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Micro forming of metallic composites

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Abstract

As the popularisation of electronical devices, the development of micro systems has attracted the attention of the researchers. Therefore, it is crucial to identify the effects of relevant parameters in micro forming process. This study mainly focuses on the impact of holding time in heat treatment process on the properties of Cu-Al-Cu laminate composite materials during micro deep drawing process. The results demonstrate that the Cu-Al-Cu laminate composite material that experiences 10-minute holding time can obtain better properties. Furthermore, a simulation model of the micro forming process is developed and the simulation results are compared with the experimental ones.

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Micro forming of metallic composites

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Abstract

As the popularisation of electronical devices, the development of micro systems has attracted the attention of the researchers. Therefore, it is crucial to identify the effects of relevant parameters in micro forming process. This study mainly focuses on the impact of holding time in heat treatment process on the properties of Cu-Al-Cu laminate composite materials during micro deep drawing process. The results demonstrate that the Cu-Al-Cu laminate composite material that experiences 10-minute holding time can obtain better properties. Furthermore, a simulation model of the micro forming process is developed and the simulation results are compared with the experimental ones.

Peer-review under responsibility of the scientific committee of the 17th International Conference on Metal Forming.

Keywords: Micro forming; Micro deep drawing; Composite; Heat treatment

1. Introduction

Nowadays, the application of micro products, especially electronical devices, spreads the whole world. Due to the significant increasing demand of micro-parts, the development of micro systems has been stimulated during last few

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decades [1-3]. Compared with conventional macro-forming products, micro components stand for higher production while the consumption of resources and energy can be saved. Because of the saved cost of micro forming process and high versatility and mobility of micro products, micro forming has a great potential in manufacture industry [2, 4]. However, the technology of micro forming process is not as mature as macro forming process [4]. Hence, it is part and parcel to develop a more mature micro forming method, which should be supported by specific parameters.

Although, micro components have significant advantages, barrier still exists in micro manufacture process due to size effects [5, 6]. Xu et al. [7] found that the grain size is the crucial factor which means the limiting size of geometrical properties can be determined by grain size. The geometrical properties not only can be affected by grain diameters, but also be determined by the thickness of materials, lubrication, chamfer and surface roughness [8, 9]. To obtain micro products with high precision, researchers have tried various methods, such as the laser shock, activated sintering technology and micro deep drawing method [10-12]. No matter which kind of method, simulation process plays an important role in micro forming industry because of its high accuracy performance and low cost.

Friction behaviour is a crucial factor to size effects. In addition to the grain structure of materials, other factors such as the coatings of die and various lubricants are essential as well, which can affect material friction behaviour significantly [13]. Normally, the size effect can be categorised into two aspects which are the size effects of first and second orders. The former one mainly represents the size effects caused by the discrete granular anisotropic nature of microstructures and the latter one stands for the strengthening effect caused by the plastic deformation of inhomogeneity [1, 14]. Currently, most researchers focus on the impacts of grain size, feature size and specimen dimensions to investigate the size effect at micro-scale.

The most common products of micro deep drawing are micro cylinder cups, micro rectangular cups, micro conical cups, and micro spherical cups [15]. Although, the micro deep drawing has so many merits, as one of the most important micro forming methods, it has to face the challenges from size effects as well [16]. In order to investigate the differences of deep drawing between micro and macro scale, Vollertsen et al. [17] tested the forming performances. The punch diameter is 1 mm with a radius of 0.19 mm. Two different foil materials are tested in this experiment, which are Al 99.5 foil and 1.0335 foil (German standards). Moreover, the thickness for the two foils are 0.02 mm and 0.025 mm respectively. The blank holder force cannot be applied precisely when the scale reduces to micro level. The size of the punch and the blank is the biggest barrier for the precision control. Furthermore, the punch and the die need to keep moving during the process, therefore, the blank holder force cannot be controlled by friction force. Compared with macro deep drawing, the friction force at the ratio of forming force in micro deep drawing is obviously higher. Inappropriate blank holder force may lead to wrinkles on the flange. In addition, cracks can also be observed on the bottom area.

