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LETTER

Effect of Ni–P amorphous phases on the wear resistance of Ni–Al alloyed layer formed by pulsed laser irradiation

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Introduction

Aluminum alloys are a group of the most widely used materials in the industry due to their low specific weight, good corrosion resistance, and high thermal conductivity. However, the low hardness and low wear resistance have limited the applicability of aluminum alloys in certain cases [1–2]. Laser alloying processes are frequently utilized to increase the wear resistance of aluminum alloys [3–4]. Novel phases in the laser-processed zone can be formed due to rapid heating and cooling rate aroused by laser irradiation [5–6]. In our previous research [7], Ni–P amorphous phases formed in the laser processed Al with electroless deposited Ni–P coating were reported. This article is a further report on YAG laser alloying of Ni–P electroless deposited coating with aluminum substrate. The concentration will be focused on the effects of Ni–P amorphous phases on the wear resistance of Ni–Al alloyed layer.

Experimental details

The material used for laser alloying was commercial-purity aluminum with a size of 10 × 30 × 3 mm^3. Before laser alloying process, Ni–P coating was chemically deposited on aluminum substrate. The bath solution containing 15 g l^{-1} $NiSO_4$; 14 g l^{-1} $Na_2H_2PO_2$; 13 g l^{-1} $NaC_2H_3O_2$ and 30 g l^{-1} boric acid was employed to coat the samples, operated at 70 °C and the PH value was kept as constant at 5, the deposition thickness of the coating on the samples was about 25 μm. The composition of the coating was detected to contain 6.74 at% P and Ni balance.

The laser alloying was performed by a pulsed Nd-YAG laser having a beam size 500 μm in diameter under an argon shielding gas. The following parameters at work piece were selected for subsequent laser processing: laser power densities 4.31–6.46 × 10^9 W/m^2, scanning speed 3.0 mm/s, pulse duration 5 ms, and frequency 10 Hz. Surface treatment was achieved by overlapping tracks at 50%. After laser treatment, the samples were tempered at 400 °C for 2.5 h.

After the laser treatment, selected specimens were sectioned and polished. Microstructures and phase analysis were examined by transmission electron microscope (Model JEM−2000EX, Japan). X-ray diffractometer (Model D/Max 2500PC Rigaku, Japan) operated with Cu $K\alpha$ was employed to identify phase structure.

The microhardness of laser-treated zone was measured by an HX-1000 type micro Vickers loaded at 200 g and loading time set at 15 s. Wear resistance was tested on a Universal Micro-Tribometer using a 4 mm stainless steel ball (9Cr18) with a hardness of 56 HRC as a counterpart. The sample was fixed on a metal plate and repeatedly slid against the steel ball within a distance of 20 mm under a load of 15 N at a speed of 0.06 m/s. After sliding for 10 min, the width of wear scars was measured by an optical microscope. The test was continued and repeated until a total wear time of 50 min was reached.

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Results and discussion

TEM observations were carried out to identify microstructure formed in the laser-treated layer. Figure 1a, b shows the obtained morphology and associated electron diffraction pattern. It is believed that Ni–P amorphous structure was formed under the condition of power density 5.36×10^9 W/m^2 and scanning speed 3.0 mm/s. According to previous reports [8–9], Ni–P alloy coating can be formed as amorphous structure only when P content is around eutectic point (about 10 at%). As it is well known, short-pulsed laser beam irradiation with high power density can make phase and microstructure change rapidly due to fast heating, melting, and solidification. Cooling rate in the laser process was reported to be up to 10^{13} K/s [10], it is possible for Ni–P coating to form the amorphous structure under such rapid cooling rate.

Figure 2 shows the results of the microhardness along the cross-section plane of the alloyed layer tempered at 400 °C for 2.5 h, which was much higher than that of the substrate (less than 100HV). The improvement of the hardness is attributed to the presence of Ni–Al intermetallic compounds confirmed by XRD (shown in Fig. 3). From Fig. 3, Ni–Al intermetallic compounds were confirmed as the main phases in the alloyed layer. Meanwhile, peaks of α-Al were also presented, which could be attributed to the abundance of Al and its low solidification point [11]. However, it shows the highest hardness near 500HV at laser power density 5.36×10^9 W/m^2, which was obviously attributable to the presence of the hard particles Ni_3P which was confirmed in our previous report [7].

