USING HOT EXTRUSION TO MAKE CORE-SHELL TYPE METAL COMPOSITE BULKS

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Abstract

Lightweight is one of methods for low-carbon design. Based on the lightweight applications potential of metal composite bulks and on the fact that the interface between metals is externally visible currently, this study aims to investigate the feasibility to create core-shell type metal composite bulks. In this study, extrusion is proposed to realize such type of composite. The shell material is suggested to be made as socket shape by backward-extrusion of a metal rod, while the core metal keeps its rod shape. The latter is inserted in the former and then completely encapsulated by using forward-extrusion. In this article an aluminum alloy 6061 is used as the shell metal and alloy 7075 as the core metal of the bulk.

Before carrying out the experiments, the feasibility of the process is studied with a commercial finite element software DEFORM according to the Taguchi method regarding the influence of the four primary factors - its area reduction ratio, die angle, die radius, and working temperature - respectively with three levels, on the top end shutting of its shell metal. As a result, the two most important factors are the area reduction ratio and the die angle while corner radius practically has no effect. Six processes with higher area reduction are examined by experimentation. From the results in both of finite element analysis and experiment, the feasibility making the core-shell type metal composite bulk by using hot extrusion is positively confirmed.

Keywords: Core-shell type metal composite bulk, hot extrusion, aluminum alloy, finite element analysis

1. INTRODUCTION

Low carbon life is nowadays not just a trend; it has been already developed as a policy and even become as trade constraints, which every enterprise wants to overcome. Product manufacturers turn therefore not only to greening their supplier chains and reducing wastes in house but also introducing low-carbon technologies in their products to follow this general direction. Consequently, more and more low-carbon designs can be found in automobiles. One of them is the lightweight design. Ultrahigh strength steels, aluminized steels, and metal matrix composites are examples implemented in body chassis system, exhaust system, engine, driveshaft, brake systems, and so on. Parallel to the metal matrix composites, composites of metal alloys without any enhances of ceramic particles or fibers also emerge to extend the capacity in this lightweight application. By constitutively integrating them, a particular property can be raised in this type of metal composites. By geometrically fastening them an innovative configuration of functions can be achieved as well [1].

This type of metal composites can be manufactured explosively [2], by spraying [3], by rolling [4], or by friction-stir-welding [5], if they are made as sheet metals. On the other hand, if they are prepared as bulks in the shape of rods or profiles, they are produced by extrusion [6, 7], by friction welding, by compound forging, or by forged welding [8]. The metal composites fabricated by the above mentioned methods, the interface between metals is externally visible either on the ends or from the sides. Because of the limitation of the application of such type of metal composites, this study aims to investigate the feasibility to create core-shell type metal composite bulks, in which the core metal can be completely encapsulated by the shell metal, in order to spread out their applications.

Fig. 1 shows an extrusion process used in this study, which is one of manufacturing approaches making core-shell type metal composite bulks. The shell material is made as socket shape either by backward-extrusion of a metal rod or by drilling, plugged with the core metal, which keeps its rod shape, and then together put into the container for further forward-extrusion. The inner height of the socket shell is higher than that of the core rod, so that the material in the upper extended tube of the socket shell can be further formed and seal itself together to completely encapsulate the core material after extrusion. Thus a bury type of metal composite bulks without showing any interface externally can be created.

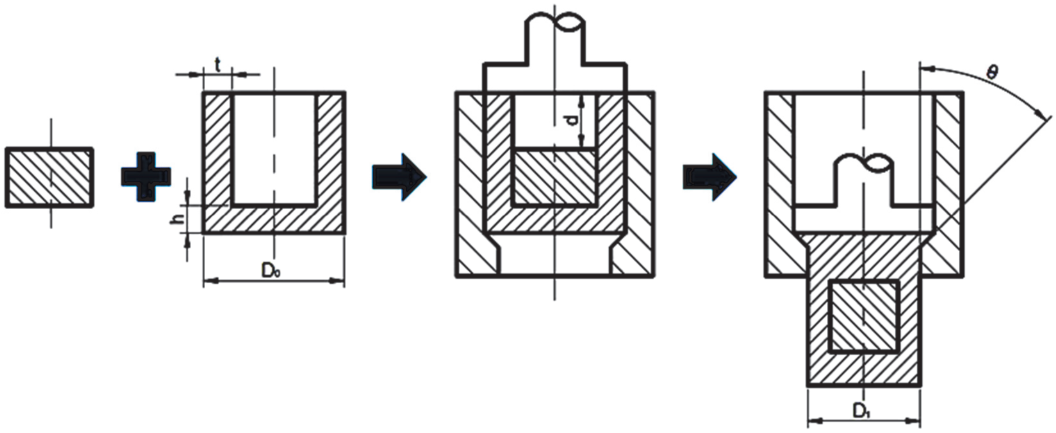


Fig. 1 Process using extrusion to make core-shell type metal composite bulks

2. STUDY SETUPS

To get rid of residual stress and cracks around the interface of the composite bulks during cooling by choosing materials with comparable coefficients of thermal expansion, this study utilizes aluminum alloy 6061 for the socket shell and 7075 for the core rod, so that the investigation on the feasibility of the process suggested by this study can be determined.

