Short communication

Highly Anisotropic Stainless Steel Fiber Reinforced Aluminum Composite Fabricated by Hot Isostatic Pressing and Rotary Swaging

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1. INTRODUCTION

Aluminum based metal matrix composites (Al-MMCs) are developed rapidly in these years and have been used in various fields from the aerospace technology to general industries. The most popular reinforcements used in Al-MMCs are ceramic, such as particles or fibers of SiC or Al₂O₃ [1]. Relatively there is less study on Al-MMCs reinforced by metallic reinforcements due to their high density and the harmful interface reaction at high processing temperatures. On the other hand, there are also advantages for metallic reinforcements, such as their low cost and relatively small degradation effects on the ductility or toughness of the obtained composites [2]. For inhibiting the deleterious reaction between the metallic reinforcement and the aluminum matrix, optimization of the process parameters is important and various processes such as liquid metal infiltration, squeeze casting and investment casting have been investigated [3-5].

Hot isostatic pressing (HIP) is considered to be an effective metallurgical technology for producing products with fine grain size, inhibited interface reaction and strong interface bonding [6,7]. Composites with a homogeneous microstructure can be expected after HIP, but for gaining an arranged orientation of the reinforcements that is benefit to the properties of composites, a secondary treatment is necessary. In this work, we investigated the preparation of a highly anisotropic stainless steel fibers (SSFs) reinforced aluminum composite by the combination of HIP and rotary swaging considering the flexibility and effectiveness of the rotary swaging process in re-arranging the orientation of fibers in composites [8].

2. EXPERIMENTAL PROCEDURES

The original materials were pure aluminum powder (purity 99.78%, main impurities included Si 0.06%, Fe 0.16%; particle size and its percentage (wt%): ≤100μm (0.1), 100-150μm (17.5), 150-200μm (65.7), ≥200μm (16.7)) and SUS304 stainless steel fibers (density 7.91 g/cm³, diameter 20±1μm, tensile strength 3,100MPa, elongation 2-4%). In the present work only a small amount of 0.78vol% SSF was added to the aluminum

matrix and the sample was marked as Al-1S. The pure aluminum sample with no SSF addition was marked as Al. The original materials were weighed according to the designed weight percentage and mixed with a V-shape mill mixer at a speed of 60rpm for 30min. The obtained blend was charged into a mild steel capsule with a cylinder shape of φ 30mm × 40mm, followed by a degassing treatment at 450°C for 60min before HIP. The pressure for HIP was 130MPa and the temperature was 450°C that is far below the melting point 660°C of pure aluminum. It is believed that interface reaction would hardly occur and the degradation of the mechanical properties of the matrix and reinforcement would not take place during processing at such a low temperature. The temperature rising rate was 10°C/min, soaking time was 60min and the temperature decreasing rate was 20°C/min. The obtained billets were in the shape of cylinder after removing the outside capsule. In addition, for obtaining a highly anisotropic composite, rotary swaging was employed to rearrange the fiber distribution in specimen Al-1S. The ratio of diameter of the specimen before and after rotary swaging was 4:1.

The density of the obtained materials was measured by the water immersion method. The theoretical density was calculated according to the rule of mixture using density values (g/cm³) of 2.70 for aluminum and 7.91 for SSF. The mean grain size after HIP was measured with an optical microscope equipped with a digital measurement system. Vickers hardness in both the transverse and longitudinal directions was measured with a microhardness tester using a load of 25gf. The tensile strength was measured with a universal testing machine (SHIMADZU EHF-10 type) with a load speed of 20mm/min. Optical microscopy (OM) and scanning electron microscopy (SEM) were performed to observe the microstructures of the obtained composites. The characteristics of the interface were studied by electron probe micro analysis (EPMA) (line scanning).

3. RESULTS AND DISCUSSIONS

The properties of the pure aluminum specimen Al and the composite Al-1S are listed in Table 1. It can be seen

Table 1. Static mechanical properties of aluminum based composites reinforced by stainless steel fibers.

