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Review

Review of solid state recycling of aluminum chips

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ABSTRACT

In contrast with the conventional remelting recycling of aluminum and its alloy chips, the solid state recycling techniques, which can convert the chips directly into dense bulk materials, have attracted significant attention primarily because it possesses many advantages including lower energy consumption, lower metal loss as well as almost no emissions of harmful gases and solid wasters. In this keynote paper, with a view to the current researches of the solid state recycling techniques based on the severe plastic deformation (SPD) and powder metallurgy (P/M), the characteristics and applications of several typical methods, such as hot extrusion, equal channel angular pressing (ECAP), cyclic extrusion compression (CEC), friction stir extrusion (FSE), high pressure torsion (HPT), screw extrusion and spark plasma sintering (SPS), are introduced. A growing number of researches and literatures suggest that the mechanical properties of solid state recycled specimens are primarily dependent on the chip bonding quality and microstructure of the corresponding bulk materials. Then, the mechanism analysis of consolidation of chips is carried out, and three relevant theoretical modes, characterizing the bonding quality, are also mentioned. Moreover, the factors influencing the density and microstructure of chip-consolidated product are discussed comprehensively. Eventually, recommendations in the improvement of solid state recycling techniques and the future prospects are put forward.

1. Introduction

Non-ferrous metal recycling has a number of benefits, the most outstanding being the potential to reduce the extraction of virgin ores considerably, thus preserving those non-renewable resources. During the mining of these metals, negative environmental impacts are caused, including the emissions of carbon dioxide and hazardous gases, the generation of considerable amounts of solid waste, and the destruction of landscape (Gaustad et al., 2012). Moreover, in terms of energy consumption (Shao, 2017), relying on the types of metals and the forms of scraps, recycling can save as much as a factor of 10 or 20 (Rankin, 2011). Consequently, more and more attention has been paid to the reusing of the scrap metals.

To the present, two major processes have been proposed to recycle the nonferrous metal scraps, i.e. the conventional remelting method (Hao et al., 2017; Razi, 2016) and the newly developed solid state or meltless recycling process. As for the remelting recycling, there exist several remarkable problems listed as follows: (1) relatively higher metal loss ascribed to the higher chemical reactivity and larger specific surface area of metal chips; (2) toxic gases generated from the combustion of the oil emulsion adhering to the scrap chips; (3) relatively higher energy consumption and recycling costs. Based on comprehensive consideration of recycling efficiency, energy consumption, expense, as well as environmental impacts, the solid state recycling process is considered to be a more suitable choice especially for the scrap chips or turnings, and it can convert the scraps directly into bulk products and semi-products of superior mechanical properties, bypassing the step of remelting. In recent years, numerous studies have been reported on the solid state recycling of nonferrous metal chips (such as Mg, Ti, Cu, Al chips). For example, Thein et al. (2006) developed nanostructured Mg-5 wt%Al-x wt%AlN composite synthesized from Mg chips by hot extrusion. In the study of Ji et al. (2009), the as-extruded alloys were fabricated from Mg-2.4Nd-0.6Zn-0.6Zr magnesium alloy chips, exhibiting better mechanical properties. Li et al. (2011) studied low temperature mechanical properties of solid state recycled product from AZ91D Mg alloy chips, with the highest ultimate tensile strength of 360.65 MPa, the lowest elongation of 5.46%, and the lowest impact toughness of 3.06J/cm^2 at -130 °C. In addition, consolidation behavior of magnesium alloy chips during solid state recycling was also investigated. Peng et al. (2010) suggested that both the physical bonding caused by plastic deformation and the atom diffusion between chips triggered by shear deformation helped to enhance the

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consolidation of Mg-10Gd-2Y-0.5Zr chips. Interestingly, in 2009, the semisolid extrusion process was set forth to recycle minute metal scraps (such as machined chips). The pre-compacted chips had to be heated to a specified semisolid temperature before the final extrusion (Sugiyama et al., 2010). Similarly, Xu et al. (2010, 2012) attempted the strain induced melt activation (SIMA) method to prepared AZ91D magnesium alloy semi-solid billet from chips. The Titanium and its alloy chips were also recycled by solid state recycling process based on equal channel angular pressing (ECAP). According to the work of McDonald et al. (2012), they prepared fully dense as-recycled materials from Ti-6Al–4 V machining chips by ECAP, and found that the chip boundaries could be removed by heat treatments (at 700–1000 °C). Besides, it was also reported that fully dense bulk Ti with ultra-fine grains was fabricated from machining chips of pure Ti by ECAP with high strength (up to 650 MPa) and good ductility (~ 16%) (Luo et al., 2010, 2012a,b, 2013). In 2008, Zhilyaev et al. (2008) utilized high-pressure torsion approach to consolidate machined copper chips, and the consolidated discs exhibited high microhardness and extremely fine microstructures.

To our knowledge, compared with the conventional remelting recycling, direct conversion of aluminum and its alloy chips into compact specimen by extrusion leads to savings of 40% in materials, 26–31% in energy and 16–60% in labor (Gronostajski et al., 2000). Although the hot extrusion was proposed as the direct recycling method by Stern in 1945, many other solid state recycling techniques based on severe plastic deformation (SPD) and powder metallurgy (PM) are currently emerging. To date, the comprehensive summary of solid state recycling processes of aluminum chips has not been previously attempted. The intent of this paper is to carefully review the solid state recycling of aluminum and its alloy chips or turnings.

