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Environmental assessment of solid state recycling routes for aluminium alloys: Can solid state processes significantly reduce the environmental impact of aluminium recycling?

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ABSTRACT

Solid state recycling techniques allow the manufacture of high density aluminium alloy parts directly from production scrap. In this paper the environmental impacts associated with 'meltless' scrap processing routes based on three different techniques, namely hot extrusion, screw extrusion and spark plasma sintering (SPS), are compared with the corresponding remelting route as reference. Analysis of the obtained results allows clear conclusions on the perspectives offered by solid state recycling for systematic environmental impact reduction of aluminium recycling with material and energy savings as most important influencing factors. An overall impact reduction with a factor 2 for the SPS route and 3–4 for the extrusion routes is found to be realistic.

1. Introduction

Various phenomena causing environmental impact are associated with recycling light metals. During the smelting process considerable amounts of energy are required and metal losses occur [1]. Depending on the available input streams and the targeted output alloy, dilution of impurities with higher purity alloys or primary metals may be required and/or quality losses have to be taken into account [2]. In recent years a considerable interest can be observed in recycling aluminium scrap at temperatures below solidus. 'Meltless' processes, more commonly denoted as solid state recycling, can offer significant environmental benefits in terms of energy and materials savings. The target of this article is to document the potential environmental impact reductions that such solid state recycling routes can achieve for aluminium production scrap in comparison to conventional remelting based procedures.

1.1. Context

The final remelting step in aluminium recycling is an energy intensive treatment, although favourable compared to virgin aluminium production [3]. Energy savings result from by-passing this remelting step by recycling relatively pure production scrap streams directly into billets or semi-finished products at lower temperatures. Moreover, in this way significant metal savings can be achieved by avoiding some of the intermediate metal losses. For aluminium up to 41% of the material stream goes into recycling before ever serving as a functional component [4]. These losses depend on the scrap input, the melt treatment, the furnace technology and the material efficiency of the forming processes. Process scrap can typically be retrieved in an additional recycling loop. In contrast, oxidation losses that occur during smelting, also referred to as metal losses, cannot be recovered as the metal property is lost. The 2012 global aluminium mass flow shows average values of 3.7% for 2012 and 5.4% for 2013 (forecast) as metal losses after remelting [5]. Especially light gauge aluminium scrap, like chips from material removal processes, results in much higher metal losses. Due to its high surface-to-mass ratio, this fraction tends to float in the melt, leading to losses of up to 16% with a flux treatment [6] or even up to 20–25% otherwise [7].

1.2. State of the art in solid state recycling

Besides remelting, recent literature reveals also some potential meltless recycling routes in which aluminium alloys are undergoing severe plastic deformation at temperatures below solidus. To be effective the plastic deformation should be large enough to fracture the always-present surface oxide layers that inhibit the metal–metal bonding. Cooper and Allwood [8] presented a model

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on solid state aluminium welding, analysing the influence of deformation conditions on the weld strength.

Direct recycling of machining chips by means of hot extrusion was patented by Stern in 1945 [9], and has recently been demonstrated to allow high quality output if appropriate die design and process parameter control are respected [10–12]. Haase et al. [12] integrated equal channel angular pressing (ECAP) into a hot extrusion die for processing chips, introducing additional strain and shear deformation through the ECAP turns. Utilizing complex deformation routes (porthole and ECAP die-sets), direct recycling by hot extrusion provides comparable or better mechanical properties compared to cast based profiles.

Screw extrusion has been tested as a continuous variant in which the scrap pre-compaction step as well as scrap preheating can be avoided [13]. More recently spark plasma sintering (SPS) has been demonstrated as a solid state recycling technique for scrap consolidation [14]. Dynamic scrap compaction, combined with pulsed electric current joule heating, cleans and activates the metallic surfaces and achieves efficient fracture of the stable surface oxides and desorption of the entrapped gases, resulting in void-less material. Fig. 1 shows examples of scrap consolidation for the presented solid state forming techniques.

Fig. 1. Scrap input (up) and fully dense profiles and near-net shape semi-finished products (down) obtained from the ECAP hot extrusion, screw extrusion and SPS processes respectively.

1.3. Objective

The environmental benefits of solid state recycling techniques listed above have not been analysed in detail yet. This paper contains the results of an extensive comparative LCA study, quantifying three technically explored ‘meltless’ recycling techniques for aluminium production scrap. Recycling by means of ECAP hot extrusion, screw extrusion and SPS have been compared with the corresponding conventional remelting routes.