Specimens	Density, g/cm ³		Hardness, HV, kgf/mm ²		Tensile strength MPa	Reduction in area, ϕ , %
	Theoretical	Tested	Transverse Direction	Longitudinal Direction		
Al	2.70	2.72	46.6	47.0	147	36.1
Al-1S	2.74	2.78	87.1	93.4	227	21.0

that the density of specimen Al-1S increased only a little (about 2%) compared to that of the pure aluminum specimen. It should be noticed that the measured density was in a good accordance with that of the theoretical one, and the specimens were considered being fully densified according to the following microstructural observation (see micrographs below). Although it was something difficult to see the grain structure in Al-1S specimen, a result of the mean grain size of $25 \mu\text{m}$ by OM in Al specimen after HIP was obtained, that indicates the fine microstructure of the obtained material. On the other hand, the hardness obviously increased in both the transverse and longitudinal directions and a little bit higher hardness was measured in the longitudinal direction.

Figure 1 shows the microstructure of specimen Al-1S. It is apparent that the SSFs were aligned in the elongation direction during rotary swaging. The degree of fiber orientation can be measured using the orientation coefficient, f , according to the following equation [9]:

$$f = (3 \cos^2 \theta - 1) / 2 \quad (1)$$

Where θ is the angle between the axis of a fiber and the specimen. $f = 1$ indicates that fibers parallel completely to the axis of specimen while $f = 0$ means that the orientation of fibers is completely random. In this study, θ was measured using an optical microscope.

The obtained value of f was 0.84 for specimen Al-1S, indicating that the composite had a good anisotropic microstructure through rotary swaging.

Fig. 1. Preferred orientated fibers in Al-1S after rotary swaging. The longitudinal direction of composites is the elongation direction during rotary swaging.

The tensile strength is also listed in Table 1. It is evident that by adding stainless steel fibers into aluminum matrix, the tensile strength increased by 54% compared to that of the pure aluminum material. According to the values of reduction-in-area, ϕ , the ductility of the composite was decreased a little, but the extent of degradation was far below that of the aluminum composites reinforced by ceramic reinforcements [10]. These results indicated that SSF/Al composite with excellent mechanical properties was obtained by the process combination of HIP and rotary swaging.

Fig. 2. Main fracture pattern of SSF/Al composites: (a) traces of the pulled out fibers and (b) the breakage of SSF clusters. Arrows indicate the position where fibers and clusters existed.

Fig. 3. Microprobe E-image traces of Al-1S composites: (a) traces for Al and Fe elements (b) traces for Cr and Ni elements (30keV, $\times 500$).

Figure 2 presents the typical fracture surfaces of specimens Al-1S. Specimen Al exhibited ductile fracture represented by equi-axial dimples while on the contrary, for the composite Al-1S, pull out of SSFs (Fig. 2 (a)) and the breakage of SSF cluster can be clearly observed (Fig. 2 (b)) representing the main fracture pattern in SSF/Al composites. In addition, no excessive interface reaction layer was detected for specimen Al-1S through SEM observation and EPMA analysis. As shown in Fig. 3, the typical electron microprobe image traces (E-image) presented no severe interface reaction between aluminum matrix and SSFs existed. This result indicates that the interface reaction was well inhibited in the present study.

Detail characterization of the interfaces and their effect mechanism on the material properties need further investigation.

According to the strengthening effect by the addition of SSFs (Table 1), the applied stress is effectively transferred to the SSFs through the interfaces. It means that suitable interface bonding strength is obtained by the present processing. HIP gives the composite with fine microstructure and strong interface bonding strength between SSFs and the aluminum matrix. Rotary swaging makes the composite with anisotropic microstructure and provides excellent reinforcing effect in the longitudinal direction of oriented fibers.

As a summary, the aluminum composite reinforced by SSFs with excellent mechanical properties was produced by the process combination of HIP and rotary swaging. The density of the specimen with 0.78vol% SSFs increased only about 2%, but the tensile strength increased by 54%. By HIP, composites with well densified and fine microstructure and controlled interface reaction can be manufactured and a sufficient interface bonding strength can be obtained. Rotary swaging is an effective process for rearranging the distribution direction of fibers and obtaining composite with excellent anisotropic microstructure.

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