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Solid State Recycling of Die-Cast Aluminum Alloy Chip Wastes by Compressive Torsion Processing

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Solid state recycling without melting has been developed and expected as promising process to save energy for recycling of metal scraps. Applying a severe plastic deformation processing for solid state recycling has advantages not only saving energy for melting scraps but also increasing yield rate and upgrading properties of recycled alloys. In the present work, the solid state recycling and upgrading processes of ADC12 die-cast aluminum alloy chip wastes are investigated by using a severe plastic deformation process "compressive torsion process (CTP))" which was originally developed by authors. In this process, a cylindrical work piece is subjected simultaneously and continuously to compressive and torsional loading at elevated temperature without changing its shape. Effects of rotation repetition and processing temperature on the consolidation and subsequent tensile property were investigated. The chip wastes were preliminary compacted as cylindrical shape (40 mm in diameter, 15 mm in height) with 400 MPa at room temperature. In the following CTP, the processing temperature was varied from R. T. to 773 K, and rotation repetition was varied from 10 to 50. The compressive pressure and the rotation rate were fixed to 100 MPa and 5 rpm respectively. After processing, the microstructure was observed in the radial cross section by optical microscopy and tensile testing was carried out at room temperature. As a result, the chip wastes were successfully consolidated by the CTP. The precipitate particles of the alloy were refined and dispersed homogeneously in the aluminum matrix. The ductility of the recycled alloy was significantly increased with increasing rotation numbers.

Keywords: *Solid state recycling, Compressive torsion processing, Die-cast aluminum alloy, Severe plastic deformation.*

1. Introduction

The application of die-cast aluminum alloys to the structural components of vehicles is becoming important for the reduction of its weight. The machining of these die-casted components produces much machined chip wastes. Therefore recycling of the chip wastes is also important issue for their increasing applications. The recycling of the chip wastes is mostly carried out by the melting process, and the recycling process is required enormous heating energy to melt the wastes. Saving of not only resource but also energy is also important for establishing the sustainable environment.

Recently solid state recycling without melting has been developed and expected as promising process to save energy for recycling of metal wastes [1-8]. The solid state recycling has been reported for magnesium alloys [1-5] or aluminum alloy scraps [5-8]. In these reports, hot extrusion is mostly used to consolidate the scraps. The solid state recycling of aluminum scraps, however, shows lower mechanical property than those of cast billets. Because the surface oxide of aluminum alloy scraps is very strong and stable, it is very difficult to consolidate in solid state without forming voids and defects in the recycled alloys. Therefore, the enormous shear deformation is required to consolidate with well bonding of aluminum scraps. Using severe plastic deformation to the solid state recycling has advantages not only saving energy for melting scraps but also improving yield rate of recycling materials and upgrading of recycled alloys by microstructure control. We developed "compressive

torsion process (CTP)" [9, 10] as a severe plastic deformation process. In this process, a cylindrical work piece is subjected simultaneously and continuously to compressive and torsional loading at elevated temperature without changing its shape. The CTP has great advantages in easy consolidating of metal powder and upgrading of metals by microstructure refinement due to its severe plastic deformation [11-14]. In particular, participates refinement of hypereutectic Al-Si alloy was significant results [12, 13]. The solid state recycling applied CTP was investigated using wrought aluminum alloy [15, 16]. As a result, dense consolidate specimen which has high tensile strength and elongation was successfully obtained. Applying the CTP to die-cast aluminum alloy chip waste was expected not only dense consolidation but also microstructure refinement of grain and precipitates.
In the present work, the recycling and upgrading processes of die-cast aluminum machined chip wastes are investigated by using CTP. The aluminum machined chip wastes were consolidated with different process temperature and torsional rotation times. The usefulness of the CTP for the solid state recycling of aluminum alloy chips was investigated by observing microstructure and measuring tensile properties after consolidation.

2. Experimental

The compressive torsion process (CTP) was developed as one of severe plastic deformation processes for the direct consolidation of powder metal with hard surface oxide such as aluminum alloy [9, 10]. Fig. 1 shows an appearance of the compressive torsion processing. In the processing a work-piece is subjected simultaneously to compressive and torsional loading between upper and lower dies in a cylindrical container at elevated temperature. Top faces of upper and lower dies are rugged around 1mm depth so that the torsional loading can be sufficiently given to the specimen. By using this process a work-piece can be easily subjected to severe share deformation under hydrostatic pressure condition. Therefore it is very useful for consolidation of powder metal and chips metal, and they can be easily consolidated into dense bulk metals in short process time.

