Investigation on the formability of Al-Cu composite material in micro deep drawing process with different lubrication conditions

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Abstract. In microforming, the interface behaviour between die and workpiece is an important factor which determines the forming limit of the process and the quality of the formed product. In this paper, the formability of a two-layer aluminium (Al)-copper (Cu) composite in micro deep drawing (MDD) process was studied under different lubrication conditions. Oil-based TiO_2 nanolubricant, oil lubricant and dry friction were chosen in this study to act as lubrication variables, and then the formability of the drawn cups under three lubrication conditions were investigated and compared. Also, Voronoi finite element (FE) models which consider size effects of materials were developed. The results show that Al-Cu composite has the best formability with TiO_2 nanolubricant. The simulation results agree well with the experimental results, which confirms the FE simulation is applicable for simulating the MDD process.

Introduction

As a potential microforming method, micro deep drawing (MDD) process is gaining more and more attention from modern industries because of its advantages of high productivity, low production cost, high product quality, and less pollution. Compared with other microforming process, MDD has extensive applications in the forming of hollow, thin walled, cup or box-like micro parts. However, due to the size effects existed in the forming of metals in microscale, more comprehensive research on MDD is still needed [1-3].

Metal composite materials are becoming popular because they provide materials for more specific application [4]. Aluminium (Al)-Copper (Cu) composite possesses the advantages of high conductivity, low cost and light weight, which is a preferred material for electrical. Therefore, micro drawn parts made by Al-Cu composite will have a potential applications in micro electronic industry [5,6].

Tribology in metal forming has a significant effect on the quality of the formed part, the tool lift time and the process stability. Lubrication condition is one of the key factors for tribology behavior in metal forming, which determines the forming limit of the forming process and the quality of the produced parts. In MDD, Gong et al. [7] carried out MDD tests with copper C1100 under the lubrication of polyethylene film, soybean oil and castor oil, and found that the drawn cups with polyethylene film had the minimum drawing force, maximum limit drawing ratio and the best surface quality. Wang et al. [8] used three kinds of surface coating, including diamond-like carbon (DLC), tin and MoS_2, on the surfaces of die in MDD experiments, and the results showed that there was a lower coefficient of friction (COF) and a higher wear resistance under the condition of large strain/stress when DLC film was used. Nanoparticles have outstanding physicochemical properties and some researches have showed that base lubricant with nanoparticles could reduce friction and enhance anti-wear properties[9-11]. Wu et al. [10] investigated the tribology behavior of TiO_2 nano-additive water-based lubricant and found that water-based nanolubricants can significantly reduce the COF. Xia et al. [11] used oil-in-water based TiO_2 nanoparticles in pin-on-disc tests with high-speed steel and achieved an excellent reduction of COF and improved the anti-wear properties of pins.

In this paper, two-layer Al-Cu composite material was used to investigate its formability in MDD process under dry friction, oil lubricant, and oil-based lubricant with TiO_2 nanoparticles. The quality of the formed cups and forming limitation of the composite material were compared in all the lubrication conditions. Then finite element (FE) model considered each lubrication condition and real grain tessellations of both Al and Cu were established, and then the simulation results were verified by comparing with the experimental results.

Experiments

Material. Al-Cu composite material with thickness of 50µm (40µm for Al and 10 µm for Cu) was used in the present work. Al-Cu composite samples were heat-treated at 400 ^{o}C for 5 min under argon gas protection to make sure a good formability. To assign real grain size of both materials to the FE model in micro forming, the microstructures of the composite blank were observed. The average grain sizes of Al and Cu were determined 20 µm and 105 µm respectively.

Lubricant. The lubricants used in this research were oil lubricant and oil-based TiO_2 nanolubricant. TiO_2 particles, the size of which is 30 nm, were first dispersed into the lubricant oil with a 1 wt%, and then stirred with high speed for 8 min. To improve the dispersibility of the nanoparticles, ultrasonic vibration was used for 10 min after stirring. The oil lubricant used was oil with a viscosity of 1.20 Pa·s and a density of 0.9 g/cm^3 at 23 ^{o}C and a viscosity of 0.18 Pa·s at 80 ^{o}C.

