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Evolutionary in Solid State Recycling Techniques of Aluminium: A review

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Abstract

This paper provides an intensive review on past and current research works in solid state recycling of aluminium and its alloys. The review relates the extrudates quality of the solid state recycled aluminium to certain aspects noted as chips preparation, reinforced materials addition, die geometry, processing parameters, and performance of miscellaneous solid state recycling techniques. Finally, concluding remarks underline challenges for aluminium recycling by the solid state and also highlight the potential future work on making the method as a promising alternative for sustainable manufacturing and hence technologically feasible for industrial implementation.

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Keywords: solid state recycling; aluminium;

1. Introduction

The benefits of solid state or direct recycling of aluminium are perceived important by researchers. It can reduce fund for environmental protection and better energy consumption than the conventional recycling by remelting can offer. In addition, significant amount of carbon footprint also can be cut down. In secondary aluminium production, energy about 10 GJ/ton of the material is needed, making up about 5-10 % of the energy in the primary aluminium output, and the trend is increasing for the subsequent years [1]. In 2030, a recycling rate of 50% is expected [2]. The figures indicate that demand for energy in secondary aluminium processing through remelting is increased significantly. Although there have been several successful efforts to improve energy efficiency of melting furnaces since the 1980s, nevertheless the energy consumption for secondary aluminium production can still go up to 20 GJ/ton depending on the condition of aluminium scrap, production facilities and processes [3, 4].

In the case for aluminium chips, the conventional recycling method was unfavourable due to a significant metal loss. Low density of the compacted chips enhances losses through oxidation. There are further losses on each stages of subsequent processing caused ultimately no more than 54% of the metal is recovered during conventional recycling by melting [5]. For instance, conventional recycling of aluminium turnings caused to approximately 45% losses in the metal [6]. Those losses impacted to costs rising in labour, energy and expenditures for environmental protection which subsequently increase the general cost of the process.

The direct recycling of aluminium fewer in steps involved, higher recovery efficiency and capable of enhancing material properties to the great extent [6, 7]. These advantages attracted more and more researchers to further explore the potential of direct recycling to manufacture the end products. However, despite great advantages of the direct recycling, its adoption by industry has been very sluggish so far due to notion that the property improvement is still uncertain.

It is very important to discuss and highlight the various factors in making solid state recycling of aluminium successful and practicable. This paper reviews evolutionary in the solid state recycling for aluminium which together demonstrates how different factors and advancement in the techniques affect property enhancement of the extruded profiles. Finally, some challenges to be overcome in the solid state recycling technique are also discussed in the concluding remarks.

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2. Experimental studies of solid state recycling

A number of experimental works have been attempted to optimise quality of the extruded profiles through the solid state recycling. The influence can be due to the material-based parameters such as chip constituents including types of chip, reinforced material, and their morphology. While for the process-based factors, method of chips cleaning, compaction strategy (temperature and force applied), heat treatment and types of plastic working method include the process parameters were the critical aspects to be taken care. As for the geometry-based parameter, the die design determines the level of strain and pressure imposed to promote the inter-chip welding quality during the deformation.

2.1. Effects of chips preparation

The quality of the recycled chip-based billet produced by plastic working is significantly affected by the way chips are prepared for consolidation at the early stage. Common factors to influence the chips preparation are pressure and duration of pressing, method of recycling, chips types, and their morphology.

Fogagnolo [8] found the quality difference between the extruded material from the cold and hot pressed chips is not significant. An increase in the pressing pressure or pressing time produces higher degrees of consolidation. The direct powder metallurgy method was also attempted in direct aluminum recycling [9]. Heat and a low pressure was used on granulated aluminium to soften the particles and reduce the springback action. The results showed that the method was inferior by 9-12% in green density, 2-13% in compressive strength, and 18-29% in Brinell hardness as compared to the commercial aluminium powder method pressed at 360 MPa.

Distinct forms of aluminium scraps was reported used in solid state recycling. The 1050 aluminium alloy in the pin forms was mixed by Guley [1] with 6060 aluminium alloy chips. Findings revealed that no optical difference can be seen between the extruded profiles and the as-cast billets microstructures. The extruded profiles of the mixture of AA6060 chips with AA1050 pins have an intermediate character between AA6060 as cast billet and AA1050 source material in tensile test results.

Tekkaya [10] investigated the properties, yield behaviour, microstructure and drilling behaviour of extrudates by direct hot extrusion of re-use of aluminium AA-6060 alloy chips produced by milling and turning operations with different sizes and shapes. The mechanical properties of the seam welds surrounding the chips are nearly as good as the properties of the base material. The yield strength of extruded chips is comparable to solid billet extrudates. The chips of the drilling process tend to have a reduced in total size for profiles extruded from recycled chips.

In overall, the quality of the chip-based extrudates is affected by the chips morphology if insufficient stress and strain are applied during the forming process. Therefore, minimum stress, strain, and temperature conditions are needed for creating a metallic bonding regardless of different chip geometries. In economic direct recycling, the cold pressing and hot extrusion route is more preferable then the hot pressing and hot extrusion route due to the cost benefit ratio as recommended by [8].

2.2. Effects of reinforcing phase and mixture of different aluminium alloys

The effects of adding reinforced materials in the consolidated chips were noticeable in terms of their mechanical and physical properties. The fabrication of composites from Al, AlCu4-alloy and AlMg2-alloy granulated chips with different amounts of tungsten powder addition (≈ 80 mesh size) was proposed by [7, 11]. Composites with low porosity, good diffusion bonds and the relative density exceeding 98% were obtained with tungsten powder addition. The heat treatments on Al and AlCu4-base composites caused the strength to increase meanwhile the plastic properties is decreased.

The direct conversion of granulated aluminium and its alloys chips ($AlMg_2$ and $AlCu_4$) into finished products through hot extrusion process were developed by [5, 12, 13]. The reinforcing phases used were aluminium oxide, tungsten, carbon, ferro-chromium and aluminium bronze comminuted chips. The findings reveal that the relative densities of the composites after hot extrusion are almost identical (over 98%) as those of solid materials made from aluminium powder with the hardening additions. A tungsten-powder addition and the aluminium oxides formed during the process, improved the strength and hardness properties. According to [8], the oxides content when introducing Al_2O_3 hardening phase in recycling aluminium alloy chips caused the higher UTS of the recycled composite material compared with the original composite.

Carbon addition results in discontinuities in the structure of the composite and thus impairs the strength and plastic properties of the composite. For ferro-chromium composite, a smaller fraction of granulated chips results a better mechanical properties due to uniform distribution of the ferro-chromium phase in the aluminium matrix. The effect of different presintering medium neither in air nor vacuum was negligible. The fractures strain of the composites increases with temperature and decreases with ferro-chromium content.

Composites with comminuted aluminium-bronze chips found to produce good tribological properties. The strength and plastic properties have meet the requirements for bearing materials [12]. Bearing composites were also developed by [14, 15] through cold compaction and hot extrusion. Hot extrusion did improve the density to above 95% of the theoretical density of the materials and hard phases were created. The weak bonding could deteriorate the wear of composites. To improve the bonding, heat treatment of composites after extrusion was suggested.

Researchers [12-14] inferred that aluminium-based composites with comminuted aluminium-bronze reinforcing phase produced good tribological properties while [5, 12, 13, 15] concluded that the reinforcing phase with uniform distribution and good bonding composites can be obtained via compaction and hot extrusion.

Mixing different chips of AA6060, AA6082 and AA7075 was investigated by [16] which then compacted and hot