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Investigation of structural formation of Al–SiC surface composite under ball collisions

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ABSTRACT

An Al–SiC surface composite was fabricated on an Al surface precoated with SiC particles by ball collisions at room temperature in an ambient atmosphere. The formation of the composite was investigated at various treatment intervals between 5 and 30 min. The structural formation was affected by the treatment time, which was associated with the accumulation of strains introduced by ball collisions. In the strained zone, Al became plasticized and flowed. The Al plastic flow trapped, occluded and transported the SiC particles. Ball collisions refined the coarse grains of the initial Al plate and the SiC particles. The initial rolling texture of the Al plate, consisting of $\{1\,1\,2\}\langle 1\,1\,1\rangle$ and $\{1\,1\,0\}\langle 1\,1\,2\rangle$ orientations, was completely destroyed by 10 min of ball collisions. After 15-min treatment, the composite structure consisted of three phases: ultrafine-grained Al matrix, coarse SiC reinforcement and nanocrystalline Al–SiC composite interlayers. The hardness of the as-fabricated composite was increased almost threefold compared to that of the initial Al plate.

1. Introduction

Ball impacts can provide a simple and effective solid-state processing for coating fabrication [1–4]. The principle of this technique is that a substrate is fixed at the top of the vibration chamber and the balls and powder are loaded into the vibration chamber. As a ball impacts the substrate surface, the powder particles are cold welded to the surface, leading to the coating formation. The main processing advantage is that ball collisions refine the grain structure to the nanometer scale, which enables the fabrication of different kinds of nanostructured materials [2–9]. The fabrication of the coatings under the ball collisions demonstrated the intermixture of the materials at the substrate/coating interface and the possible formation of a surface composite layer [4–6]. Composite materials show significantly improved hardness and strength when compared to the two component materials. From a practical point of view, the surface composite might be more suited to some applications than the application of a coating or the use of bulk composite materials. The key point is that the solid-state processing of the fabrication of the surface composite may be less expensive than the fabrication of a coating layer or a metal-matrix composite. In addition, such problems as poor bonding of the coating and a greatly reduced ductility of the bulk composite could be overcome. The most exciting processing techniques for forming surface composites are based on liquid phase processing at high temperatures. Controlling the processing parameters is critical in high-temperature processing to obtain the ideal solidified microstructure in the surface layer. There are also some solid-state methods for the fabrication of the surface composite [10–12]. However, after friction stir processing, the surface becomes rather rough, and, there is a limit to the thickness of the workpieces being worked. Friction stir processing cannot be used for machining of the thin sheets. Obviously, ball collisions can be effectively used to create the surface composite. Ball collisions are not so severe for the surface as a rotary pin in friction stir processing, which enables the thin sheets to be treated. In addition, the ultrasonic-based vibration chamber that accelerates balls can be so constructed that it can be moved across the sheet in such a way making a process continuous [1,4]. However, the development of this method requires a better understanding of the solid-state process that occurs under the ball impacts in order to determine the relation between such parameters as surface-induced strain, strain rate, plastic flow of the material, material transport and grain refinement. In the present paper, therefore, the structural formation of the Al–SiC surface composite was investigated as a function of the treatment time.

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2. Experimental details

The experimental equipment used for the ball treatment has been described in detail by Komarov et al. [4]. Therefore, we here only briefly introduce the process principle. Fig. 1 shows a schematic illustration of the ball milling process. The vibration chamber with a diameter and height of 90 mm was attached to an ultrasonic transducer powered with a high-frequency generator at a resonant frequency above 20 kHz. Zirconia balls with a diameter of 3 mm and weighing 125 g were loaded into the vibration chamber. Resonant high-amplitude vibrations accelerate the balls towards the substrate surface, which induced high frequency, ball-to-substrate collisions. In the present experiment, an Al (99.99%) plate of dimensions 3 mm × 100 mm × 100 mm provided by Nilaco Corp., Japan was used as the substrate. SiC (99.5%) powder with an average particle size of 0.5 μm (Wako Corp., Japan) was used as the reinforcing material. Coarse particles with sizes greater than 1 μm were also observed in the SiC powder, but their volume fraction did not exceed 20%. The Al plate was first precoated with a SiC particle-containing ethanol suspension and dried. Then, the surface precoated with the SiC particles was ball treated for 5, 10, 15 and 30 min at room temperature under ambient pressure. The temperature of the chamber walls during ball treatment did not exceed 50 °C.

The structure and phase composition of the as-fabricated samples were studied by X-ray diffraction (XRD) analysis using a Rigaku diffractometer with CuKα radiation in the 2θ range of 30–140°. To determine the average microstrain ε and the crystallite size D, broadening of the well-separated Al peaks was measured at a step width of 0.01° and an exposure time per position of 10 s. Rigaku Standard Reference Silicon Powder RSRP-43275G was used as a standard to calibrate the peak position error and instrumental broadening of the X-ray diffractometer. The residual stresses of the Al coatings were calculated by using the $\sin 2\psi$ method, by measuring the shift in the diffraction peak position [13]. Reflections from the (4 2 2) crystal planes were used for the X-ray stress analysis. Stress was evaluated from strain values using Young's modulus and the Poisson ratio. The microstrains, crystallite size, and residual stresses were evaluated using Jade 7 software. The (2 2 0) pole figures were measured up to a maximum tilt angle of 75° by the Schulz reflection method on a Rigaku Ultima IV texture goniometer using CuKα radiation.