MDD experiments. MDD experiments under different lubrication conditions were performed on the desk-top servo press machine DT-3AW with the annealed Al-Cu composites. The drawing speed of the punch was set as 0.1 mm/s. Drawing forces and displacement were recorded from the press machine and load cell during drawing process, which were used for further analysis of the relationship between drawing force and displacement. Different lubrication conditions were realised by applying lubricants between the blank and the die, for reducing the friction and improving the drawability, as shown in Fig. 1.

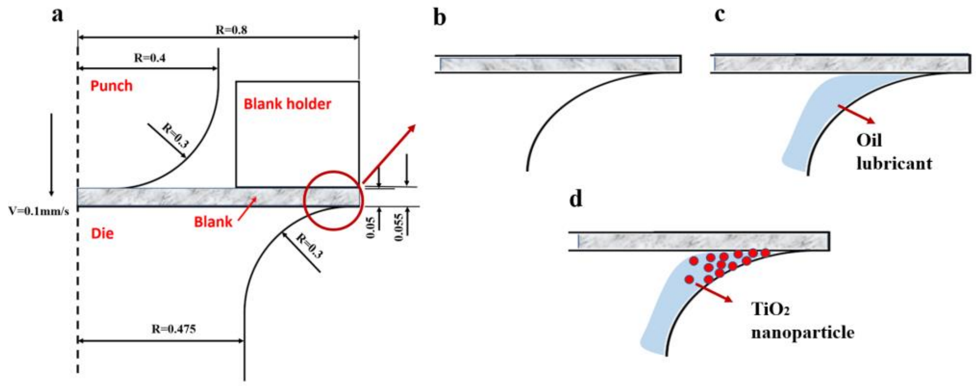

Fig. 1. (a)Geometry dimension of MDD model and schematics of MDD tests with (b) dry friction and (c) oil lubricant and (d) oil-based TiO_2 nanolubricant

Observation. KEYENCE 3D laser-scanning microscope was used in this test to observe the geometries and dimensions of the drawn cups, and then the formability of the cups under different lubrication conditions was compared and analysed.

FE models

FE models of MDD with Al-Cu composites were created by using ABAQUS, as shown in Fig. 2. To improve the calculation efficiency and reduce the computing time, a quarter of the blank was created. All parameters used in this model were the same as those in MDD experiments.

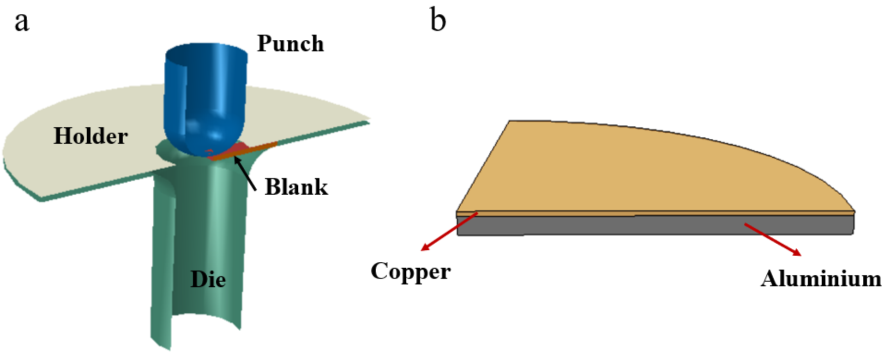

Fig. 2. FE Model of (a) MDD and (b)Al-Cu composite blank

For the FE models, the blank was built as a deformable part with continuum shell elements, while the punch, die and blank holder were regarded as rigid part. Continuum shell element has geometrical structure in thickness, and high accuracy in contact modelling which includes two-sided contact and the same analysis efficiency compared with conventional shell element. The model of Al-Cu blank was divided into two layers, as shown in Fig. 2(b). For blank model, both material layers were defined being tied together, and there was no sliding in the interface during the process.