As the rapid development of manufacture technology, single-component materials cannot reach the requirement of fabrication. Hence, composite material plays a crucial role in modern industry field. In addition, due to the limited quantity of copper resources, the high price becomes a significant barrier to spread the application in the communications and electric conduction industries. The weight of Cu-Al composite material may be only half of the weight of pure Cu. Yet, some key properties are similar with copper alloys. On the other hand, Cu-Al composite material also has an excellent performance comparing with pure Al. The strength and solderability of Cu-Al clad composite are much higher than that of pure aluminium. In addition, the electrical connection of Cu-Al composite material is more reliable than any Al alloys. Cu-Al composite material as a perfect substitution for pure copper and pure aluminium, thus, has attracted a great attention nowadays [18].

According to the research [19], heat treatment can cause the atom diffusion reaction which appears at the interface. Furthermore, the diffusion of Ti/ steel can affect the hardness of the composite. Moreover, according to Jana et al. [20], the grain size can grow as the increase of both the heating temperature and time. In addition, Hsieh et al. [21] found that the growth of interphases in Al/Cu composites is related to the annealing temperatures and rolling cycles. Therefore, a proper heat treatment for composite materials is required in fabrication industry.

Compared with pure metal, Cu-Al composites perform higher mechanical properties, such as low density, high thermal and electrical conductivity. Moreover, as an important industry material, the competitive price is another feature of Cu-Al composites [22-24]. Therefore, it can attract the attention from researchers and engineers. In addition to that the weight of Cu-Al clad composite is only 50%-65% of copper alloy [25].

To conclude, micro forming industry is a burgeoning industry. However, as a new developing technology, micro forming is also facing many barriers. Therefore, it is necessary to improve the quality of micro forming product. This research investigates the micro forming performance of Cu-Al-Cu clad composite material. To gain accurate results, both experimental and Finite Element Method simulation have been used in this study, which mainly focus on the heat treatment impact on the quality of micro deep drawn products.

2. Experiment and simulation

2.1. Experiment

This heat treatment experiment applies annealing method to improve the mechanical property of the specimens. Moreover, electrical conductivity can be improved as well through heat treatment which needs to heat the material in the first period, then cool down at a specific rate to obtain a refined microstructure.

Cu-Al-Cu laminate composite material is applied as the testing material. The percentage of each layer of Cu-Al-Cu clad composite material is 10, 80 and 10% respectively. Normally the range of the annealing temperature for aluminium and aluminium alloy is 300-450 ℃ which depends on the type of the alloy, and the annealing temperature for copper is 350-650 ℃. Therefore, with the consideration of the two ranges of temperature mentioned above, the heating temperature is set at 400 ℃ and heating speed is 10 ℃/min with total heating time of 40 min. To investigate the impact of holding time on mechanical properties of Cu-Al-Cu composite material, the holding times are set as five groups: 2, 5, 10, 60 and 120 min, respectively (Table 1), and then the materials are cooled down to the room temperature gradually.

Table 1. Heat treatment conditions.

Group	Heating temperature (℃)	Heating speed (℃/min)	Holding time (min)
1	400	10	2
2	400	10	5
3	400	10	10
4	400	10	60
5	400	10	120

This experiment aims to figure out the performance of micro deep drawing. The results are illustrated by the quality of the micro formed cup. Moreover, the micro deep drawing process contains four steps which are reducing the gap between the rigid punch and the specimen surface quickly, decreasing the punch speed to 0.1 mm/s, keeping the punch speed and obtaining the micro formed cup.

2.2. Finite element analysis

The geometry section can set the material that each component needs to be applied. In this study, each component uses structural steel as the assignment material except the material sheet that needs to use specific material based on the experimental results. In addition, the models of the simulation are built via Solidworks and the simulation process is conducted by ANSYS. The simulation uses transient structural section in the ANSYS, which is based on the implicit method.

