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Cold extrusion of hot extruded aluminum chips

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ABSTRACT

The direct conversion of aluminum alloy machining chips into finished parts by hot extrusion with subsequent cold extrusion was investigated. While the process of hot extrusion was utilized to break the oxides covering the individual chips and to lead to bonding of the pure metal, the processes of cold forward rod extrusion as well as cold backward can extrusion were used for the production of chip-based finished parts. For the hot extrusion process, a flat face die and a die with integrated equal channel angular pressing (iECAP die) were used in order to investigate the influence of the deformation route on the quality of the chip-based finished parts. The flat-face die is a conventional tool for the fabrication of solid sections, while the iECAP die is an experimental tool that integrates the severe plastic deformation process of equal channel angular pressing into a conventional hot extrusion die. Tensile tests revealed superior mechanical properties of chips extruded through the iECAP die compared to those of chips extruded through the flat-face die. The hot extruded chips were further processed at room temperature by either backward can extrusion to cans with different wall thicknesses or by forward rod extrusion to shafts with different values of extrusion ratio and cone angle. For all fabricated chip-based finished parts, the mechanical properties and the microstructure were analyzed. Backward can extrusion of chip-based extrudates fabricated with the iECAP die resulted in defect-free cans for all investigated wall thicknesses, while the cans obtained from flat-face die processed chips showed cracks within the walls. Shafts without visible internal defects could be produced by forward rod extrusion of previously hot extruded chips, independent of the hot extrusion die design. However, subsequent compression tests revealed a dependency of the mechanical properties of chip-based shafts on the hot extrusion die design.

1. Introduction

The production of primary aluminum is one of the most energy intense processes in primary metal production. By remelting aluminum alloy scrap, the amount of energy required for the production of aluminum can be significantly reduced (Schmitz, 2006). However, the remelting of aluminum scrap can lead to a material loss of up to 20% due to oxidation of the molten metal (Gronostajski and Matuszak, 1999). Particularly aluminum machining chips are one of the most difficult types of scrap to recycle by remelting, as the oxidation of the material is intensified due to the high surface to volume ratio of the chips (Sharma et al., 1977). An alternative approach to overcome the problem of material loss during remelting of aluminum chips and to further improve the energy balance of the aluminum production, is the direct conversion of aluminum alloy machining chips into finished or semi-finished products by hot extrusion, first presented and patented by Stern (1945). In this process, the chips are compacted to chip-based billets and extruded on a conventional hot extrusion press to chip-based extrudates. Different kinds of aluminum chips can be recycled by hot extrusion, for example turning chips or milling chips (Tekkaya et al., 2009). As all kinds of aluminum chips are naturally covered by an oxide layer, large plastic deformation (i.e. strain) and compressive stresses (i.e. pressure) must affect the chips during the extrusion process in order to break the oxide layers and to enable contact between surfaces of pure metal (Chmura and Gronostajski, 2006). Those requirements for the extrusion of chips are in accordance with the investigations of Bay (1979), who proposed a theory for cold pressure welding. He showed that the process of cold pressure welding of aluminum includes the mechanisms of fracture of a work-hardened surface layer, the expansion of the surface and finally the pressing of material around the particles of the cracked hard surface layer. Based on experiments, Bay (1983) proposed a model for cold pressure welding, in which a threshold strain is necessary for the initiation of welding. Cooper and Allwood (2014) proposed a new model regarding the weld strength, which introduces a variable threshold strain for the initiation of welding, calculated as a function of temperature and normal contact

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stresses. In hot extrusion of chips, the amount of strain and pressure affecting the material is determined by the extrusion ratio *R* (ratio between the cross sectional area of the upset billet and the cross sectional area of the extruded profile) as well as by the design of the hot extrusion die (Güley et al., 2013). While the extrusion of chips with a low extrusion ratio is leading to a high amount of residual porosity and therefore to substandard mechanical properties of the chip-based extrudates (Gronostajski et al., 1997), the extrusion of chips with a high extrusion ratio is capable of producing chip-based profiles with mechanical properties comparable to the mechanical properties of cast material extruded with the same parameters (Chino et al., 2006). A disadvantage of using high extrusion ratios for chip extrusion is the limited size of the cross section of the extrudates for a given size of the extrusion press. However, by using an appropriate die design for the hot extrusion of chips, it is possible to produce high quality chip-based extrudates with mechanical properties comparable to those of extruded cast material, even for low values of the extrusion ratio (Misiolek et al., 2012). Haase et al. (2012) investigated the influence of the die design on the mechanical properties of chips hot extruded into a 20 mm × 20 mm rectangular solid section, resulting in an extrusion ratio of $R = 8.6$. Three different die designs were used for the extrusion of chips, a conventional flat-face die, a modified porthole die with a shortened mandrel and a hot extrusion die with integrated equal channel angular pressing (iECAP die). Tensile test results revealed superior mechanical properties of the chips extruded with the iECAP die compared to those of chips extruded with the other dies. However, no comparison of the mechanical properties of iECAP die processed chips and cast material extruded through the same die was conducted and the possibility of further processing the extruded material was not investigated.