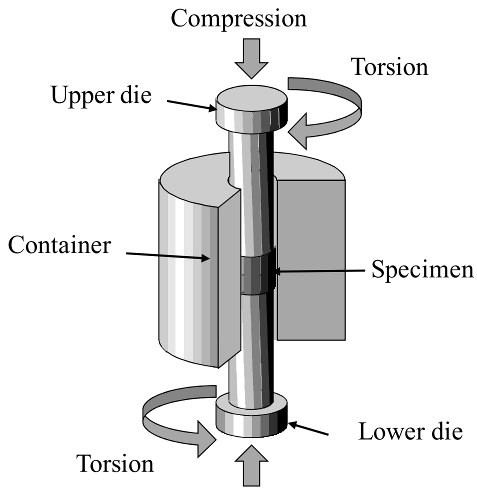

Fig. 1 Schematic illustration of apparatus for compressive torsion processing

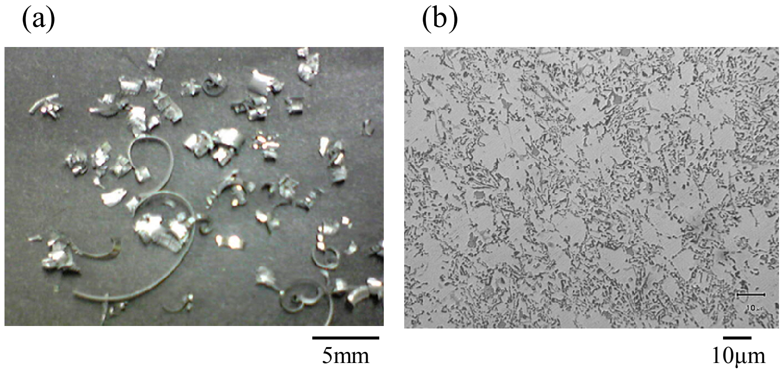

Fig. 2 Die-cast aluminum alloy machined chip wastes used in the present work, (a) appearance and (b) microstructure

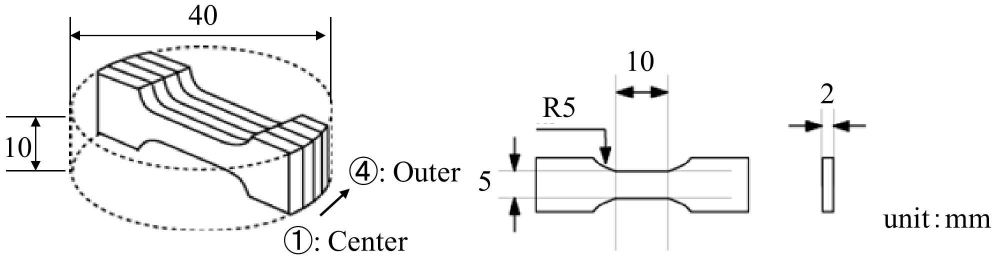

Fig. 3 Machined positions 1 to 4 from CTPed cylinder and geometry of tensile specimen

The appearance and its microphotograph of machined chip waste, which was ADC12 die-cast aluminum alloy, were shown in Fig. 2. Almost chip wastes show small strip that is around 2mm (Fig.2 (a)). The microstructure of chip wastes (Fig.2 (b)) shows usual cast microstructure that consist primary aluminum and eutectic silicon. The chip wastes were pre-formed by compression under 400 MPa at room temperature, and then it was consolidated to a cylindrical specimen ($\phi 40\times 10$mm) by the CTP under the following processing conditions; process temperature: room temperature (R. T.), 573 K and 773 K, compressive stress: 100 MPa, rotation speed: 5rpm, rotation repetition: 10, 30 and 50 times. In the present work the effects of process temperature and rotation repetition on the consolidation of machined chip wastes were investigated. The microstructure of the processed specimen was observed with an optical microscope in the vertical cross section in the cylindrical specimen. The tensile test was carried out by using specimens machined from the processed cylindrical alloy. As shown in Fig. 3 four test pieces were machined from the CTPed cylinder and they were numbered 1 to 4 sequentially from the center to the periphery as shown in the Fig. 3.