Material properties were obtained from experiments, as shown in Table 1. In the FE model, symmetry constraints were set for two sides of the blank and full constraints were set for blank holder and die. The movement of punch was controlled by displacement. In order to simulate the MDD tests under various lubrication conditions, different friction coefficients were employed between blanks and die. As former tests, the friction coefficients were set 0.1, 0.04 and 0.03 for dry friction, oil lubricant and oil-based nanolubricant respectively. For punch-blank contact, the COF was set 0.2 for all the three models.

Table 1. Material properties of Al and Cu in the composite materials.

Material	Elastic modulus [GPa]	Poisson's ratio	Yield strength [MPa]	Tensile strength [MPa]
Al	79.3	0.33	34.9	136.2
Cu	110	0.3	70.6	211.5

Voronoi model was introduced to the FE model to describe the information of information of size effects which has more influence on microforming than macroforming. Voronoi structures can be employed to characterise material properties in microscale because of the similarity between their geometrical features and material's micro structures. The Voronoi model was built to simulate real grain size of Cu and Al. The grains of both materials become more uniform after annealing, so centroid Voronoi method in which Voronoi cells are in the similar shape and same size was used. Both Voronoi cells of Cu and Al were classified into five groups which were assigned different material properties. The Voronoi model of both layers are shown in Fig. 3, and each colour indicates one cell group.

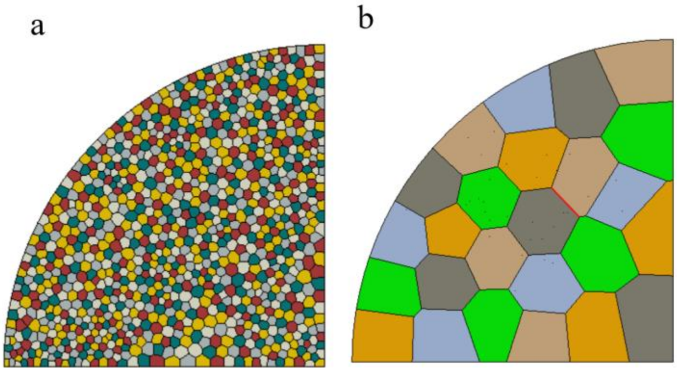

Fig. 3. The Voronoi model of (a) Al and (b) Cu layer.

Results and discussion

MDD with Al-Cu composite blanks under different lubrication conditions were investigated by both experiments and FE simulation methods, and their results were then compared.

Drawing Height. According to the experimental results, the maximum values of cup height are found to be different under three lubrication conditions, as shown in Fig. 4. The average heights of the cups are shown in Fig. 4(b), which are collected from ten times tests for each condition. The drawn cups under TiO_2 nanolubricant condition possess the largest maximum height with an average value of around 711.35 µm. Also, the forming limit of Al-Cu blank without lubricant is the worst among the three experiment results, and the average maximum height value is only 576.23 µm, which is smaller than those with oil lubricant. The results indicate that both oil lubricant and TiO_2 nanolubricant are beneficial in improving the formability of Al-Cu composite in MDD.

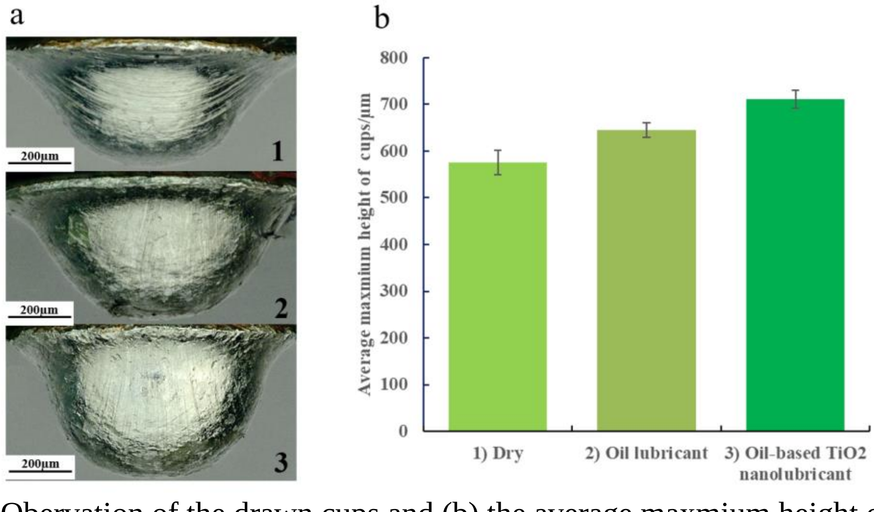

Fig. 4. (a) Obervation of the drawn cups and (b) the average maxmium height of the cups

