Solid-state recycle processing of light alloys

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New solid-state recycle process to form high performance materials directly from wasted light metals such as Al or Mg alloys has been developed. It consists of the high-speed mixing/refining via the repeated backward extrusion, and direct hot forging with keeping fine microstructures by rapid pre-heating.

Keywords: Solid-State Recycle, Light Alloy, Repeated Plastic Deformation, Energy Consumption

I. INTRODUCTION
The application of light alloys, such as Al, Mg and Ti alloys, to automotive components is one of the effective solutions for the reduction of environmental burdens and fuel consumption. On the other hand, the weight reduction of medical equipments is also much effective on "Barrie-free" environmental system for aged people. In applying light alloys to the actual components, its recycling process must be considered. The conventional remelting and solidification is not suitable due to both much energy consumption and air pollution materials such as CO$_2$, NO$_x$ and SO$_x$ in re-melting.\(^1\)

Bulk Mechanical Alloying (BMA), which consists of repeated plastic deformation via one forward extrusion and two compaction processes within a closed die at room temperature, was developed as an important key technology for recycling of light alloys.\(^2\) It shows a possibility for the solid-state recycle with small energy consumption. However, when applying this technology to the mass production process, there are some technical and economical issues on productivity and reduction of the waste energy. Furthermore, the consolidation process of BMAed green compact by hot working must be established while keeping fine microstructures which cause higher performance like physical and mechanical properties. Based on these issues, new solid-state recycle process to form high performance materials directly from wasted light metals has been developed.

II. TECHNICAL AND ECONOMICAL ISSUES IN BMA
II-A. Minimizing thermal history in consolidation of BMAed green compact by hot working

Even employing wasted materials, the green compact with fine microstructures can be directly formed via BMA process. As show in Fig.1, the network intermetallic compounds Mg$_{17}$Al$_{12}$ exist in the matrix of the input wasted AZ91D chips. With increase in the number of cycles in BMA, the fragmentation of the compounds occurs and fine intermetallics, having less than 5 \(\mu\) m in diameter after 500 cycles, are distributed uniformly in the matrix. XRD patterns shown in Fig.2 also reveal the changes in Mg$_{17}$Al$_{12}$ intermetallic size. By using the empirical rule, which means that the yield stress of alloys can be estimated by dividing its Vicker's micro-hardness by three, BMAed green compact has a possibility to show the high yield stress as shown in Fig.3.
However, BMAed green compacts must be consolidated to full dense by hot working such as extrusion, forging and rolling process. The hot working acts to coarsen the fine microstructures of BMAed green compact, that is, the mechanical properties of hot worked billet decrease. Therefore, it is important to minimize the thermal history in consolidating BMAed green compact by hot working.

II-B. Minimizing non-effective input energy in green forming via BMA

In employing AZ91D chips as input materials, the average energy consumption in BMA process is 8.6kJ/cycle. Input energy is consumed in moving heavy dies and punches (4.5kJ), heat from friction and plastic work (~0.6kJ), friction due to scuffing and die wear (minimal) and plastic work to materials. 30–50% to the total energy consumption is non-effective on forming green compact in BMA process. On the other hand, the hydraulic press system is applied to the BMA equipment. It causes low productivity due to the slow punch/die speed in applying BMA technology to the mass production. Furthermore, the material seizure/sticking with the die surface often occurs because of the poor lubrication between the input materials and die in BMA process. For new solid-state recycle process via the repeated plastic work, the high-speed press with fixed heavy dies must be employed.

III. NEW SOLID-STATE RECYCLE PROCESS OF LIGHT ALLOYS

III-A. Direct hot forging with rapid pre-heating

To consolidate the BMAed green compact, the direct hot forging process is employed in this study. Once heating the green compact in furnace, it is fed into the heated die (diameter; 35mm) set in 1000kN hydraulic press and is consolidated to full dense by applied pressure of 800MPa. In pre-heating before hot forging, the infrared gold image furnace is used here because it has remarkably high heating rate, for example with the maximum of 100K/s, compared to the conventional electric furnace with a maximum heating rate of 1K/s. Figure 4 shows the dependence of Vicker's hardness of hot forged AZ91D billet after BMA with 200cycles on holding time in pre-heating. The conventional electric furnace causes the softening of the matrix by
the further thermal exposure due to the small heating rate such as less than 0.1K/s. On the other hand, rapid heating with about 3.6k/S of heating rate serves the high micro-hardness compared to the heating by using the conventional electric furnace. As shown in Fig.5, the ultimate tensile strength (UTS) of the direct forged AZ91D via BMA process also has the same dependence as the micro-hardness shown in Fig.4 on the holding time in pre-heating.

Based on the above issues, the concepts for new solid-state recycle processing of light alloys are as follows:
1) Minimizing non-effective input energy and high productivity
2) Reduction of friction loss due to material seizure with die surface

To improve the wasted input energy and productivity, 1000kN high-speed screw press, having upper punch speed of 100-800mm/s, has been introduced. The heavy die and lower punch are fixed and the light upper punch is only movable for consolidating materials, that is, non-effective can be remarkably reduced. Input energy to the plastic deformation of starting materials can be easily controlled by the upper punch speed. It is also easy to calculate the energy consumption by using the following equation (1) in this equipment when in-process monitoring the punch speed.

\[ W = 2.94 \times 10^{-5} \times V^2 \]  

where, \( W \); input energy/kJ, \( V \); punch speed /mms\(^{-1}\)

Figure 6 shows the typical pass schedule of one cycle in high-speed refinement (HISR) process. It consists of one compaction and one backward extrusion process. Employing the upper punch with sharp profile (about 1 degree) and diamond like carbon (DLC) coating in backward extrusion process prevent materials seizure on the punch/die surface perfectly. Also it is not necessary to add some lubricants into the input materials to control the material seizure. Figure 7 reveals optical microstructure of AZ91D after HISR process with 80cycles. Fragmentation and refinement of Mg\(_{17}\)Al\(_{12}\) intermetallic occur remarkably by the repeated plastic deformation.

The green compact billet via HISR process is columnar, and it is convenient to consolidate the billet to the final component by warm compaction or hot forging. Figure 8 shows macro-hardness (HRE) of direct forged AZ91D after rapid pre-heating via HISR process compared to the conventional BMA. When maintaining the same mechanical properties as the BMAed billet, HISR process consumes much smaller energy, for example about 10% of the energy consumption via the conventional BMA.
Fig. 6. Typical pass schedule of one cycle in HISR process with repeated backward extrusion and compaction.

Fig. 7. Optical microstructure of AZ91D chips via HISR process (N=80cycles).

Fig. 8. Dependence of macro-hardness of direct hot forged AZ91D alloys on energy consumption in forming green compact by repeated plastic deformation.

IV. CONCLUSION

New solid-state recycle process of light alloys has been established by employing high-speed screw press with the repeated backward extrusion and compaction process. This process gives the rank-up service for superior properties in recycling wasted materials under the small energy consumption and high productivity. To consolidate green billet with fine microstructure into final components under small thermal history, rapid pre-heating process is introduced by using the infrared gold image furnace. The hot forged AZ91D via rapid pre-heating shows superior mechanical properties.

REFERENCES


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