3. Results and Discussion

3.1 Microstructure

Fig. 4 shows the optical micrographs of the vertical cross section of the cylindrical specimen consolidated by CTP with the process condition of R. T. and 10 times rotations. The microstructure was observed at 9 points in the vertical cross section shown in the figure. From geometrical reason of torsional loading, the shear deformation is varied along radial direction in the cylindrical specimen. The consolidation of chips, therefore, would be depending on the radial position in the cylindrical specimen. Some chips boundaries were observed in a center part of the specimen, while such clear chips boundaries were disappeared in a peripheral part. The microstructure of specimen was quite different from the initial state. The elongated primary aluminum was observed on the center part. On the peripheral part, initial shape of primary aluminum was disappeared and eutectic silicon particles were homogeneously dispersed. The machined chips might be densely compacted but not be well bonded each others in the center part of the cylindrical specimen. In contrast, the chip was well bonded each other in the peripheral part and the microstructure significantly changes to homogeneous. Fig. 5 shows the micrographs of the specimen consolidated by CTP with the process condition of R. T. and 30 times rotations. No chip boundaries were appeared even in a center part of the specimen and

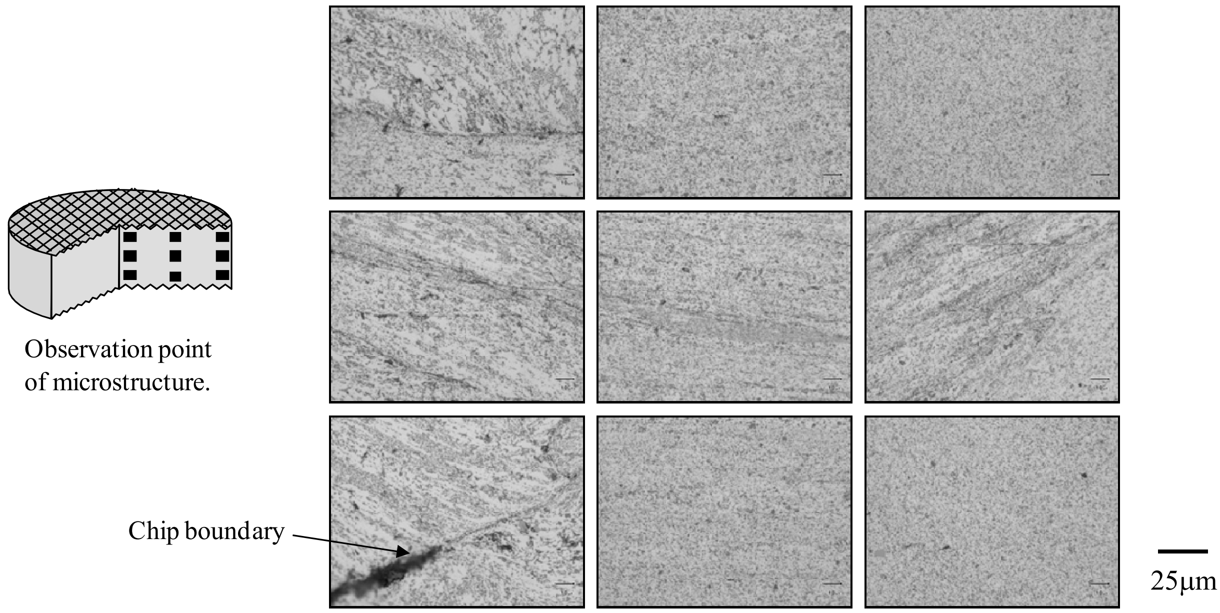

Fig. 4 Microstructure of specimen after CTP processed at R.T. with 10 times.