While the hot extrusion of aluminum chips to continuous profiles has been widely investigated, only limited research was conducted regarding the application of cold extrusion as a process for the direct recycling of chips to chip-based finished parts. Allwood et al. (2005) investigated the feasibility of the direct conversion of aluminum chips to shafts by forward rod extrusion. They found that an extrusion ratio above $R = 4$ was necessary to achieve sufficient bonding between the individual chips. However, Chiba et al. (2011) observed the formation of surface cracks in cold extruded aluminum chips, when an extrusion ratio of $R = 4$ was used. This was related to an insufficient formability of the metal at room temperature. They also found that the final density of the cold extruded chips was below 97% of the density of cast material, which was related to the presence of internal voids. The process of cyclic compaction and cold extrusion followed by single hot forging of magnesium chips was investigated by Kondoh et al. (2001). In this process, the material is conventionally cold extruded by an upper ram and afterwards re-compacted in the container by using the ejector as a counterpunch. They repetitively cold extruded and re-compacted the machining chips with an extrusion ratio of $R = 1.44$ for 500 cycles and finally hot forged the cold extruded part at 450 °C with a forging pressure of 784 MPa to a cylinder with a diameter of 35 mm. Although they reached a final density of the forged parts of more than 99% compared to cast magnesium, the long duration of the extrusion and compaction process, with 9 s per cycle, is a significant disadvantage for utilizing this approach for the direct recycling of machining chips.

As the process of hot extrusion is capable of recycling machining chips to chip-based extrudates without residual porosity (Mabuchi et al., 1995), it is expected that chip-based extrudates can be used as pre-products for cold extrusion in order to produce fully dense cold extruded parts, even when the cold extrusion is conducted with a low extrusion ratio. Furthermore, the design of the hot extrusion die significantly influences the mechanical properties and the microstructure of the chip-based extrudates, as it determines the amount of strain and pressure affecting the chips during hot extrusion. Therefore, it is expected that the hot extrusion die design also influences the mechanical properties of the cold extruded parts based on previously hot extruded chips.

Fig. 1. Produced AA6060 aluminum alloy machining chips used in this study.

In this paper, the influence of different deformation routes on the mechanical properties of chip-based finished parts based on hot extruded chips is investigated. Two types of hot extrusion dies, a conventional flat-face die and a hot extrusion die with integrated equal channel angular pressing (iECAP die) were used for the extrusion process. The hot extruded chips are subsequently processed by either backward can extrusion or forward rod extrusion. In backward can extrusion, the feasibility of producing cans with different wall thicknesses was investigated, while forward rod extrusion was used for the production of different types of shafts by varying the extrusion ratio and the cone angle.

2. Materials and methods

2.1. Experimental material and processing steps

For the fabrication of chip-based finished parts, aluminum alloy AA6060 was processed in six consecutive steps.

- Production of the chips
- Compaction of the chips
- Homogenization of the chip-based billets
- Hot extrusion of the chip-based billets to chip-based extrudates
- Machining of chip-based extrudates to preforms for cold extrusion and coating
- Cold extrusion of the chip-based preforms to chip-based finished parts

In order to allow an evaluation of the performance of the fabricated chip-based parts, the above shown processing steps, starting with the homogenization of the billets, were also conducted with cast billets of AA6060 to produce finished parts based on cast material as a reference. The AA6060 aluminum chips were produced by turning off an as-received cast bar without lubrication. The chemical composition of the cast AA6060, shown in Table 1, was analyzed by apt Hiller GmbH by optical emission spectroscopy using a Thermo Scientific ARL 3460 Metals Analyzer.

The casting skin was removed by an additional turning operation prior to the chip production step. After the turning operation, the chips had an average hardness of ≈82 HV0.2. The chips were produced with a cutting speed of $v_c = 400$ m/min, a feed of $f = 0.4$ mm and a cutting depth of $a_p = 2.25$ mm. The fabricated chips are shown in Fig. 1.