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The use of Spark Plasma Sintering to fabricate a two-phase material from blended aluminium alloy scrap and gas atomized powder

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Abstract

Recently innovative solid state / 'meltless' recycling techniques have been developed and proposed for the consolidation of aluminium alloy scrap, aiming both at energy and material savings by eliminating the melting step. In this context, a powder metallurgy route is examined as a solid state recycling technique for the fabrication of a two-phase material via Spark Plasma Sintering. By mixing aluminium atomized powder and machining chips of the same alloy, a two-phase material was produced, where the powder phase acts as a binder/matrix for the Al scrap. Hardness, density, compression testing along with microstructural and computed tomography analysis of the densified Al 6061 alloy are presented.

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Keywords: Spark plasma sintering, aluminium alloys, recycling, powder metallurgy, machining chips.

1. Introduction

1.1. Challenges in aluminium recycling

A trend towards energy and resource efficient manufacturing could be observed in recent years driven by public concerns for environmental protection and resource conservation, but also as result of the prospective stricter policies on climate change avoidance [1]. In order to meet the global greenhouse-gas (GHG) targets, stabilizing the global average temperature at 2^0C above the pre-industrial level by 2050 and a reduction of GHG emission by 50-85% below year 2000 levels are required [2]. For the aluminium sector, a 50% total emissions reduction is translated into 85% decline to the emission-intensity, since global aluminium demand is expected to at least triple by 2050 [3]. This challenge can only be addressed by aiming at both energy and material/resource efficiency improvements [1,4].

Secondary aluminium from scrap requires much less energy than primary production. The theoretical energy to remelt and cast aluminium scrap is 1.14 MJ/kg [5]. However, despite considerable improvements in energy efficiency of the melting furnaces, the overall energy consumption of secondary aluminium production still can be as high as 7.7 MJ/kg [5] or 20 MJ/kg [6] depending on the type of aluminium scrap, the furnace technology and the production energy mix used.

Globally, 41% of liquid Al becomes process scrap, and in consequence does not directly become part of a functional product [4]. A scrap mass flow balance model presented by Boin and Bertam [7] for the EU in the reference year 2002 shows that ‘turning scrap’ (e.g. turnings, chips and cuttings) represents a relatively big flow of approximately 18% of the total industrial aluminium scrap mass. The recycling of this scrap category is considered to be problematic, mainly due to its high metal losses during remelting. Light-gauge scrap, having an extremely high surface area to volume ratio, tends to float on the surface of the melt. This causes significant oxidation losses of around 16% [8] or even up to 25% [9] that cannot be recovered since the metal property is lost. By avoiding the remelting, significant amounts of both energy and metal can be saved. Moreover, during the final recycling step of remelting, dilution losses (dilution with of scrap mixture with primary aluminium to reduce the concentration

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of impurities/residuals) as well as quality losses/down-cycling (loss of original functionality, reducing purity) occur that can limit the scrap usage [10]. A decision support tool for environmentally conscious metal management and improved scrap sorting has been developed, aiming in the minimization of those losses during recycling of Al [10].

1.2. 'Meltless' recycling techniques

Recently, various solid state recycling techniques have been developed, targeting aluminium scrap consolidation by plastic deformation [11-15]. This plastic deformation should be large enough to break-up the surface oxide layer of the chips in order to join clean and non-oxidized metal surfaces and allow the formation of adhesive metal bonds. Tekkaya et al. [11] and Güley et al. [12] hot extruded a cold pre-compacted Al alloy chips billet directly into profiles. The authors reported potential energy savings of nearly 90% compared to the conventional recycling route. Haase et al. [13] improved the solid state chips welding as well as the mechanical properties of the extrudates by introducing additional plastic strain into the material using an Equal Channel Angular Pressing (ECAP) die set during hot extrusion. Comparable tensile strengths and density as for reference base materials can be achieved following this approach. Widerøe et al. [14] developed a direct screw extrusion method of shredded scrap, introducing rotational movement to the scrap compacting and extruding in a single step. A different approach was presented by Sherafat et al. [15], who recycled Al 7075 alloy chips with the use of commercial air atomized, pure Al powder to fabricate a two-phase Al7075/Al material. The mixture of chips and powder was cold compacted and hot extruded in various mass fraction ratios.