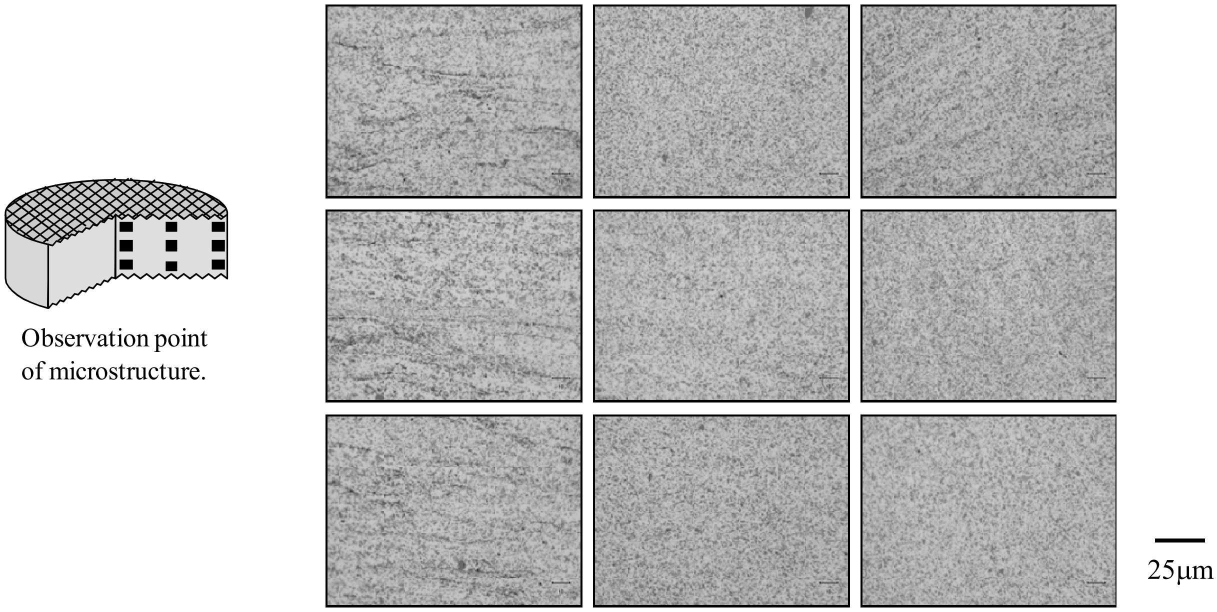

Fig. 5 Microstructure of specimen after CTP processed at R.T. with 30 times.

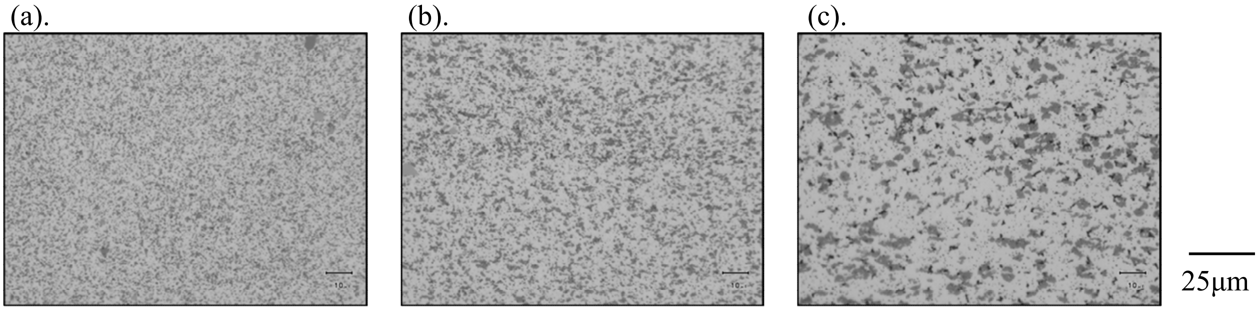

Fig. 6 Microstructure of specimen after CTP processed at (a) R.T. ,(b) 573 K and (c) 773 K.

firm consolidation with well-bonded chips, as well as the homogeneous microstructure, was achieved all over the cylindrical specimen. Fig. 6 shows the micrographs of the specimen consolidated by the condition of R. T. to 773 K with 30times rotations. These microphotographs were taken on the most refined points on the longitudinal sections of the specimen. The fine silicon particles which size is around 1μm were observed at R. T. processing. The particles size was slightly increased with increasing processing temperature.

3.2 Tensile properties

Fig. 7 shows the stress-strain curves of tensile tests carried out for the specimens machined from consolidated cylinders processed at R. T. with 10 and 30 rotation times. The numbers attached to the curves show the machined position of tensile specimens shown in Fig. 3. In the case of specimens consolidated with the condition of R. T. and 10times (Fig. 7(a)), the tensile strength and elongation are quite poor for the specimen, No. 1, machined from center part of the consolidated cylinder. The tensile strength and elongation were increased with increasing the test piece number (No. 1 to No. 4). However, the tensile strength and elongation of specimen, No. 4, machined from middle part of the consolidated cylinder was around 300MPa and 2%. This result was same level of as-casted ADC12 aluminum alloy. This result of the tensile test corresponds to the microstructure of the cylinder shown in Fig. 4. Namely, from the result of the tensile test, it can be concluded that the machined chips might not be well bonded each others in the center part but successfully bonded away parts from center even with the rotation of 10times. On the other hand, in the case of processed with 30 times rotations (Fig. 7(b)), tensile strength and elongation were significantly increased for all four specimens machined from consolidated cylinders. The elongation of specimen machined from middle part was more than

