Journal of Manufacturing Processes 17 (2015) 1–8

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Technical Paper

Solid-state recycling of aluminium alloy swarf into c-channel by hot extrusion

Ryoichi Chiba*, Morihiro Yoshimura[1]

Department of Mechanical Systems Engineering, Asahikawa National College of Technology, 2-2-1-6 Shunkodai, Asahikawa, Hokkaido 071-8142, Japan

ARTICLE INFO

Article history:
Received 3 October 2013
Received in revised form 1 October 2014
Accepted 15 October 2014
Available online 13 November 2014

Keywords:
Aluminium alloy
C-channel
Extrusion
Machining swarf
Mechanical property
Solid-state recycling

ABSTRACT

In this study, we have investigated the possibility of the solid-state recycling of aluminium alloy machining swarf into c-channels using hot extrusion. Side milling swarf and lathe turning swarf generated from a cast Al–Si alloy ingot were cold compacted into columnar billets and successfully profile-extruded into equilateral c-channels at 600 K, under extrusion ratios of 10 and 18. The c-channels obtained at an extrusion ratio of 18 showed straight extrusion without warping, except in the front-end region. In case of the material recycled from the milling swarf at an extrusion ratio of 10, the optical microscopic study indicates the presence of coarse residual voids and cracks existing in regions where sufficient plastic strain was not introduced. In contrast, the material recycled from the same swarf at an extrusion ratio of 18 did not contain any coarse voids, rather had a density comparable to that of the original ingot. This could be attributed to the large strain of over 4.3 that was introduced in the sample recycled at the extrusion ratio of 18, as predicted by finite element analysis. Uniaxial tensile tests showed that the dense recycled material had a higher ductility than the original ingot, with a reduction of around 30% in the ultimate tensile strength. The material recycled from the turning swarf exhibited insufficient bonding among the individual pieces of the swarf, as compared to that recycled from the milling swarf under the same conditions, thereby resulting in inferior mechanical properties.

1. Introduction

Currently, most aluminium scrap, including machining swarf, i.e., small chips, is remelted in furnaces and recycled into ingots or die-casting products. However, the conventional recycling method is associated with the following disadvantages: (1) the metal yield rate is very low, i.e., approximately 55% [1]. (2) Unavoidable reduction in the purity of recycled ingots at the remelting stage results in the degradation of their mechanical properties. (3) The remelting process requires significantly large amount of energy, which is unfavourable in terms of energy conservation. These limitations drive the development of alternative technologies for the recycling of aluminium scrap.

Recently, solid-state recycling, which involves direct recycling of metal scrap into bulk material by using severe plastic deformation (SPD), has emerged as a potential alternative to the conventional remelting and recycling techniques [2]. The solid-state recycling method not only reduces the energy consumption but also improves the recycling efficiency dramatically (up to more than 95% for aluminium [1]). In addition, the solid-state recycling method offers the advantage of microstructural control during the recycling process, which allows the metal scrap to be recycled into materials with excellent mechanical properties. Thus far, several solid-state recycling processes have been intensively studied since 1980s, especially to recycle the machining swarf discharged from factory machine tools.

A great majority of studies on this topic have focussed on recycling machining swarf into cylindrical bars [3–12] or rectangular bars [13–15], using hot/warm forward extrusion. In addition, recycling processes based on other SPD methods such as cyclic extrusion compression (CEC) [16], equal channel angular pressing (ECAP) [17–19], high-pressure torsion (HPT) [20] or compressive torsion [21], and combined use of forward extrusion and ECAP [22,23] have also been reported. Recently, another study [24] aimed at producing a composite material including nano-particles from machining chips via hot extrusion, and a new method was proposed to produce clad plates from iron chips by using hot rolling [25]. Almost all of the abovementioned methods require pre-compaction of the machining swarf, the technical details of which have been reported elsewhere [26]. A brief review of the relevant

* Corresponding author. Tel.: +81 166 55 8003; fax: +81 166 55 8003.
E-mail address: chiba@asahikawa-nct.ac.jp (R. Chiba).
[1] Present address: Engineering Division, Oji Materia Co., Ltd., 20-6 Tokuda, Nayoro, Hokkaido 096-8555, Japan.

http://dx.doi.org/10.1016/j.jmapro.2014.10.002
1526-6125/

Table 1
Chemical composition of the AC4CH aluminium alloy used in this study [27].

Element	Cu	Si	Mg	Zn	Fe	Mn	Ti	Sb	Al
Mass%	0.01	6.9	0.37	0.02	0.13	0.01	0.13	0.001	Bal.

literature published before 2010 can be found in our previous paper [27].