To simplify the process determining the geometry of the raw materials for this study, the extrusion stroke is set the same as the height of the socket shell. Besides, the tube thickness t, the bottom height h, the diameter D_0, and the total height of the socket shell are fixed for the study. That means that the geometry of the socket shell is completely given. Furthermore, under a homogeneous deformation assumption and under the consideration that the height above the core rod is the same as the height below it after extrusion and cutting off the top truncated cone portion of the composite (referring to the right most picture in **Fig. 1**), the parameters determining the geometry of the raw materials can then be reduced as the area reduction ratio R and the half angle of the extrusion die θ. Thus for the study, the socket shell has diameter D_0 in 16 mm, total height in 16 mm, bottom height h in 3 mm, and tube thickness t in 3 mm, while the core rod has diameter in 10 mm and total height determined by the distance d between the ends of the two raw materials as follows:

$$d = \frac{D_0^2}{4t(1+t)}\left[6h\tan\theta + D_0\left(1-\sqrt{R^3}\right)\right], \tag{1}$$

where the area reduction ratio R is defined with the part diameter D_1 after extrusion as

$$R = \frac{D_1^2}{D_0^2}\,. \tag{2}$$

2.1 Taguchi method of orthogonal array

To get a glimpse of the process parameters working on encapsulating the core rod by the socket shell, the Taguchi method is used in this study. For this purpose, an L_9 (3^4) orthogonal array according Taguchi method is chosen to investigate the influence of the four primary factors of the process - area reduction ratio, die angle, die radius, and working temperature - respectively with three setting levels on the top end shutting of its socket shell metal after extrusion, so that the feasibility of the bury type of metal composite bulks by using extrusion can be examined preliminarily. **Table 1** lists the factor settings for each experiment according Taguchi method of orthogonal array L_9 (3^4). As shown in **Table 1**, the levels for working temperature are set as 450 °C, 400 °C, and 500 °C; 0.44, 0.23, and 0.61 for area reduction ratio; 0.5 mm, 0.4 mm, and 0.3 mm for die radius; and 45°, 30°, and 60° for half die angle, respectively.

According to the area reduction ratio R and the half die angel θ listed in **Table 1**, the die and the core rod can be prepared according eqs. (1) and (2). **Table 2** lists the important dimensions for the die and the core rod for each experiment.

Table 1 Factor settings of each experiment in Taguchi method of orthogonal array L_9 (3^4) for processing the core-shell type of metal composite bulks by using extrusion

experiment	factor			
	A area reduction ratio	B half die angle [°]	C die radius [mm]	D working temperature [°c]
1	0.44	45	0.5	450
2	0.44	30	0.4	400
3	0.44	60	0.3	500
4	0.23	45	0.4	500
5	0.23	30	0.3	450
6	0.23	60	0.5	400
7	0.61	45	0.3	400
8	0.61	30	0.5	500
9	0.61	60	0.4	450

Table 2 Dimensions for the die and the core rod prepared for each experiment listed in **Table 1**

experiment	extrusion diameter D_1 [mm]	half die angle θ [°]	distance d [mm]	core rod height [mm]
1	12	45	6.86	6.14
2	12	30	8.71	4.29
3	12	60	5.79	7.21
4	14	45	7.33	5.67
5	14	30	8.39	4.61
6	14	60	6.72	6.28
7	10	45	6.31	6.69
8	10	30	8.73	4.27
9	10	60	4.92	8.08

2.2 Modeling for Finite Element Analysis

According to the setups listed in **Table 1** and **Table 2**, nine rotation-symmetric models for finite element analysis are created and executed in an isothermal state with a commercial code DEFORM. The constitutive model of the shell alloy 7075 and the core alloy 6061 is set as rigid-plastic and directly taken from the software database, while the extrusion die is set as rigid. A shear friction factor is defined as 0.3 between the shell alloy and the die and 0.4 between the alloys. The socket shell has about 5000 elements, while the core rod has 2500 elements. Total 1000 steps are set for the stroke of 16 mm within 1000 s.