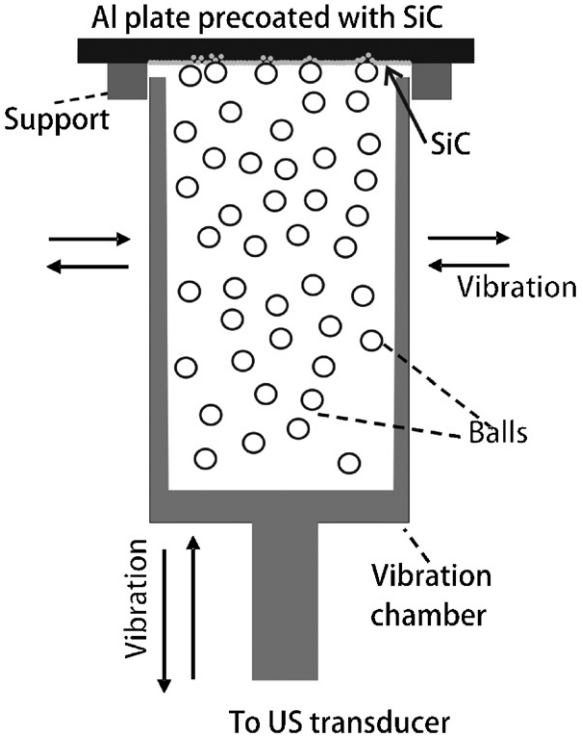

Fig. 1. Schematic illustration of the ball milling process.

The microstructure of the samples was studied by using scanning electron microscopy (SEM; Keyence VE-9800) in the backscattered-electron mode. For transmission electron microscopy (TEM) observations, the specimens were cut, ground, dimpled, and ion-thinned at low temperatures. The TEM specimens were examined using a JEM-3010 TEM instrument operated at 300 kV. All TEM images shown in this paper are cross-sectional images.

The microhardness measurements were carried out using an automated load Akashi hardness testing machine at a load of 10 g and a dwell time of 10 s. Fifteen measurements were taken for each sample and the average value obtained.

3. Results and discussion

3.1. General observation of the structure

Fig. 2 shows SEM images of the microstructure of the samples fabricated at different treatment times. After 5-min treatment, the microstructure was not uniformed. The SiC particles were either cold welded to the Al plate or embedded in the Al surface. The conglomeration of the particles on the surface and the embedded SiC are shown in Fig. 2a. The embedded particles were not completely enclosed by Al and the chain of embedded particles formed a veined structure on the surface. Features of the structure may be seen in the cross-sectional image of the 5-min treated sample (Fig. 2b). The ball collisions enabled rather large particles to embed to the depth up to 10 μm. The space between the coarse neighboring particles and the particle trails was filled with smaller SiC fragments. The SiC particles and the Al matrix had not formed an intimate contact. There were discontinuities and voids at the SiC/Al interface. After 10-min treatment, no conglomerations of the large SiC particles were observed on the surface in the SEM image (Fig. 2c). The SiC particles had sunk into the Al plate. The microstructure was relatively uniform. However, there were many discontinuities and voids. These surface voids were the traces of the SiC particles that had not been completely enclosed by Al. As the treatment time was further increased to 15 min, the voids shrunk and gradually disappeared and the surface appeared to become flattened (Fig. 2d). The structural components after 15-min treatment were not well resolvable by SEM and therefore the details of microstructural development were studied by TEM. The thickness of the composite layer ranged from 10 to 15 μm after 15-min treatment and from 20 to 30 μm after 30-min treatment. The SiC weight fraction in the Al plate at a depth of 10 μm in the 15-min treated sample according to glancing angle XRD analyses was around 10%.

Fig. 3 shows a series of XRD patterns indicating the structural evolution as a function of the treatment time. The XRD pattern of the original Al plate exhibited sharp and narrow Al peaks with visible CuKα1 and CuKα2 splitting (Fig. 3a). The 2 2 0 peak was strongly favored in the XRD pattern of the original Al plate. After 5-min treatment, the intensity of the Al diffraction lines completely changed, indicating crystallite rotation due to the effect of the ball collisions (Fig. 3b). The pole figures in Fig. 4 display the texture evolution under the ball collisions according to the treatment time. The texture evolution is discussed below along with selected-area electron diffraction (SAED) patterns. After treatment, the diffractograms displayed face-centered cubic Al peaks and lines of hexagonal SiC (Fig. 3b–d). As the treatment time increased, the Al and SiC peaks became broader.