Paraskevas et al. [16] used Spark Plasma Sintering (SPS), an advanced pressure assisted sintering method, as a novel solid-state recycling technique for the case of aluminium alloy scrap in form of chips. The technical feasibility of this approach was proven as well as the microstructure and the mechanical properties of the recycled material were investigated. The present study investigates the feasibility to recycle Al alloy chips with the aid of aluminium powder of the same alloy, at temperatures below the solidus, via SPS. In this approach, chips can partially substitute a mass fraction of the atomised powder in the sintered products. Fully-dense near-net-shape products can be directly produced via SPS, targeting both energy and material efficiency improvements.

1.1. Spark Plasma Sintering description

SPS is a pressure assisted, pulsed electric current Joule heated sintering method [16,17] recently pioneered in the field of powder metallurgy. SPS is also known as Field Assisted Sintering Technique (FAST) or Pulsed Electric Current Sintering (PECS), plasma pressure compaction, pulse electric discharge process, plasma activated sintering, electric field sintering, plasma pressure consolidation, pulse current pressure sintering and pulsed current hot pressing. SPS recently attracted considerable attention as a rapid sintering method capable of producing highly dense and homogeneous nanostructured sintered compacts and various advanced new materials in shorter sintering times than can be realised by conventional processing methods. The power consumption during SPS consolidation is about one-third to one-fifth of that of traditional techniques, including pressure-less sintering, Hot Pressing (HP) and hot isostatic pressing.

The applied pulsed electric current is combined with a uniaxial mechanical pressure to achieve very fast powder sintering. The pulsed current in the powder compact results in a very high thermal efficiency because of the direct volumetric heating of the sintering mold and especially the stacked powder material. In contrast to conventional HP, SPS is designed to have a very special power supply system as well as a special tool design that enables electrical current flowing directly through the compact and/or the die, depending on the electrical conductivity of the components. This allows very high heating and cooling rates with relatively low energy consumption [18].

Besides the benefit of direct volumetric Joule heating, the use of high current DC pulses may assist the consolidation process of difficult to sinter metal powders [17]. Aluminium/aluminium alloy powders are difficult to sinter due to the always present and stable surface oxide layer that inhibits bonding. SPS however has been successfully applied for aluminium powder consolidation, achieving full densification [19-20]. Despite some physical similarities with hot pressing (HP), SPS has demonstrated a potential to provide distinct technological and economic benefits over HP due to shorter processing times, reduced temperature and pressure requirements to achieve full density, and extremely high heating rates.

2. Materials and experimental procedure

2.1. Starting materials

Chips generated by dry machining of an Al 6061 alloy ingot in –0 temper (annealed), and gas atomized spherical powder (D_{10}=9.2, D_{50}=29.9 and D90=72.0 μm) of the same alloy were used as starting materials. A shaking device was used for mixing the chips/powder in a 50:50 ratio. The chemical composition of the Al 6061chips and 6061 gas atomized powder is comparable and presented in Table 1. Figure 2a-b presents the starting materials used.

Table 1: Chemical composition (wt %) of chips and powder

Element	Chips	Powder
Al	97.86	97.94
Fe	0.142	0.121
Si	0.695	0.692
Cu	0.278	0.249
Mg	0.989	0.979

2.2. Sintering cycle and tool set-up

The blended chips and atomized powder were cold pre-compacted in order to efficiently fill the SPS die. The SPS equipment (HPD 25/1, FCT Systeme, Frankenblick, Germany) consists of a 250 kN hydraulic press, a power supply system, a vacuum/gas chamber and a fully automated thermal and hydraulic process controller. Steel dies and punches (Uddeholm grade QRO 90), and a 0.35 mm thick