2. LCA methodology and scope definition

Since a comparative LCA study was targeted and the studied solid state forming processes have different primary shape generation capabilities, two different references for comparison were chosen: for the assessment of direct recycling via hot extrusion and screw extrusion, a 1 kg profile obtained by extrusion after remelting was used, while for the SPS process 1 kg of raw material in prismatic near net shape form was compared to a billet of the same weight obtained after remelting. In terms of functional equivalence, the material properties obtained by the respective solid state recycling processes, as partially reported in [10–14] and summarized in Table 1, allow to conclude that the incorporation of the aluminium oxides present in the production scrap into the recyclates does not negatively affect the functional performance of the obtained materials if dispersion or breakage of these oxides layers during the solid state processing can be assured. It can be observed that the resulting materials in some cases show improved property values. Depending on the application this could result in a reduced material demand. New application opportunities can also be envisaged. For the purpose of this comparative study, such scenarios are not assumed.

Table 1
Mechanical material properties for semi-finished products obtained by three solid state recycling routes compared to their respective reference products (values between brackets).

Mechanical properties	SPS AA6061 (ref.: AA6061 cast)	Screw extrusion AA6060 (ref.: conventional extrusion AA6060 cast)	ECAP extrusion AA6060 as extruded – F (ref.: ECAP extrusion AA6060 cast)
State/temper (ref. state)	Quenched and artificially aged – T5, ([a]T4, [b]T1)	As extruded – F (as extruded – F)	As extruded – F (as extruded – F)
Hardness [MPa]	780 ± 14.7 ([a]652–720)	340 (300)	432 ± 39 (402 ± 17)
E-modulus [GPa]	78 ± 0.9 ([a]68–71.5)	–	71 ± 1 (71 ± 1)
Compressive strength at 9% strain [MPa]	337 ± 14 ([b]256)	–	146 ± 10 (149 ± 15)
Ultimate tensile strength [MPa]	–	165 (135)	166 ± 4 (168 ± 2)
σ_y yield stress [MPa]	[c]155–200 ([c]103–124)	85 (75)	64 ± 1 (65 ± 1)

[a] Data for T4 from [16].
[b] Measured for T1.
[c] Compressive yield stress.

The study was conducted using the ReCiPe Europe H/A method [15] and Simapro© 8.0.2. The endpoint level was selected as a basis for comparison as the impact of all midpoint categories is aggregated into a single unit (Pt). At midpoint level the level of detail is higher: these midpoint results are available upon request. The covered process steps for the different recycling routes are shown in Fig. 2, with indication of the mass fluxes corresponding to the chosen comparison bases. Homogenisation of the material is considered for the chips to obtain homogenous mechanical properties of the aluminium after machining. Chemical degreasing and drying as well as scrap cold compaction were also taken into account. According to the European Aluminium Association (EAA), for the Al extrusion production 1.324 kg of Al ingot is required to obtain 1 kg of finished extruded product due to the low efficiency of the forming processes [3]. Thus the same amount of material input has been considered for the hot extrusion routes. The extrusion scrap recycling is considered outside the system boundaries.

The substitution methodology, recommended by the EAA [3], is followed in this LCA study to balance the un-recovered metal losses. Consequently, metal losses need to be balanced with primary Al. This approach is valid since the availability of aluminium scrap is limited and the demand exceeds the offering [5]. This picture is not expected to change over the coming decade [5]. As proxy alloy in order to quantify material losses, primary AA6061, a broadly used wrought alloy from the Al–Mg–Si series, was modelled. The concentration of its main alloying elements was assumed to be in the middle of the alloy tolerance interval.

3. Life cycle inventory

Where available the impacts associated with well-documented processes, like primary aluminium production, were obtained from the Ecoinvent 2.2 database [17]. The medium voltage electricity mix (global average) for the aluminium industry was used [17]. A closed alloy AA6061 recycling loop was considered for all the routes, avoiding down-cycling or compositional corrections during melting. The Mg content of the scrap is expected to become half or less after remelting [18]. In contrast the concentration of the other alloying elements will not significantly change as these remain in the metal phase. An addition of 0.41 wt.% of Mg (nearly half of the

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