Extruded sections are elongated metal products that have a complex configuration of the cross section, represented by *angles* and *channels*. Their cross-sectional shapes are non-axisymmetric and more complex than those of simple-shaped bars, e.g., cylindrical bars and rectangular bars. Extruded sections are in high demand in the industry, similar to the simple-shaped bars and metal plates. In recent years, the demand for extruded sections of aluminium alloy has been significantly increasing with the growing needs of applications demanding reduction in weight. Therefore, it is highly necessary to develop methodologies for recycling metal scrap into extruded sections. This is expected to increase the opportunities of using recycled materials, thereby leading to the promotion of use of recycled resources. However, to the best of the authors' knowledge, there are no attempts reported so far on the direct solid-state recycling of machining swarf into extruded sections.

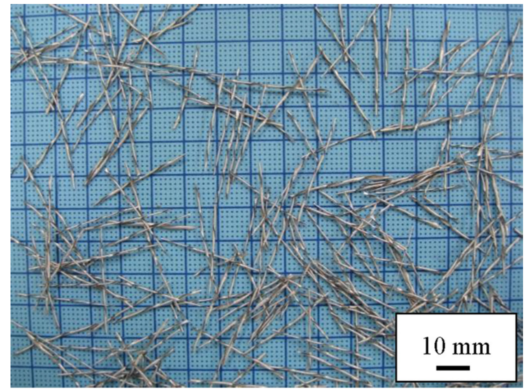
Extrusion to form complex configuration of the cross section is different in several ways from extrusion into simple cylindrical/rectangular bars. First, if the complex configuration is asymmetric, the extrudate may exhibit warping. Second, the streamlines of the plastic flow are likely to change steeply and may bifurcate. Third, because the slit width of dies can be location dependent, there exist portions that undergo deformation for a local extrusion ratio considerably larger than the global extrusion ratio. Fourth, complex configuration generally has many corners and the contact area (friction area) of die land is very large compared to the case of simple configuration for the same extrusion ratio. In other words, a wide area undergoes significant shear deformation. Of course, the performance of the solid-state recycling is affected by the above factors.

The present study investigates the possibility of recycling aluminium alloy machining swarf into c-channels using hot extrusion. Two types of machining swarfs of different shapes were cold-compacted into the shape of a billet, and subsequently respective billets were made into equilateral c-channels through hot profile extrusion process at different extrusion ratios. The surface appearance, density, microstructure, and mechanical properties of different specimens obtained under different recycling conditions were compared. Finally, we have discussed the feasibility of adopting cold-compaction followed by hot extrusion, for the solid-state recycling of aluminium alloy machining swarf into c-channels.

2. Experimental procedure

2.1. Machining swarf production and cold-compaction

Two types of machining swarfs with different shapes were produced by side milling and turning operations of a commercial AC4CH aluminium alloy ingot with cutting oil. The chemical composition of the aluminium alloy used in this study is summarized in Table 1. In case of side milling, the cutting conditions, namely, cutting rate, feed rate, and cut depth, adopted during the machining operations were 46 m/min, 0.1 m/min, and 1 mm, respectively, while those for turning were 67 m/min, 0.1 mm/rev, and 0.5 mm, respectively. Fig. 1 shows the appearance of the machining swarf. As can be seen from the figure, the machining swarf obtained by side milling is needle-shaped and spirally twisted of length 25–30 mm and width 1 mm [27]. On the other hand, the machining swarf



(a)

(b)

Fig. 1. Appearance of the machining swarf obtained by (a) side milling (reproduced from Fig. 1a in [27]) and (b) lathe turning.

obtained by lathe turning is found to be curled, short swarf of length 5–30 mm, width 1.5 mm, and thickness 0.5 mm.

The machining swarf was ultrasonically degreased with acetone for 10 min. The cleaned machining swarf was then placed in a cylindrical container and compacted at a pressure of 303 MPa [27,28] under room temperature to form billets of diameter 20.5 mm and height approximately 25 mm. The compacts were unloaded immediately after the loading pressure reached 303 MPa. A universal testing machine (Autograph AG-X 250 kN, Shimadzu) was used for the compaction as well as for the subsequent extrusion process, described in the following section. As a pre-processing step, the compacts (billets) were annealed at 300 °C for 1 h, before the extrusion process. This was performed to prevent cracks in the extrudates, which were observed in the hot extrusion of the as-compacted billets.

2.2. Hot extrusion

In the present study, the extrusion was performed by the forward extrusion method. The dies used in this study have a C-shaped orifice at the centre (Fig. 2), so that a symmetry axis passes centrally in the dies. The dimensions x and y were kept as the same, in order to maintain the ratio between the height and width of the c-channel products as 1:1. In addition, the corner radius of 0.5 mm was set at all the eight corners. An approach region with a die angle of 45° was also set to get a smooth transition from the end of the container to the inlet of the dies. Two types of dies with different extrusion ratios R = 10 and 18 were prepared, which have an identical die land length of 3 mm.