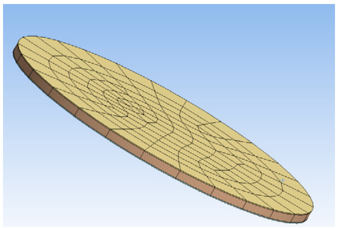

Fig. 1. Mesh model of tri-layer clad specimen.

Fig. 1 shows the mesh mesh model of the tri-layer clad specimen. In order to save the simulation time, the initial position of the punch is set to contact with the surface of the forming sheet.

Table 2. ANSYS setting parameters.

Friction coefficient of material sheet to lower die	Friction coefficient of material sheet to blank holder	Friction coefficient of material sheet to punch	Number of steps	Current step number	Step end time	Initial time step
0.1	0.1	0.3	1	1	6 s	0.2 s
Minimum time step	Maximum time step	Velocity of the punch				
0.05 s	0.4 s	0.1 mm/s				

Next, contact regions under connections section need to be set. There are three contact regions in the analysis process, which are material sheet and lower die, material sheet and blank holder and material sheet and punch. Furthermore, it is important to select the right contact and target areas, otherwise, it can lead to significant fail in final solutions. To be specific, the material sheet needs to be set as a contact area in each contact region group, and the other part should be set as a target area. Other relevant parameters are shown in Table 2.

As the cups of 10-min group have the best quality obtained, their relevant material parameters which are shown in Table 3 are chosen for the simulation process.

Table 3. Material parameters.

	Cu		Al	
Density	8900 km/m^3		2700 kg/m^3	
Young's modulus	110000 MPa		79300 MPa	
Poisson's ratio	0.33		0.3	
Plastic strain	0	0.15	0	0.088
Yield stress	70 MPa	210 MPa	35 MPa	136 MPa

3. Results and Discussion

3.1. Drawing force-stroke curves

Fig. 2 shows the trend of drawing force with the increase of the stroke for the five experimental groups.

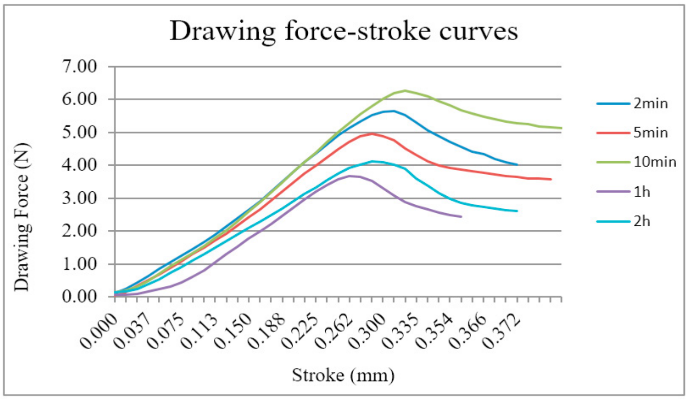

Fig. 2. Drawing force-stroke curves.

In the beginning of the process, the resistance of bending is dominant, which results in a rather slow increasing rate of drawing force initially. However, the five curves ascend significantly as the process continues, which mainly attribute to the high flow stress that caused by the large deformation. The friction increases with the increase of contact forces. Then, each of the five curves rises to the peak of the curves which are 5.64 N, 4.96 N, 6.25 N, 3.68 N and 4.11 N for 2 min, 5 min, 10 min, 1 h and 2 h holding times of heat treatment respectively. Finally, the curves fall immediately after reaching to the peak. In general, the five curves have the same change trend. Nevertheless, the 10 min curve is the highest one among the five curves. The 2 min-curve is slightly higher than that of the 5 min curve. Moreover, the 1 h curve and 2 h curve are quite similar which are obviously lower than that of the other three curves. This phenomenon is due to the different holding times of heat treatment that can finally lead to the various strength caused by the different growth styles of grains.

