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Co-extrusion of a Mg/Al composite billet: A computational study validated by experiments

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ABSTRACT

A coupled finite element analysis in conjunction with experiments was used to investigate hot co-extrusion of a novel composite Mg AZ80/Al 1100 billet assembly. To validate the computational model, results from both radiography, and metallography were used.

It is demonstrated that the billet configuration proposed in this study results in a uniform composite rod, with no indication of cracks, tears, wavy interface surfaces or voids. The computational model is first validated by the experiments and then used to thoroughly study the thermo-mechanical fields that develop during the co-extrusion process. The interplay of the thermal and mechanical fields during the process is examined for different initial temperatures, die angle and ram velocity. It is demonstrated that using the proposed billet assembly, constant compressive radial stress develops across the magnesium core, leading to sound-proportional flow conditions.

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1. Introduction

Magnesium alloys are of great interest in the automotive and aerospace industries due to their high strength to weight ratio (Mordike and Ebert, 2001). However, magnesium alloys demonstrate poor corrosion resistance and therefore their use in industry is limited. One possibility of overcoming this limitation is using composite components in which aluminum is used to protect the magnesium from the environment. Such components can be manufactured from composite billets which are hot or cold formed into the required shape using metal forming processes. A common process of this type is co-extrusion of a composite billet composed of a sleeve and a cylindrical core. The different flow stress characteristics of the materials make the process itself and the final component quality overly sensitive to co-extrusion process parameters such as temperature, ram speed and die and billet geometry. Unwanted product defects include non-uniform core or sleeve thickness or/and weak bi-material interface strength (Negendank et al., 2012). In some cases the process may result in cracking of the aluminum sleeve and/or fracture of the inner magnesium core (Kazanowski, 2004).

Past experimental studies have shown that such unwanted phenomena can be related to both the tool and billet geometry. The effect of initial billet core length was investigated in (Kazanowski, 2004) while the influence of initial core diameter was examined in (Apprely and Crosky, 2000). In (Kazanowski, 2004) it was concluded that improvement in geometric tolerances is achieved by using a shortened core while in (Apprely and Crosky, 2000) it was reported that large core diameters are required for obtaining sound flow conditions. Die shape and angle on extrusion load were examined in (Nowotynska and Smykla, 2009) while its effect on material die exit velocities was studied in (Khosravifard and Ebrahimi, 2010). The study in (Nowotynska and Smykla, 2009) concluded that by using a convex die which is optimized to a specific layer composite one can obtain a better quality extruded composite with respect to standard flat dies.

Billet preparation and assembly methods were studied in (Negendank et al., 2012), demonstrating that press fitting is preferable to mechanically interlocked fitting. Extrusion die exit velocity can also affect the quality of extruded products. Usually, Al can be successfully extruded at exit velocities of 8–140 mm/min (Laue, K. 1981), while die exit speeds of Mg alloys are much more limited (Liu et al., 2009). At high extrusion speeds of Mg the exit temperature may significantly increase due to deformation and friction. This

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can result in localized melting due to the presence of phases with low melting temperatures. The relation between die exit velocity and exit temperature in Mg AZ31 extrusion was investigated in (Liu et al., 2009). The study concluded that a combination of high initial billet temperature and low ram velocities results in near isothermal extrusion.

Theoretical analysis of the co-extrusion process has shown that if one assumes isothermal process conditions, generally low reduction ratios, low die opening angles and high material interface friction result in uniform deformation while high extrusion ratios and low flow stress ratios lead to core fracture (Osakada et al., 1978). Nevertheless, co-extrusion processes are rarely isothermal and the question of how the close coupling between the thermal and mechanical fields affects the end product quality is still unanswered. Another important aspect in bi-material forming, which has attracted numerous studies, is the influence of process parameters on the interface bond strength. The effect of rolling process parameters on Al-Mg bond strength was investigated for hot rolled Al/Mg/Al composite plates in (Zhang et al., 2011) and also in (Changzeng et al., 2013). Both studies showed that due to the formation of intermetallic layers at the material interface deformation and temperature values which develop during the process may greatly influence bond strength. Nevertheless the question of how local thermo-mechanical fields affect the development of the intermetallic layers is still unanswered.

In co-extrusion, interface bonding can be associated with material flow velocity and local interface temperature (Khosravifard and Ebrahimi, 2010). The exact values required for obtaining good interface strength are still not fully determined. This is partly due to the fact that the mechanical and thermal fields, in hot co-extrusion, are highly complex, closely coupled, and difficult to determine. As a result of the complexity of the coupled initial boundary value problem (IBVP) the thermo-mechanical fields must be investigated using computational methods.

