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Experimental and numerical study on micro deep drawing with aluminium-copper composite material

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Abstract

Micro forming is a promising technology with the trend towards miniaturisation in industry, and micro deep drawing (MMD) process is a fundamental micro forming method with potential applications in forming of cups, hollows and boxes and has great advantages comparing to other micro manufacturing methods. As the preferred material for electrical conductors, aluminium (Al)-copper (Cu) composite material processes advantages of the low density and cost of aluminium and good conductivity of copper. In this paper, MMD has been studied experimentally and numerically with a purpose of understanding the deformation behaviour of a two-layer Al-Cu composite in microscale. Al-Cu composite material was rolled to 50 μm in thickness and then annealed at 400 ºC. The drawability of the annealed composite was investigated by MDD experiments. FE models with Voronoi tessellations were established to simulate the Al-Cu composite material during MDD process. Considering the grain heterogeneity, each Voronoi tessellation has been assigned with different mechanical properties based on experimental data. The simulation results are in good agreement with the experiment ones.

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Experimental and numerical study on micro deep drawing with aluminium-copper composite material

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Abstract

Micro forming is a promising technology with the trend towards miniaturisation in industry, and micro deep drawing (MMD) process is a fundamental micro forming method with potential applications in forming of cups, hollows and boxes and has great advantages comparing to other micro manufacturing methods. As the preferred material for electrical conductors, aluminium (Al)-copper (Cu) composite material processes advantages of the low density and cost of aluminium and good conductivity of copper. In this paper, MMD has been studied experimentally and numerically with a purpose of understanding the deformation behaviour of a two-layer Al-Cu composite in microscale. Al-Cu composite material was rolled to 50 µm in thickness and then annealed at 400 ºC. The drawability of the annealed composite was investigated by MDD experiments. FE models with Voronoi tessellations were established to simulate the Al-Cu composite material during MDD process. Considering the grain heterogeneity, each Voronoi tessellation has been assigned with different mechanical properties based on experimental data. The simulation results are in good agreement with the experiment ones.

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Keywords: Micro deep drawing; Al-Cu composite material; Voronoi; FEM

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1. Introduction

With the trend of miniaturisation in fields of electronics, bio-medical, automobile and aerospace, micro forming has been considered as a promising process to fabricate metallic micro parts. Traditional technologies, including micromachining, micro wire EDM and lithographic technologies are commonly used to manufacture microcomponents with high precision, but they are constrained by the high costs and limited material types [1]. Among the micromanufacturing processes, plastic micro forming processes advantages of high productivity, low production cost, high product quality, and less pollution. The principles and theory of micro-forming are based on the micro-scale plastic deformation analysis. Even though the material properties, including flow behaviour, formability, fracture behaviour and friction in conventional plastic deformation processing have been well understood, they cannot be applied directly to micro-scale deformation processes, because the emergence of the so called size effect impedes the direct transfer of methodology for macro-scale [2, 3].

Metal composites are obtained popularity because lots of industries rely in them on providing cheaper, lighter, and stronger alternatives [4]. Laminated composite materials provide customisable materials for specific applications requiring high impact and fracture resistance. Copper (Cu) and aluminium (Al) composite materials are the preferred material for electrical conductors [5]. The material costs are much lower relative to Al and Cu has good conductivity. Therefore, the Al-Cu composite material can take advantages of the low density and cost of Al and good conductivity of Cu [6]. So, micro parts made of Al-Cu composite will have a promising application in electronic industry, although these are few researches on composite material in microforming process currently.

In this research, pure Cu and pure Al were used as the two-layer composite material for MDD experiments. In order to improve the drawability of the formed part, heat treatment was conducted before experiments. A combined blanking-drawing process was adopted in MDD experiment. Further, a finite element (FE) model of MDD process with Al-Cu material was developed by applying continuum shell element to simulate the deep drawing process. In the FE model, Voronoi diagram was introduced to represent the grains of the composite materials in order to address the size effects of blank in microforming. Voronoi structures can characterise material properties in microscale owing to the similarity between their geometrical features and material's microstructures. In microforming simulation, each Voronoi tessellation represents one grain with its own properties, and accurate results can be obtained [7-9].

2. Experimental

2.1. Micro Rolling

The as-received Al-Cu composite blanks which were manufactured by hot rolling were 235 μm in thickness (82% for aluminium and 18% for copper). The original composite blanks were cold rolled at room temperature to achieve a final thickness of 50 μm in order to the match the specification of die set in microforming. The thickness of Al-Cu composite is reduced by micro rolling with four passes as shown in Fig. 1. The appearance of Al-Cu composite material and its cross-sectional morphology after each pass are shown in Fig. 2. The thickness after rolling, reduction in each pass and rolling force were recorded in micro rolling, and their values are listed in Table 1.