Drawing force. The drawing forces of experiments under three lubrication conditions are illustrated in Fig. 5. Because the maximum heights of drawn cups are different, all the Al-Cu blanks are drawn to the same height for comparison. It can be seen that all the curves have the similar trend under different lubrication conditions, although difference exists between the maximum drawing forces. Initially, the resistant force of the bending domains, which results in a slow increasing rate of drawing force. As the process continues, large deformation causes high flow stress, and in the meantime, friction increases with the increasing contact area.

Therefore, the drawing forces rise significantly in the following period. It is clear that the curves under oil lubricant and TiO_2 nanolubricant increase more slowly than that without lubricant in the second period because the friction starts domains the drawing force in this period. The maximum drawing forces from both experiments and simulation results are shown in Fig. 6. Both simulation and experimental results show the same trend that the maximum drawing force is the smallest in tests under TiO_2 nanolubricant, and the frictions have a reduction in MDD tests with lubricants compared that without lubricant.

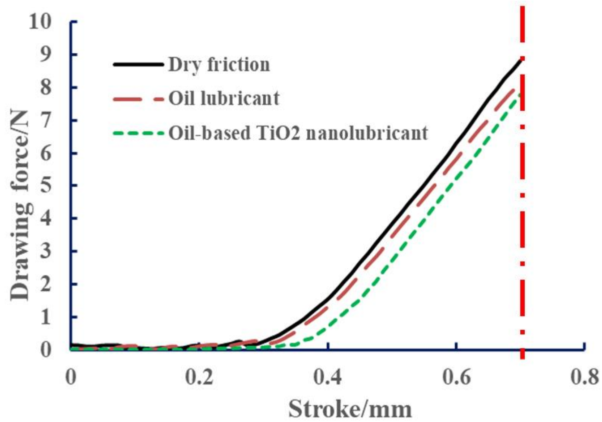

Fig. 5. Drawing forces from MDD tests in threee lubrication conditions

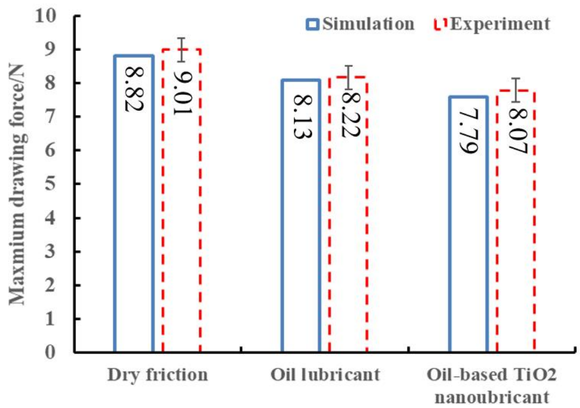

Fig. 6. Maxmium drawing forces from both experiments and simulations

Cup thickness. The thickness of the cup is one of the features to show the formability of composite materials. The composite samples were drawn to the same height to make comparison and the thickness of drawn cups from simulation results are shown in Fig. 7.