2.3 Experiment setup

To execute extrusion experiments encapsulating the core rod into the socket shell, six diverse dies for larger area reduction are chosen from **Table 2** to be made and later separately assembled along with plunger, container, and attachments such as heating chamber, cooling system, and flanges onto a material testing machine as shown in **Fig. 2**. The shells and cores are turned from 7075 and 6061 rods, respectively. The inner blind holes of the socket shells are further drilled directly. The core rod is inserted into the socket shell, then together put into the container. After closing the heating chamber, the materials along with the complete die set are heated. Once the working temperature is reached for a while, the ram comes with the plunger downwards for the extrusion stroke at a ram speed of 0.96 mm/min. At its bottom dead center, the ram together with the plunger returns its top dead center. Then the heating chamber is wide open in order to eject the extruded composite without difficulty.

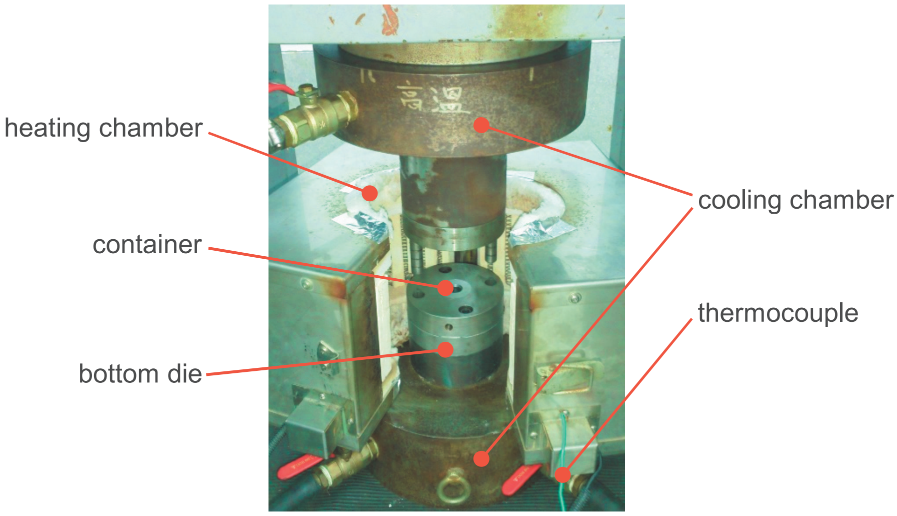


Fig. 2 Experiement setup for process using extrusion to make core-shell type metal composite bulks

3. RESULTS AND DISCUSSION

3.1 Finite element analysis results regarding Taguchi method

The quality loss function for this study is regarding the opening of the socket shell top end metal after extrusion, which is therefore a Smaller-the-Better characteristic. The Signal-to-Noise ratio (S/N) η is thus defined with the unit of dB as:

$$\eta = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} e_i\right), \tag{3}$$

where e_i is the opening measured at time i within total n times. In this study the opening is measured totally three times and each read from the top, the middle and the bottom of the opening. **Table 3** shows the opening read from finite element analysis and η for each setup according **Table 1**. It can be found in **Table 3** that the setup of experiment number 9 with a area reduction ratio in 0.61, a half die angle in 60°, a die radius in 0.4 mm, and a working temperature at 450 °C, can achieve a minimum opening as small as 0.01 mm at the top end of shell metal. That means that it is feasible to make a metal composite bulk in a core-shell type by an extrusion process with such settings.

The corresponding effect for each level set to the factors can be calculated accordingly as shown in **Table 4**, in which the total effect and the rank of the factors to the top end shutting of its socket shell metal after extrusion are shown as well. According the rank, it can be found that the area reduction and the die angle are the two most important factors to the top end shutting of its shell metal, while the corner radius practically has no effect. With the level having the highest effect, which is printed in bold font in **Table 4**, i.e. with a high area reduction ratio 0.61, a high half die angle 60°, a moderate die radius 0.4 mm, and at a high working temperature 450 °C, which are the same settings for the experiment number 9 listed in **Table 1**, a minimum opening at the top end of shell metal can be achieved.

Table 3 Opening read from finite element analysis and their S/N for each experiment listed in **Table 1**

experiment	opening top [mm]	opening middle [mm]	opening bottom [mm]	Signal-to-Noise ratio η [dB]
1	0.64	0.73	2.60	-4.10
2	1.56	1.33	6.53	-11.94
3	0.33	0.26	1.69	-0.05
4	3.21	3.65	6.46	-13.38
5	4.83	4.87	7.58	-15.42
6	2.95	3.34	7.78	-14.28
7	0.16	0.05	2.69	-3.84
8	0.42	0.08	1.53	0.75
9	0.01	0.02	0.69	7.99

