer increased as increasing Cu content and volume fraction of TiC particle, and reached a maximum of HV500 without the cracking.
4. The wear resistance of MMC layer increased as increasing hardness and reached approximately six times than that of the Al–Mg alloy substrate and also higher than that of the only Cu alloyed layer.

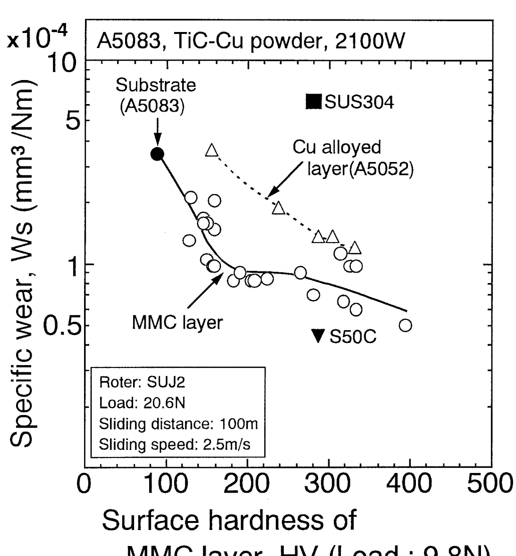

Fig. 7. Relation between surface hardness and specific wear measured by the Ogoshi type abrasive wear test of MMC layer.

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