3.2. Depth of forming cups

Fig. 3 shows the depths of the cups that formed in each control group. According to the picture, the material that experiences 10 min holding time in the heat treatment process not only performs an excellent strength, but also shows a good plasticity. Moreover, although the cup formed in the 2 min group shows a good strength (as shown in Fig. 3(a)), it has the worst plasticity among the five cups whose cup depth is only 390.8 μm.

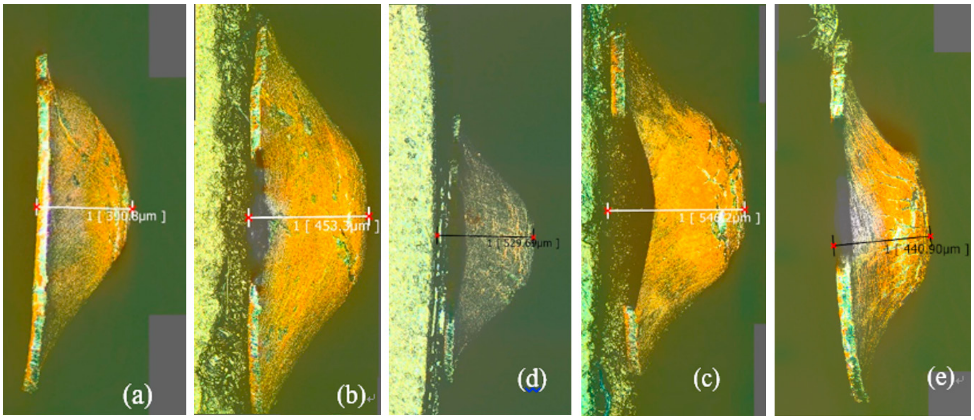

Fig. 3. Depth of the formed cups of (a) 2 min group-390.8 μm , (b) 5 min group-453.3 μm, (c) 10 min group-529.6 μm, (d) 1 h group-546.2 μm and (e) 2 h group-440.9 μm.

3.3. Quality of formed cups

Fig. 4 reveals the shape of micro cups via highlight measurement. The shape, especially the rim conditions of the formed cups can be clearly observed using the images. It can be seen that the cups of 2 min group, 5 min group, 10 min group and 1 h group have similar rim conditions. However, the rim condition of the cup of 2 h group is the worst compared with those of other groups. In addition, it can be observed that the cups of 1 h and 2 h groups exist the broken region. This phenomenon is relevant to the grain pattern, which will be discussed in the next section.

3.4. Surface of broken cups

Each group of the experiment contains five repeated individual tests. However, the quality of the cups that formed by micro deep drawing process cannot be totally the same. The main broken performances are shown in Fig. 5. According to the observation results from scanning electron microscope, the broken parts were usually occurred on the bottom of the cup. Furthermore, the breaches only occurred on one of the layers of the laminate composite material which is the copper layer. The holding time in heat treatment is the only variable in the experiment. Hence, Fig. 5 shows the impact of the holding time on the surface quality of the micro formed cups. It can be observed in Fig. 5(a)-

(c) that the cups of 2, 5 and 10 min groups show better surface quality, which have mere cracks on the bottom. However, Fig. 5(d) and (e) show that the damages on the bottom area of the cups of 1 and 2 h groups are more significant, which are shown in Fig. 4(d) and (e). This phenomenon may be due to the grain growth caused by the prolonged holding time in heat treatment process. As the gradual growth of grain, the interphase between each layer of the composite material increases. The increase of the interphase finally leads to the rise of brittleness of the forming material and the decrease of strength and formability. Furthermore, the interphase impact on plasticity is not as significant as the impact on the strength and formability of the material.