In this study the process of co-extrusion using novel composite billet geometry is investigated. An elasto-plastic coupled finite element (FE) model is developed, verified and validated. It is demonstrated that the FE model can describe accurately both the force time curve and local temperature rise due to dissipation of plastic deformation energy. It is shown, using radiographic imaging and metallurgical examination that the computational model is also able to predict inner core dimensions and bi-material flow patterns. Once validated, the FE model is used to investigate the thermo-mechanical fields which develop during the co-extrusion process and govern material flow. It is shown that using the novel billet geometry proposed in this study, a defect free composite rod of uniform core and sleeve thickness can be obtained. The proposed process also has limited sensitivity to initial extrusion temperature.

The structure of the paper is as follows: In Section 2 the experimental setup and novel billet geometry are presented. In Section 3 the finite element model and the process of model validation are described in detail. Section 4 is devoted to computational investigation of the thermo-mechanical fields which develop during the co-extrusion of the proposed composite billet. Summary and concluding remarks are given in Section 5.

2. Experimental setup

2.1. Composite billet preparation

The composite billet used in this study consisted of a Mg AZ80 rod inserted into an Al 1100 hollow tube (sleeve). In Table 1 the physical properties of the tool steel Mg core and Al sleeve are provided.

Table 1
Physical properties of tools core and sleeve material at RT.

Material	Density [kg/m^3]	T_m [°C]
Al 1100	2700	660
Mg AZ80	1800	650
H13	7800	1426

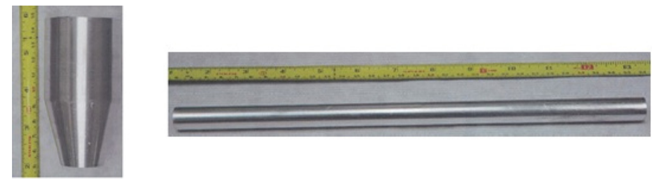

Fig. 1. Al sleeve (left) and Mg core rod (right). Billet components prior to composite billet assembly.

The Mg rods and Al sleeves were machined from cylindrical billets. The Mg rod was 300 mm long with a diameter of either 15 mm or 18.7 mm. The Al sleeve had an outer diameter of 49 mm and an inner diameter which was slightly smaller than the Mg rod. The sleeve length was 90 mm, with one end coned so as to fit into the die. The assembly process included preheating of the Al tube to 20 °C above the die temperature, while the Mg core remained at room temperature. This was done to promote a predominant soft sleeve-hard core co-extrusion assembly. Heat transfer analysis not presented herein supported this methodology. The composite billets were assembled seconds before the extrusion process. Due to the thermal gradients between core and sleeve, shrink fitting takes place. Fig. 1 shows both parts of the billet prior to assembly.

2.2. Co-extrusion procedure

The co-extrusion process was conducted using a 100 Ton press. The extrusion tools and assembly are presented in Fig. 2.

Prior to extrusion, the composite billet outer surface, container and die were lubricated with graphite based lubricants. The die and container were preheated to the extrusion temperature.

The experimental setup utilizes the concept of an apparent "floating" inner core. This is achieved by making two design changes compared to regular co-extrusion setups. First, the moving hollow ram transfers force directly from the press only to the aluminum sleeve. Second, the die diameter (22 mm) is larger than the Mg inner core diameter (Fig. 2), meaning that theoretically, the core does not have to undergo any cross section reduction. Although, due to the interplay between the thermal and mechanical fields the core undergoes deformation as will be discussed in Section 4.

Each co-extrusion experiment started seconds after composite billet assembly and terminated just before the ram entered the conical die. Then, the extruded product was extracted from the tools and left to air cool at room temperature. Temperature changes during extrusion were monitored throughout the process using thermo-couples inserted in the container and die.

Ram speed was 250 mm/min (4.16 mm/s) in all cases. The value of ram speed was selected following computations, described in the next section. This value induced exit temperature which does not exceed the material melting point and results in minimal thermal gradients along the center of the Mg core.

It is well known that process conditions such as extrusion temperature, extrusion ratio, die semi-angle and surface friction can affect the quality of the extruded product and are interrelated. In this study the effect of sleeve-to-core diameter ratio and die semi-angle on the extruded product quality were investigated, with emphasis on the effect of initial composite billet temperature.

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