Recycling of Magnesium Machining Chips via Shear Consolidation Processing

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Abstract: In this research, the feasibility of solid-state recycling of pure magnesium (Mg) chips is investigated by applying a synthesis technique called shear consolidation processing (SCP). During the SCP, machining chips are first loaded into the container and slightly compacted, and then a rotating tool with a designated diameter is plunged into the Mg chips at a selected spindle rotation speed and feed rate. Due to the huge amount of heat generation, the softened materials are compressed and synthesized to form a consolidated part eventually. The results show that the SCP process is a feasible solution for producing a void-free consolidated material directly from Mg chips in a single step. The microstructure analysis using optical microscopy (OM) and scanning electron microscopy (SEM) shows a significant grain refinement in the produced part compared with the base material (from around 900 μm to 11 μm). The recycled specimen has a much higher hardness (at least 100% increase) than the parent material and also exhibits better wear resistance. This improvement is attributed to the resulting fine-grained microstructure due to severe plastic deformation during the SCP process.

Keywords: Chips, Magnesium, Microstructure, Recycling, Shear Consolidation Processing

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1 INTRODUCTION

Magnesium is the lightest metal. Magnesium alloys are the excellent choice for structural purposes such as electric appliance cases and automobile parts [1]. Mg alloys have great machining abilities like sawing, punching, drilling, milling and turning compared to other metals. Thus, significant amounts of chips are produced at various machining processes. The Recycling of Mg chips is important from an economic point of view. It is reported with both traditional and non-traditional techniques. For many years, the chips produced from various machining processes is directly remelted and recycled into bars or other products. The efficiency of remelting based recycling processes of machining chips is very low [2]. On the other hand, compared with original alloys, the recycled products often exhibit poor properties due to impurity [3]. By contrast, regarding consumption of energy and green recycling, the solid-state recycling technique is more efficient than melting. In addition, samples produced by solid-state methods exhibit enhanced mechanical and microstructural properties due to the homogeneous oxide dispersion and finer grain size [4–6].

Experimental studies of solid-state recycling of pure magnesium [4] and magnesium alloys, such as AZ31 [7–9], AZ91 [6], [10-11], and ZK60 [12] have been reported by authors. The above processes are usually composed of two steps: (i) preheating, cold or hot pressing, (ii) double extrusion or hot extrusion. Remarkable improvements in recycled product proficiency have been reported in previous works for refined grain size and better mechanical properties in comparison with the as-received material. In separate works, Wu et al. [9] and Zhang et al. [10] studied the properties of AZ31B bars produced by cold pressing followed by hot extrusion. In the studies conducted by them, fine-grained microstructures as a result of dynamic recrystallization were observed. However, a review of the literature shows that the pointed recycling techniques require a secondary process needed extra energy and time. A new technique called SCP, follows the principle of the friction stir processing (FSP) and friction stir extrusion (FSE), in both of which frictional heat and local softening of material induced by a non-consumable rotating tool [13–15]. FSE is an extrusion method for the fabrication of wires from metal chips that has been introduced in recent years. In this process, extra energy consumptions are not required for re-melting, which is essential for the traditional recycling techniques. Recently, Tang and Reynolds studied the FSE process to recycle AA2050 and AA2195 aluminium chips [16]. Their obtained results showed that the microstructure of fabricated wires composed of equiaxed, recrystallized grains, and the hardness was homogeneous across the cross-section of the wires perpendicular to the extrusion direction. Abdi-Behnagh et al. [13-14], [17-18] found that the rotational speed of the tool had an important role in achieving defect-free wires in the FSE process of aluminium alloy AA7227 and pure Mg chips. It was also observed that microstructure consisted of equiaxed grains induced by DRX is formed in the fabricated wires. In this study, for the first time the new technique of shear consolidation process (SCP) is developed to directly convert pure Mg machining chips into the bulk disk-shaped material. Microstructure and hardness of the fabricated disc are also investigated with microscopic analysis and microhardness tests.

2 PRINCIPLES OF SHEAR CONSOLIDATION PROCESSING

The principle of shear consolidation processing is illustrated in “Fig.1”. As shown in the figure, the simplified experimental set-up for the SCP process consists of three major components: a container with a cylindrical central hole, a stirring tool, and a discharging tool. The container works as a die is fixed by a simple fixture on a computer numerical control (CNC) vertical milling machine during the process. The stirring tool has a helix groove on its face which can facilitate the tool stirring action. In the first step of the process, the machining chips are filled into the container. Then, a rotating tool is plunged into the container with a specific feed rate and rotational speed. A huge amount of friction-induced heat is generated due to the rotation and translation along the feed direction, which softens and fully consolidates the chips in the container. Depending on the amount of loaded chips, the plunge stroke of the stirring tool is determined, which also define the final thickness of the fabricated bulk disc.