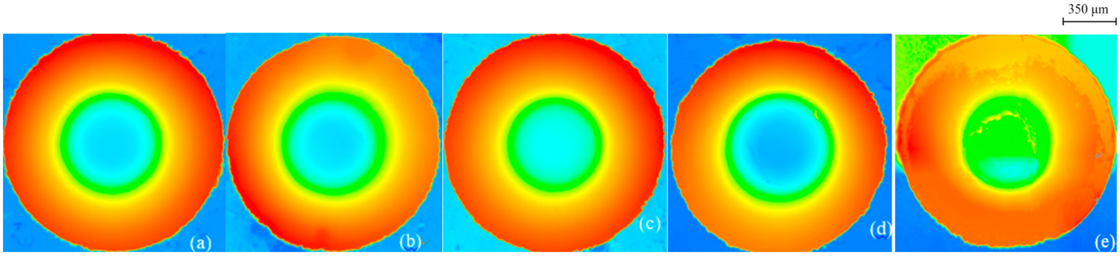

Fig. 4. Highlight images of micro cups of each group; (a) 2 min group; (b) 5 min group; (c) 10 min group; (d) 1 h group; (e) 2 h group.

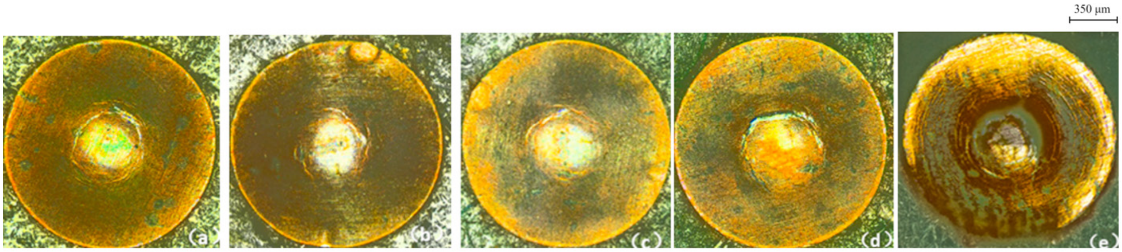

Fig. 5. Surface quality of the cup in (a) 2 min group, (b) 5 min group, (c) 10 min group, (d) 1 h group and (e) 2 h group.

3.5. Simulation results

Fig. 6 demonstrates the final results of force reaction simulation, which is obtained by ANSYS. The relevant data can be used to draw the drawing force- stroke curve of simulation.

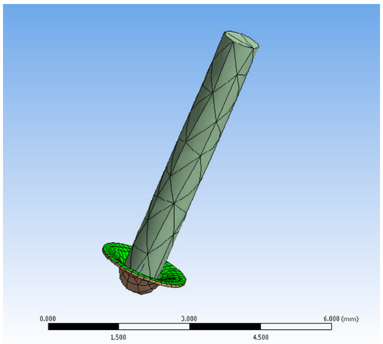

Fig. 6. Force reaction simulation result via ANSYS.

Fig. 7 shows the simulation curve obtained by ANSYS simulation. The comparison between the simulation and experimental results illustrates that the simulation values are higher than the experimental values. This is due to that the interfaces between each layer of the composite material can create special interphases. The interphase is produced due to the different properties of different materials, which can reduce the strength of the material. Although the simulation model is based on the Cu-Al-Cu laminate composite material with three layers, the properties of each layer are assigned independently. Therefore, the simulation values are higher without the consideration of the interphase impact.

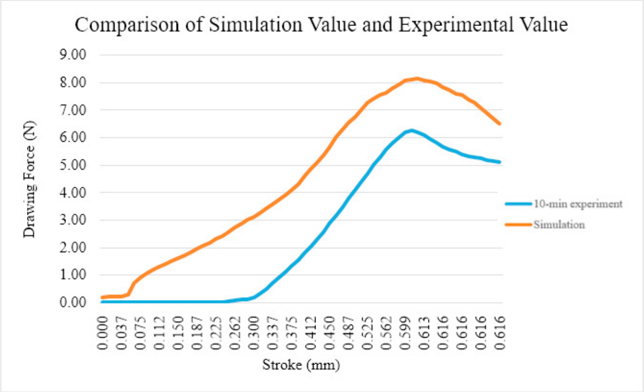

Fig. 7. Comparison between simulation and experimental values.