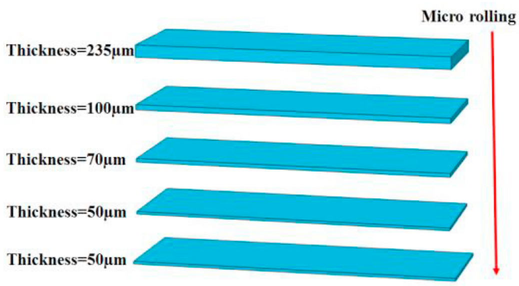

Fig. 1. Schematic of micro rolling process.

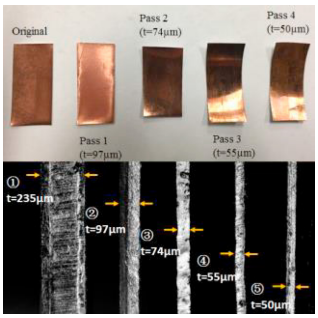

Fig. 2. Cross-sectional morphology of the Al-Cu composite at each pass.

Table 1. Data obtained from each step of micro rolling process.

Steps	Thickness before rolling (μm)	Ideal thickness after rolling (μm)	Real thickness after rolling (μm)	Reduction (%)	Rolling force (N)
Pass 1	235	100	97	58.7	6500
Pass 2	97	70	74	30	4000
Pass 3	74	50	55	23.7	2000
Pass 4	55	50	50	9.1	1500

2.2. Heat treatment

The Al-Cu composite blanks with thickness of 50 μm (about 40 μm for Al and 10 μm for Cu) were heat-treated at 400 ºC for 2 minutes under argon gas protection ambience. After heat treatment, the microstructure of the blanks was observed under a digital microscope, and the grain sizes of both materials were obtained, as shown in Fig. 3. Because the thickness of Cu layer is smaller than the grain size, only the microstructure of the specimen along rolling-transverse direction (RT) is illustrated. It can be seen that, the grain size of Al is much more even than that of copper. The average grain sizes of Al and Cu are 25 μm and 120 μm respectively.

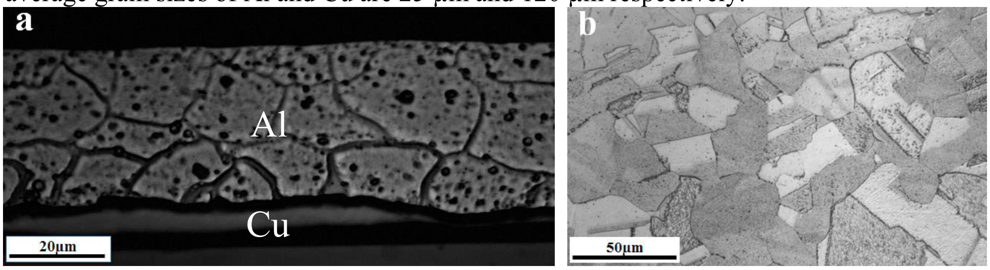

Fig. 3.Microstructures of (a) Al and (b) Cu annealed at 400 ºC: (a) cross-section (b) RT.

2.3. Micro deep drawing experiments

MDD experiments were conducted on a Desk-top servo press machine DT-3AW, as shown in Fig. 4, and the key parameters of the machine and process are listed in Table 2. During drawing process, the drawing force was recorded and exported to a computer for further analysis. Also, lubricant was used between the blank and the die in MDD process to reduce the friction and improve the drawability. In this research, copper was placed as the upper layer of the blank, due to the less fraction of copper in Al-Cu composite. Fig.5 shows the formed part which was observed by t digital microscope. From three views of observation, it can be seen that the part was formed with no fracture and fewer wrinkles.

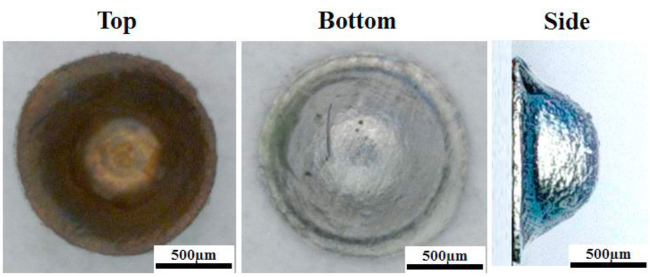

Fig. 4. Desk-top servo press machine DT-3AW.