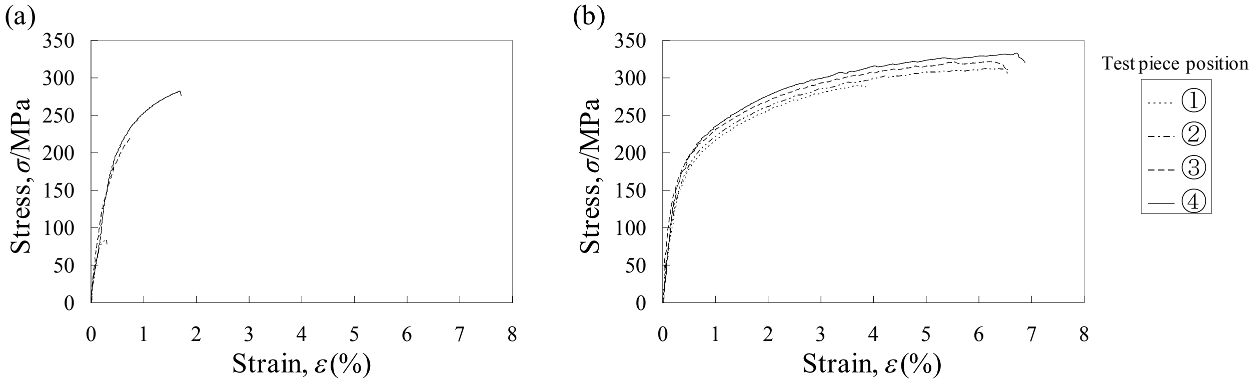

Fig. 7 Stress-strain curves of specimen after CTP processed at R.T. with (a) 10 times, (b) 30 times.

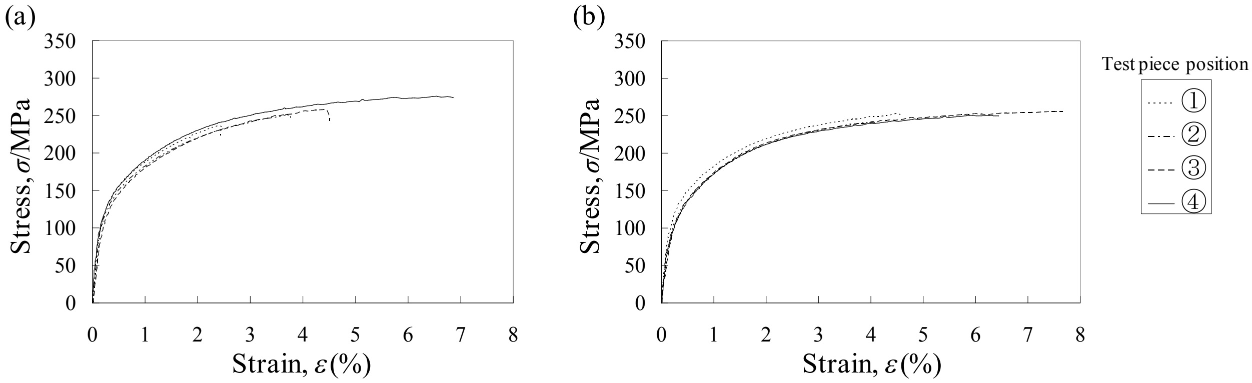

Fig. 8 Stress-strain curves of specimen after CTP processed at (a) 573 K and (b) 773 K with 30 times.

tripled than the as-cast alloy; therefore the consolidation of ADC12 alloy chip wastes using CTP was achieved by high balance of the strength and the elongation.

In the cases of the process conditions of 30 times rotations at 573K and 773K are shown in the Fig. 8. Sufficient tensile strength and elongation were obtained for all four specimens machined from consolidated cylinders. The tensile strength was reduced with increasing the processing temperature. It would be due to some work hardening in the specimen processed at R. T. and the effect of microstructure refinement would be probable in the specimen processed at lower temperature.

It is possible to conclude that the aluminum alloy machined chips can be successfully consolidated by a compressive torsion process at room and elevated temperatures with rotation of 30 times into the cylindrical bulk of $\phi 40 \times 10$ mm. And it shows sufficient tensile properties in comparison with the as-cast alloy.

4. Conclusion

The severe deformation processing, compressive torsion process (CTP) is very useful for consolidating aluminum machined chip wastes into cylindrical bulk. The chip wastes could be successfully and sufficiently consolidated by the CTP at room and elevated temperatures. The tensile strength of the consolidated alloy was higher than that of an as-cast alloy, and sufficient elongation was obtained all over the consolidated specimen.

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