Table 4 Effect of each factor setting defined in **Table 1**

level	factor							
	A area reduction ratio		B half die angle		C die radius		D working temperature	
	[-]	effect [dB]	[°]	effect [dB]	[mm]	effect [dB]	[°c]	effect [dB]
1	0.44	0.67	45	-1.08	0.5	0.15	**450**	**2.12**
2	0.23	-8.33	30	-2.84	**0.4**	**0.25**	400	-3.99
3	**0.61**	**7.66**	**60**	**3.92**	0.3	-0.41	500	1.80
effect		15.99		6.76		0.66		5.79
rank	1		2		4		3	

3.2 Experiment results vs. finite element analysis results

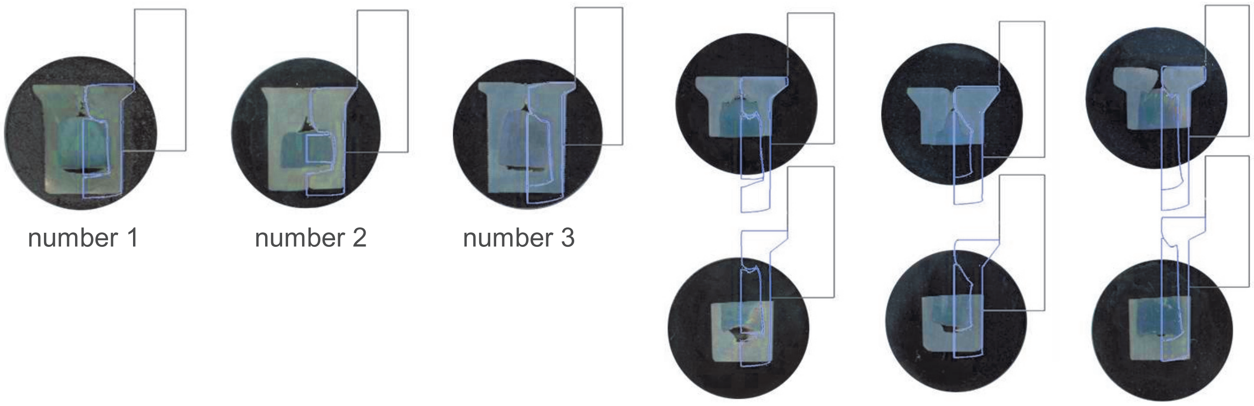
Six of nine setups listed in **Table 1** with higher area reduction are executed experimentally. They are the experiments with number 1, 2, 3, 7, 8, and 9, where those with number 1, 2 and 3 have an area reduction in 0.44, while those with number 7, 8, and 9 have 0.61. **Fig. 3** shows the cross-sections cut from the specimens experimentally extruded in comparison with the finite element analysis results, even though the ram stroke did not travel fully in some experiments. It still can be found that all the specimens have a small void on the interface around the top center of the core rod and some specimens have a split around the bottom of the core rod, while there is no separation identified on the side wall interface. Almost all the specimens expect that from experiment number 9 can have a complete shutting at the top end of shell metal. The homogeneous deformation previously assumed can be proven from the results that only little relative displacement of the materials is found around the interface. Even those voids and splits found in the metal composite bulks, they might be eliminated during the subsequent hot workings by firmly bonding them via thermomechanical processing. It is another evidence of the feasibility using hot extrusion to make a metal composite bulk in a core-shell type.

CONCLUSION

This study has proposed using hot extrusion to make core-shell type of metal composite bulks, in which a core rod metal is inserted into a socket shell metal and together extruded at a high working temperature to have core-shell type of metal composite bulk by means of shutting the end tube wall of the socket shell to encapsulate the core rod. Using aluminum alloy 6061 for the socket shell and 7075 for the core rod, this study has preliminarily investigated the process parameters by experiment and finite element analysis under Taguchi method and positively confirmed the feasibility of this process.

Within the four factors - area reduction ratio, die angle, die radius, and working temperature - chosen for this study, the area reduction and the die angle are the two most important ones for the top end shutting of its shell metal, while the corner radius practically has no effect. As a result, with a high area reduction ratio 0.61, a high half die angle 60°, a moderate die radius 0.4 mm, and a high working temperature 450 °C, a minimum opening about 0.01 mm at the top end of shell metal can be achieved.

Even a small void left on the interface around the top center and a split around the bottom of the core rod can be found after extrusion, they might be eliminated during the subsequent hot workings by firmly bonding them via thermomechanical processing. The side interface has no separation identified during this process. Before further implementing such core-shell type metal composite bulks in application, plenty of study works still need to be involved to improve the process achieving a perfect interface bonding and to understand their application properties confidently.



number 1 number 2 number 3

number 7 number 8 number 9

Fig. 3 Cross-section from selected experiements and finite element analysis

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