Fig. 5. Observation of the formed part by digital microscope.

Table 2. Parameters of Desk-top servo press machine DT-3AW and process.

Punch diameter (mm)	Die diameter (mm)	Radius of punch fillet (mm)	Radius of die fillet (mm)	Drawing speed (mm/s)	Initial blank diameter (mm)
0.8	0.975	0.3	0.3	0.1	1.6

Five experiments were repeated under the same processing condition, and the average drawing forces were obtained, as shown in Fig. 6. In the beginning of the process, the resistance of bending is dominant, which results in a rather slow increasing rate of drawing force initially. As the process continues, the large deformation causes high flow stress, and also the friction increases with the increase of contact forces. So the drawing forces rises significantly in the following period.

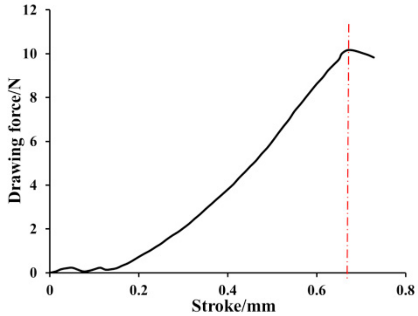

Fig. 6. Mean drawing force of micro deep drawing.

3. Simulation

FE model of MDD with Al-Cu composite material was established by using ABAQUS. Fig. 7 shows the assembly model of MMD in ABAQUS. A quarter of the blank model was created in order to reduce the computational time and improve the calculation efficiency. All the parameters used in this model were the same as those obtained in experiments. The mean mechanical properties of the annealed Al-Cu are shown in Table 3.

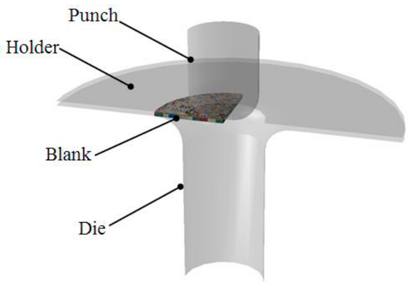

Fig. 7. Assembly model of MDD in ABAQUS.

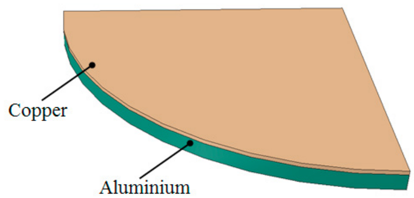

Fig. 8. Blank model of aluminium-copper material.

Table 3. Mean mechanical properties of annealed Al-Cu composite material.

Material	Elastic modulus /GPa	Poisson's ratio	Yield strength/MPa	Tensile strength/MPa
Copper	79.3	0.33	70.6	211.5
Aluminium	110	0.3	34.9	136.2

In the FE model, the blank was regarded as a deformable part with continuum shell element while the other parts were analytic rigid. Continuum shell elements (SC8R) are three-dimensional stress/displacement elements for use in modeling structures that are generally slender, with a shell like response but the continuum element topology. Compared with conventional shell elements, the continuum shell elements have geometical structure in thickness, more accurate contact modeling which includes two-sided contact and the same analysis efficiency. As for the Al-

Cu composite, the model of blank was divided into two layers for both materials, as shown in Fig. 8. In order to compare the simulation results of Voronoi model and non-Voronoi model, two kinds of blank model were built as shown in Fig. 9. For the Voronoi model, each cell represents one grain which has the similar size to the real grains size of the blank. The simulation precision will be improved if a high mesh quality is obtained. For this purpose, a centroidal Voronoi has been developed in order to eliminate short edges and small facets. Fig. 9 shows the Voronoi tessellations model of Al-Cu composite blank which was created based on the real grain size. For this Voronoi model, all the tessellations were classified into five groups, and each group had its own material parameters. Each colour in the Voronoi model indicates one tessellations group. Further, different contact friction coefficients were set for different surfaces according to the real contact properties. The friction coefficients used were 0.3 for punch-blank contact, 0.05 for both die-blank and holder-blank contract. From Fig. 9, the contours of equivalent plastic strain are more uniform in non-Voronoi model than those in Voronoi model, because different mechanical properties have been embedded in different Voronoi cells in Voronoi model, which is more close to the real conditions.