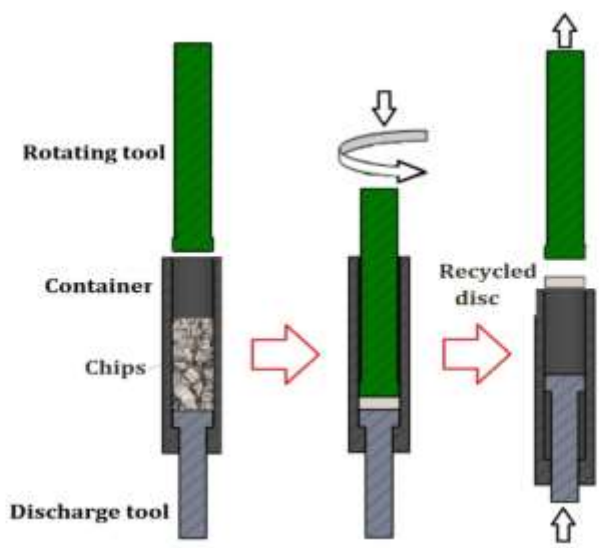

Fig. 1 Schematic view of SCP method.

As shown in "Fig. 1", the process is to be terminated when the stirring tool reaches the plunge stroke. Discharging tool is used to eject the consolidated disc from the container.

3 EXPERIMENTAL PROCEDURE

The materials applied in this work were dry and clean chips created by shaping of pure Mg ingot without using any lubricants. The chemical composition of as-received ingot based on mass percentage was Mg-Al < 0.01- Mn 0.03-Cu 0.006- Ca 0.005- Zn 0.005 and Sn < 0.002, and the average grain size was about 900 µm. Optical micrograph of the base Mg ingot is shown in "Fig. 2". The process was performed on a CNC vertical milling machine. The major components were made from H13 tool steel. To avoid sticking of Mg, all the components were treated with the case hardening and subsequent nitriding processes. The stirring tool was 20 mm in diameter. In the container, the cavity was 50 mm in depth and 20.6 mm in diameter, which had a clearance fit of 0.3 mm between the tool and the container wall. A constant axial feed rate of 20 mm/min and the rotational speed of 500 rpm were chosen. The plunge stroke for the stirring tool was set to 45 mm, aiming at 5 mm thickness discs. After SCP, the fabricated discs were sectioned following standard metallographic techniques. Top surfaces of the disks were ground with 600-grit silicon carbide sandpaper and then cleaned with alcohol.

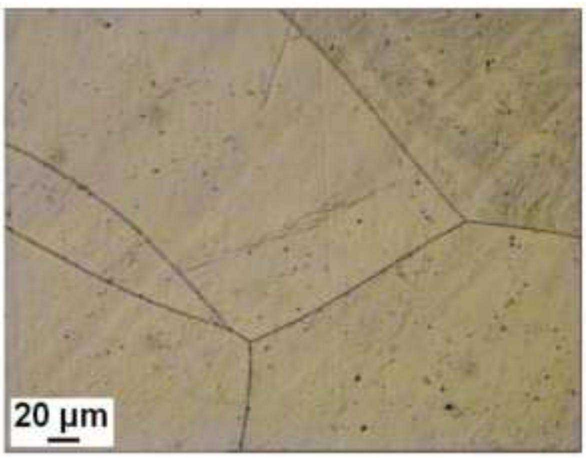

Fig. 2 Microstructure of the as-received pure Mg ingot.

For microstructural observations, the samples were etched at room temperature using acetic-picral (6 g picric acid, 5 mL acetic acid, 100 mL ethanol, and 10 mL water). OLYMPUS PMG3 optical microscopy was used to examine the microstructure formed in the process. Vickers microhardness tests were conducted on the disc cross-section. Microhardness test was performed by using a 50-grf load for 5 sec.

4 DISC FORM INTEGRITY

The appearance of the disc fabricated by the SCP is shown in "Fig. 3". It can be seen that machining chips interfaces are not visible in the consolidated disc. The surface of the specimen appears to have macroscopic cracks over the top surface of the disc. Following investigations showed that the cracks are superficial and have not extended through the thickness of the disc. A spiral pattern can also be seen on the surface of the disk. This phenomenon happened due to the scrolled face in the rotating tool that significantly influences the material flow during the process. Moreover, some of the material flashes can be seen in the lateral view as a result of clearance between the rotating tool and the interior wall of the container.

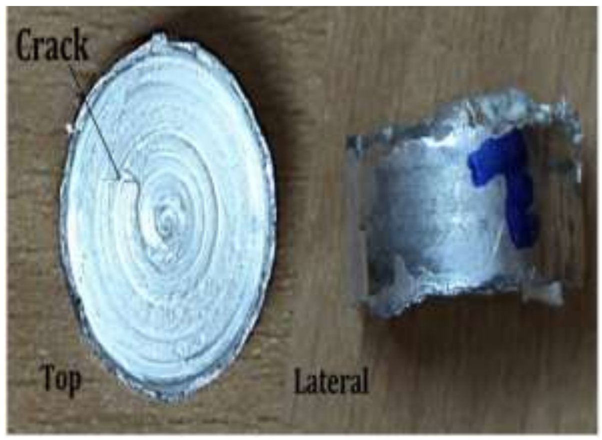

Fig. 3 Recycled disc in the top and lateral view.