Fig. 8 compares the deformation image of the simulation cup and the cup depth of the 10 min group experiment. The deformation data obtained via ANSYS also reveals the plasticity of the composite material. The depth of the simulation cup is 583.37 µm. Therefore, the simulation result is acceptable compared with the experimental result 546.2 µm. The small gap between the experimental and simulation results proves again that the interphase impact on plasticity is not significant.

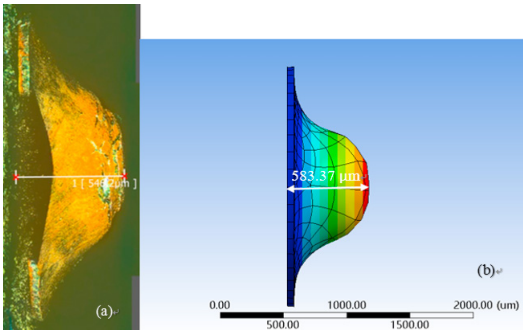

Fig. 8. Depths of (a) experimental and (b) simulated cups.

4. Conclusions

This study has investigated the formability of Cu-Al-Cu laminate composite material based on the micro deep drawing process. According to the analysis results of the experiments, different holding times of heat treatment can cause various forming performance of the composite material. The material that experiences 10 min holding time in heat treatment process can perform excellent properties in strength, plasticity and formability. Furthermore, the strength and plasticity can reach to a perfect balance point. The cups that experience long holding time of 1 h and 2 h show a poor performance of formability due to the growth of grain over time. In addition, the strength of both of the 1 h and 2 h groups are significant lower than that of other three groups. Moreover, this study also establishes a simulation model of the micro deep drawing process of composite material. Although there is a gap between the simulation results and the experimental results, the trend and relevant numbers are still close. Therefore, it can be confirmed that the developed finite element model is applicable.

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References

[1] H. Zhang, X. Dong, Physically based crystal plasticity FEM including geometrically necessary dislocations: numerical implementation and applications in micro-forming, Computational Materials Science, 110 (2015) 308–320.

[2] A.R. Razali, Y. Qin, A review on micro-manufacturing, micro-forming and their key issues, Procedia Engineering, 53 (2013) 665–672.

[3] H. Lu, D.B. Wei, Z.Y. Jiang, X.H. Liu, K.I. Manabe, Modelling of size effects in microforming processes with consideration of grained heterogeneity, Computational Materials Science, 77 (2013) 44–52.

[4] Y. Zhao, L. Luo, Z.Y. Jiang, X.M. Zhao, D. Wu, Study on simulation and experiment of micro sheet metal forming, Materials and Processes Technologies V, 941-944 (2014) 1876–1881.

[5] L. Luo, H. Xie, D. Wei, X. Wang, C. Zhou, Z. Jiang, A New micro scale FE model of crystalline materials in micro forming process, MATEC 1Web of Conferences, 80 (2016) 02002.

[6] T.T. Qiu, Y.K. Hou, H.L. Cao, Review of research progress on size effect in micro-forming, Key Engineering Materials, 717 (2017) 118–121.

[7] J. Xu, X. Zhu, L. Shi, D. Shan, B. Guo, T.G. Langdon, Micro-forming using ultrafine-grained aluminum processed by equal-channel angular pressing, Advanced Engineering Materials, 17-7 (2015) 1022–1033.

[8] C.C. Chen, Experimental study on formability of phosphor bronze thin sheet in micro bead forming process, International Journal of Advanced Manufacturing Technology, 84-9-12 (2016) 1897–1905.

[9] L. Luo, Z. Jiang, D. Wei, K. Manabe, D. Wu, T. Furushima, Effects of surface roughness on micro deep drawing of circular cups with consideration of size effects, Finite Elements in Analysis & Design, 111 (2015) 46–55.