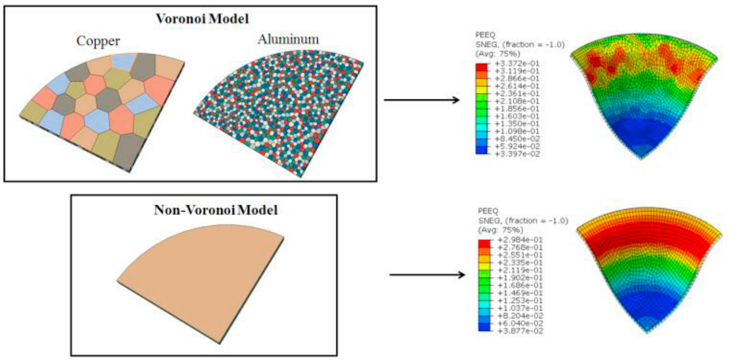

Fig. 9. Voronoi and non-Voronoi model of blank.

4. Comparison

Simulation and experiment results are compared in this section. The drawing forces obtained from both experiment and simulation are illustrated in Fig. 10. It can be seen that the drawing forces from numerical simulation have the similar trend and with those from experiments, although there is a small difference of the strokes when the forces reach the peak values. For the two FE models, the force-stroke curves have the same trend initially and then achieve the maximum force at the same stroke of 0.62mm. As the material parameters used in Voronoi model were from different material properties and that in non-Voronoi model was from the mean value. For Voronoi model, the overall effects of different cell properties on drawing force are balanced resulting a close value to that in non-Voronoi model, although different areas on the blank has different material properties in the Voronoi model. Because flow stress in some cells are higher than the mean values, peak force in Voronoi model is greater than that in the non-Voronoi model, which is also close to the experimental result.

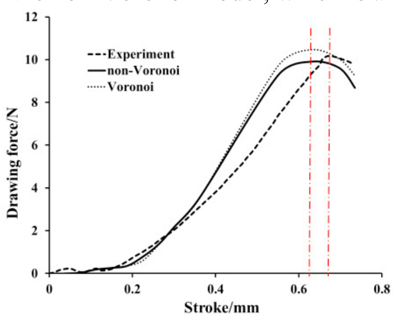

Fig. 10. Draw forces of experiment and simulation results.

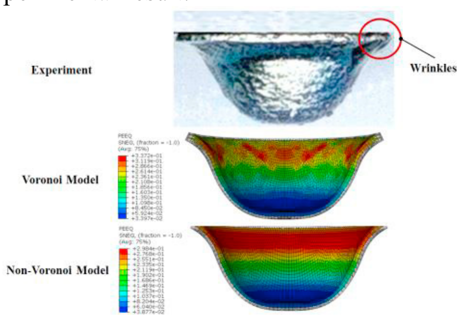

Fig. 11. Formed parts in experiment and simulation.

Fig. 11 shows the formed parts by experiment and the contours of equivalent plastic strain in simulation. The drawability and defects of the formed parts in experiments and FE simulation are compared by the wall thickness, cup mouth radius, and flange height at the cup mouth as presented in Table 4. The average wall thickness at the mouth cup is close for both experimental and simulation results. The difference between the maximum radius and the minimum radius can be defined as the judgement of the wrinkles. Wrinkles appear because a limited number of grains on the thickness section decrease the formability, and the compression stability on the flange is weak. So, more wrinkles are needed to compensate the compression instability. For the non-Voronoi model, the radius is quite even, meanwhile, there are more wrinkles in the Voronoi model which is similar to the experimental results. Also, the flange height of the formed part by experiment is also greater than those by FE simulation. In general, the result of Voronoi model is more close to the real experimental results than that of the conventional model.

Table 4. Comparison of drawability between experimental and simulation results.

Parameters	Experiment	Non-Voronoi model	Voronoi model	Error	
				Non-Voronoi model	Voronoi model
Average wall thickness at cup mouth/μm	55.32	54.18	54.195	2.06%	2.03%
Maximum radius/μm	692.32	689.97	692.42	0.34%	0.05%
Minimum radius/μm	686.51	689.17	688.40	0.39%	0.28%
Flange height/μm	52.39	51.10	52.65	2.46%	0.5%

5. Conclusion

Micro parts with two-layer Al-Cu composite material annealed at 400 ºC can be formed with MMD process, and the formed cup shows no fracture and fewer wrinkles.

Grain sizes of both Al and Cu can be embedded onto Voronoi model to improve the accuracy of FE simulation. By comparison, the result of FE model with Voronoi diagram is more close to the experimental result in terms of drawing force, drawability (wall thickness of cup mouth, cup mouth radius and flange height) and wrinkles.

Acknowledgements

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