5 MICROSTRUCTURAL ANALYSIS

"Fig. 4a and b" illustrates micrograph of the disc cross-section recycled by SCP method. No remarkable defects, such as incursions and voids, can be seen in the optical microscopy image and the boundaries between the chips are not observed, indicating that DRX occurs during the process. Refined grain microstructure was found in the fabricated disc, while an extremely coarse-grained microstructure was observed in the as-received Mg ingot ("Fig. 2"). Also, twinning structures can be seen in large numbers within the recrystallized grains shown in "Fig. 4a". These twinning boundaries occur due to the HCP structure of Mg and the shear forces occurred during the severe plastic deformation process [19]. The specimen produced by SCP has finer average grain size (d) compared with the base material. The grain size distributions in the recycled disc are shown on the histogram of the "Fig. 4b". As seen on the histogram, the average grain size ($\bar{d}$) in Mg ingot decreased from around 900 µm to 11 µm in the recycled disc by SCP.

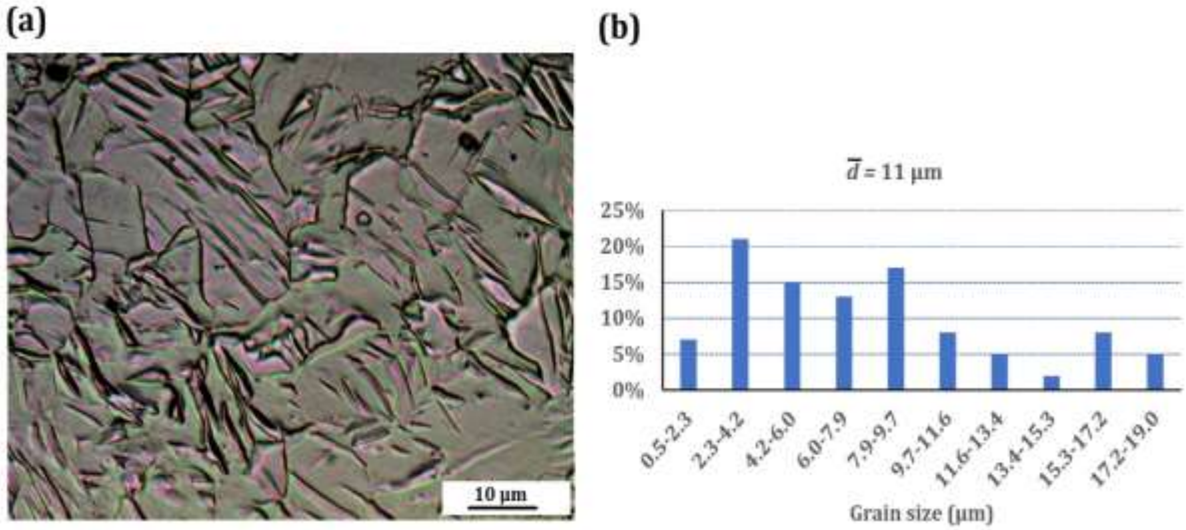

Fig. 4 Fine-grained microstructure in the recycled specimen: (a): optical microscopy image and (b): histogram of the distribution of grain size.

6 MICROHARDNESS

Compared with the hardness of 25 HV for the as-received pure Mg ingot, the average hardness in the recycled specimen was improved by at least 100% to more than 50 HV. The increase of the hardness is likely to be a result of recrystallized fine grains during the SCP. A fine-grained material will certainly improve the hardness and is stronger compared with coarser grains because a fine-grained structure has a larger area of grain boundaries to curb the movement of dislocation [19]. There is an inverse relationship between grain size (d) and room-temperature hardness (H), as represented by the Hall–Petch equation [19]:

$$H = H_0 + kd^{-1/2} \quad (1)$$

Where H_0 and k are material constants. From "Eq. 1", smaller grain size leads to higher hardness. As shown in "Fig. 4", the grain size in the disc recycled by SCP was around 11 µm while the grain size of Mg ingot was about 900 µm. Thus, the room-temperature hardness of the recycled disc should be increased drastically from the Mg ingot hardness, due to the linear relationship between room-temperature hardness and the square root of grain size.

7 CONCLUSIONS

In this study, a new method of solid-state recycling called shear consolidation processing was introduced suitable for recycling Mg machining chips. Fine dynamic recrystallization microstructure was observed in the recycled pure Mg disc fabricated by SCP. A remarkable grain size reduction could be achieved from 900 µm for as-received Mg ingot to around 11 µm after the SCP. The hardness of the recycled specimen by SCP was significantly improved by at least 100% that of the reference specimen.

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