[10] X. Wang, L. Li, Z. Shen, C. Sha, S. Gao, C. Li, X. Sun, Y. Ma, H. Liu, Experimental investigation on: laser shock micro-forming process using the mask and flexible pad, Optics and Lasers in Engineering, 88 (2017) 102–110.

[11] M. Wu, G. Yang, J. Liu, D. Yin, Y. Yang, Densification mechanism of copper micro-components prepared by the micro-forming fields activated sintering technology, Journal of Alloys and Compounds, 692 (2017) 434–439.

[12] L. Luo, Z. Jiang, D. Wei, Influences of micro-friction on surface finish in micro deep drawing of SUS304 cups, Wear, 374-375 (2017) 36–45.

[13] N. Takatsuji, K. Dohda, T. Funazuka, Influence of tribological condition on construction of minute parts in micro-meso extrusion of A6063 alloy, Advanced Materials Research, 966-967 (2014) 336–343.

[14] H. Liu, X. Sun, Z. Shen, C. Li, C. Sha, L. Li, S. Gao, Y. Ma, X. Wang, The size effect on deformation behavior in microscale laser shock flexible drawing, Optics and Laser Technology, 86 (2016) 93–102.

[15] F. Gong, Z. Yang, J. Yang, Q. Chen, D. Shu, Z. Xie, Influences of lubrication conditions and blank holder force on micro deep drawing of 1100 micro conical-cylindrical cup, Precision Engineering, 42 (2015) 224–230.

[16] L. Luo, Z. Jiang, H. Lu, D. Wei, K. Linghu, X. Zhao, D. Wu, Optimisation of size-controllable centroidal Voronoi tessellation for FEM simulation of micro forming processes, Procedia Engineering, 81 (2014) 2409–2414.

[17] F. Vollertsen, Z. Hu, H.S. Niehoff, C. Theiler, State of the art in micro forming and investigations into micro deep drawing, Journal of Materials Processing Technology, 151 (2004) 70–79.

[18] S. Chen, G. Chang, X. Yue, Q. Li, Solidification process and microstructure of transition layer of Cu-Al composite cast prepared by method of pouring molten aluminum, Transactions of Nonferrous Metals Society of China, 26 (2016) 2247–2256.

[19] X.G. Yuan, L. Lv, H.J. Huang, X.J. Zuo, H. Liu, Effect of diffusion heat treatment on thickness of cold-rolled Cu/Al composite laminate interface, Applied Mechanics and Materials, 310 (2013) 112–116.

[20] S. Jana, N. Overman, T. Varga, C. Lavender, V.V. Joshi, Phase transformation kinetics in rolled U-10 wt. % Mo foil: Effect of post-rolling heat treatment and prior γ-UMo grain size, Journal of Nuclear Materials, 496 (2017) 215–226.

[21] C.C. Hsieh, M.S. Shi, W. Wu, Growth of intermetallic phases in Al/Cu composites at various annealing temperatures during the ARB process, Metals and Materials International, 18 (2012) 1–6.

[22] M. Abbasi, A.K. Taheri, M.T. Salehi, Growth rate of intermetallic compounds in Al/Cu bimetal produced by cold roll welding process, Journal of Alloys and Compounds, 319 (2001) 233–241.

[23] T.T. Sasaki, R.A. Morris, G.B. Thompson, Y. Syarif, Y. Syarif, Formation of ultra-fine copper grains in copper-clad aluminum wire, Scripta Materialia, 63 (2010) 488–491.

[24] I. Kim, S.I. Hong, Effect of heat treatment on the bending behavior of tri-layered Cu/Al/Cu composite plates, Materials and Design, 47 (2013) 590–598.

[25] W.N. Kim, S.I. Hong, Interactive deformation and enhanced ductility of tri-layered Cu/Al/Cu clad composite, Materials Science and Engineering: A, 651 (2016) 976–986.