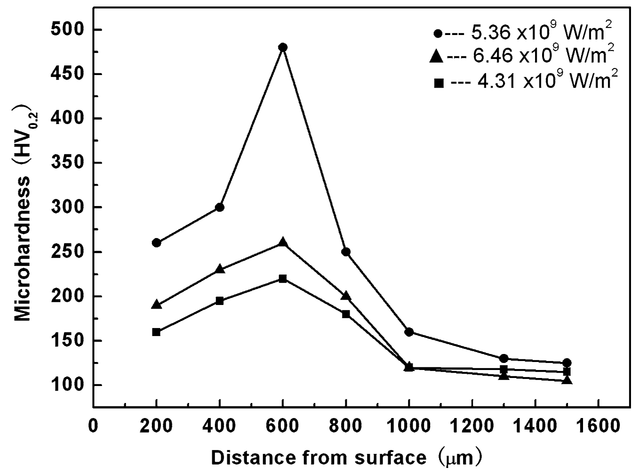


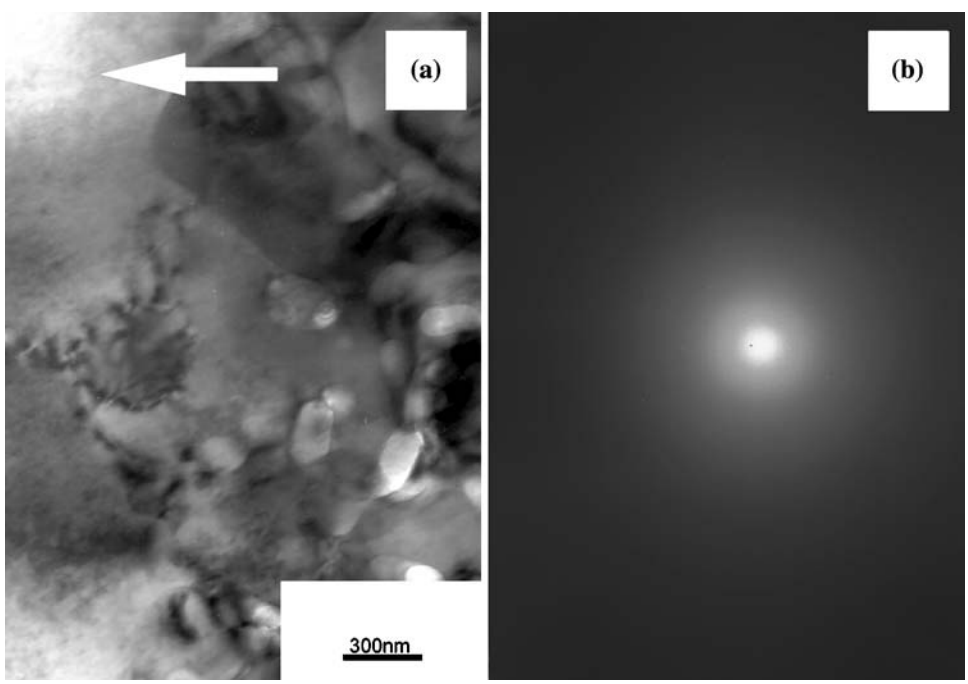
Fig. 2 Microhardness profile measured in the cross-section of the laser alloyed layer under the condition of scanning speed 1.0 mm/s, power density 4.31×10^9 W/m^2, 5.36×10^9 W/m^2, 6.46×10^9 W/m^2

The wear resistance of both the alloyed layer formed under the condition of different power densities and aluminum substrate were measured using the Universal Micro-Tribometer. The volume loss at the sample surface in wear test was calculated from the following equation [12]:

$$\Delta V = L_0 \left(r^2 \arcsin\frac{d}{2r} - \frac{d}{2}\sqrt{r^2 - \left(\frac{d}{2}\right)^2} \right) \quad (1)$$

where L_0 is the reciprocating distance, d is the width of the wear scar and r the radius of the ball. The volume