2. Solid state recycling techniques based on severe plastic deformation (SPD)

The SPD techniques, defined as metal forming processes, are viable avenues for microstructure refinement of metals, alloys and intermetallics (Azushima et al., 2008; Estrin and Vinogradov, 2013; Sakai et al., 2014). By imposing a very large plastic strain on the bulk metal, ultra-fine grained or even nanostructured metallic material can be produced with gain sizes lying within the submicrometer (100–1000 nm) and nanometer (< 100 nm) ranges (Estrin and Vinogradov, 2013). Consequently, the processes of SPD have been applied to the consolidations of chips successfully by inducing large shear deformations. Besides, the chip-consolidated product of finer microstructure usually shows better mechanical properties compared with the reference specimen from the original ingot (Anilchandra and Surappa, 2013; Misiolek et al., 2012). Up to now, several different solid state recycling techniques based on severe plastic deformation have been proposed, developed and evaluated, and they include hot extrusion, equal channel angular pressing (ECAP), cyclic extrusion compression (CEC), friction stir extrusion (FSE), high pressure torsion (HPT) and screw extrusion.

2.1. Hot extrusion

Hot extrusion is a very popular solid state recycling technique, as shown in Fig. 1, and its common recycling process consists of three major procedures, that is, comminution, cleaning and drying of chips firstly, subsequently cold pre-compaction, and finally hot extrusion. For example, Gronostajski et al. (1997) recycled aluminum and its alloy chips by hot extrusion. Tekkaya et al. (2009) presented direct hot extrusion to reuse aluminum AA-6060 milling and turning chips. However, as depicted in Table 1, aluminum and its alloy chips are usually recycled with the addition of reinforcing phases, such as tungsten, SiC, aluminum bronze, FeCr25, Al_2O_3 et al. Moreover, without reinforcing-phase addition, mechanical milling of chips in air atmosphere can also result in the formation of strengthening oxide particles (Samoshina and Bryantsev, 2012). Hence particle reinforced aluminum matrix composites can be generated after the hot extrusion.

Attempts were made to achieve better bonding of aluminum chips using cold compression only, but it was found that disintegration of outer surface of the cold compressed billets occurred during free upsetting although the obtained billets showed high relative density and compactness (Kuzman et al., 2012). Besides, the high compressive forces with the long pressing time were confirmed to be not enough to obtain sound chip bonding (Fogagnolo et al., 2003). Hence, an additional shear force, such as extrusion process, was applied to the as-pressed billet to produce chip-consolidated product of high quality. However, considering relatively higher thermal energy requirements and processing costs during the hot working (such as hot extrusion), some researchers were devoted to recycle chips through cold working absolutely. Chiba et al. (2011) studied the possibility of recycling A-C4CH aluminum alloy chips through cold extrusion and a subsequent cold rolling process. Their results showed that the mechanical properties of recycled materials were comparable to the original ingot, indicating sufficient bonding between chips.

2.2. Equal channel angular pressing (ECAP)

At present, ECAP is an extensively used SPD processing technique to fabricate bulk ultrafine-grained materials with high-angle grain boundaries via pure shear (Valiev and Langdon, 2006), and the main advantage of this process is that exceptionally large, unidirectional, uniform deformations can be brought to the bulk solids even under relatively low loads (Segal, 1995). The principle of ECAP is presented schematically in Fig. 2. When the sample passes though the channel, simple shear is introduced. Despite a very intense shear strain produced with sample, the cross-sectional dimensions of the sample remain unchanged, allowing for repetitive deformation (Horita et al., 2000; Haase et al., 2012; Valiev and Langdon, 2006; Langdon, 2007; Azushima et al., 2008; Estrin and Vinogradov, 2013).

Although ECAP is generally applied to the severe plastic deformation of the bulk materials, it can also be used to consolidate metallic particles or powders. For instance, in the work of Matsuki et al. (2000), they demonstrated the use of ECAP process for the consolidation of 2024Al-3Fe-5Ni alloy powder. They obtained almost fully dense compaction with very fine microstructure. According to Xia et al. (2007), pure Al particles were successfully pressed into bulk materials of very high density by using back pressure equal channel angular pressing (BP-ECAP) in just one pass, furthermore, it was found that better particles bonding was achieved via BP-ECAP compared to the ECAP without back pressure (Xia and Wu, 2005). In addition, the well mixed powders, i.e. carbon nanoparticles and pure Al particles, were consolidated into the fully dense Al-C nanocomposites, and significantly higher mechanical properties of the nanocomposites were possibly ascribed to the formation of fine equiaxed grains and uniform distribution of C particles into the Al matrix (Goussous et al., 2009). Similarly, during the consolidation of the fresh ultrafine Al particles by BP-ECAP, fully dense Al-Al_2O_3 nanocomposite consisting of nanocrystalline Al and amorphous γ-Al_2O_3 was synthesized successfully (Xu et al., 2009).

For the solid state recycling of granulated metal chips, the ECAP process can also exert an important influence on the good bonding between chips. As described in the introduction section, Luo et al. have converted the Ti and its alloy machining chips directly into fully dense materials of superior mechanical properties using the process of ECAP.

2.3. Cyclic extrusion compression (CEC)

The CEC method is one of the promising SPD techniques to induce very large strain in the sample. In the CEC process, the sample contained within the chamber underwent extrusion and compression, and these two procedures alternate in each pass (Richert and Richert, 1986; Richert et al., 1999).