Fig. 1 Typical TEM morphology of (**a**) amorphous structure of Ni–P after laser treatment at power density 5.36×10^9 W/m^2, scanning speed 3.0 mm/s, (**b**) selected area diffraction pattern (SADP) corresponding to the area arrow indicated in (**a**)



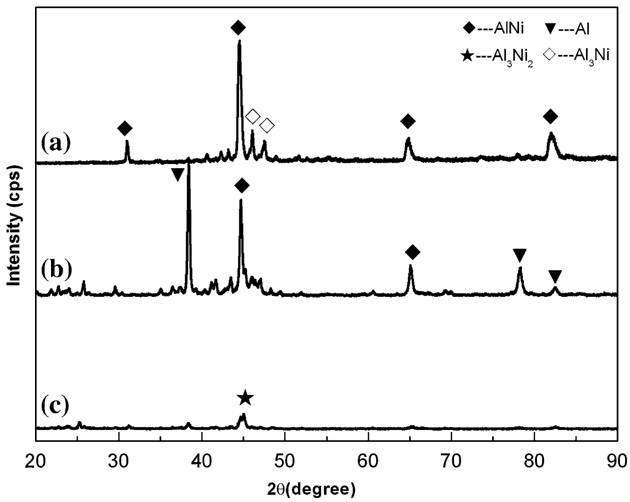


Fig. 3 XRD results of the laser alloyed layer under the condition of scanning speed 2.0 mm/s and power density (**a**) $4.31 \times 10^9 W/m^2$, (**b**) $5.36 \times 10^9 W/m^2$, (**c**) $6.46 \times 10^9 W/m^2$

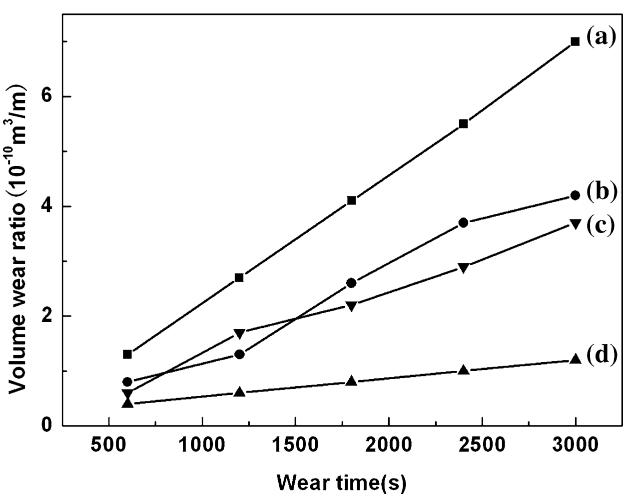


Fig. 4 Comparison of wear loss of (**a**) as-received aluminum alloy and laser alloyed layer under the condition of scanning speed 3.0 mm/s and power density (**b**) 4.31×10^9 W/m^2, (**c**) 6.46×10^9 W/m^2, (**d**) 5.36×10^9 W/m^2

wear rate could be expressed as ΔV/L, where L is the total reciprocating distance. Based on the above equation, the calculated results of ΔV/L for aluminum alloy and the laser-treated samples after heat treatment are shown in Fig. 4. It is clear that the wear resistance of the alloyed layer is much superior to that of the aluminum substrate due to the presence of Ni–Al intermetallic compounds. Moreover, as a result of the presence of hard Ni–Al intermetallic compounds together with the Ni–P phases formed after heat treatment, the alloyed layer with Ni–P amorphous phases exhibits the best wear resistance.

Summary

The amorphous structure was found to form in laser alloying layer of electroless deposited Ni–P coating on aluminum under the condition of power density 5.36×10^9 W/m^2 and scanning speed 3.0 mm/s. As a result, after heat treatment, the alloyed layer with Ni–P amorphous phases shows the highest microhardness and the best wear resistance than the other alloyed layers.

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