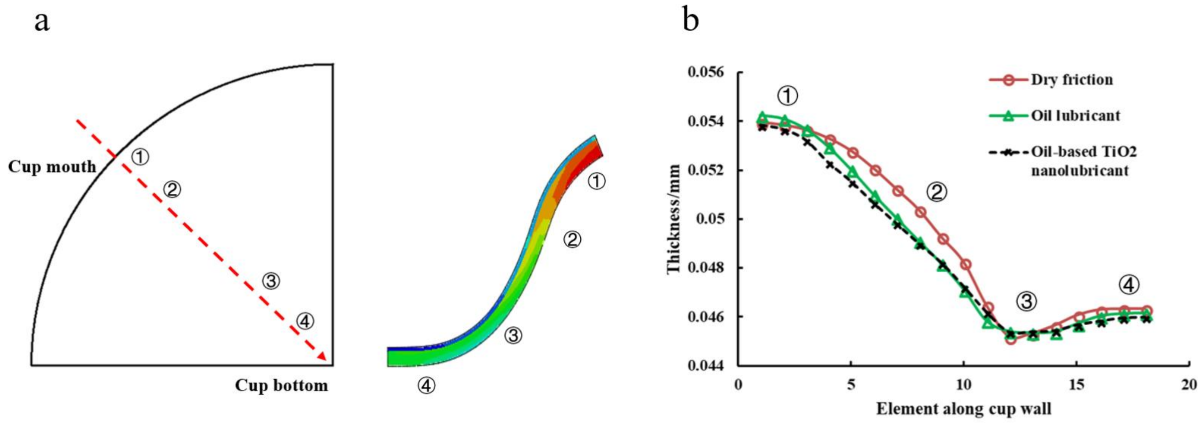

Fig. 7. (a) Four sections on the drawn cups and (b) the thickness of each drawn cup along the side wall

Four special sections along the cups are chosen to analyses the thickness change, as shown in Fig. 7(a). Fig. 7(b) shows the thickness of drawn cups under different lubrication conditions. Thickness of all the cups is reduced from section 2 to section 3 which is located on the cup corner at punch fillet. While in dry friction, the thickness decreases more significantly and has the smallest value compared with other conditions. Section 3 is the most dangerous zone in MDD, because there is more thickness reduction occurring here, which results in fracture on the cup easily. By contrast, the thickness distributes more even on the cup drawn in oil lubricant and oil-based TiO_2 nanolubricant conditions, which also explains the results in Fig. 4 that cups possess larger height limitation under lubrication conditions.

Surface roughness. Surface roughness is another factor to show the quality of the drawn cup. The side wall area of the cup is chosen for analysis. The surface roughness was measured by

KEYENCE VK-X100-3D laser microscope. The mean values of the surface roughness were shown in Fig. 8. Both section 2 and section 3 in Fig. 7 were chosen for analysis.

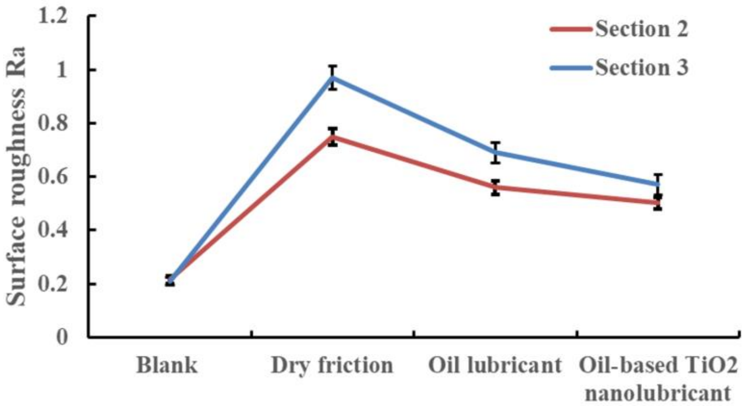

Fig. 8. Surface roughness R_a of original blank and cup walls

It can be seen that the surface roughness increases after forming, and the values in section 3 are generally larger than those in section 2 because of large deformation. The surface quality of drawn cups under dry friction is still worse than those under lubrication conditions. The drawn cups under TiO_2 nanolubricant have the lowest R_a value, and the difference between section 2 and section 3 is smaller than the other conditions.

Conclusions

1. Oil-based TiO_2 nanolubricant is used in the MDD process with Al-Cu composite material and is found to have beneficial effect on improving the formability of the drawn parts.
2. Voronoi model which considered size effects is developed and applied to simulate the MDD process under different lubrication conditions.
3. TiO_2 nanolubricant helps to improve the drawing limitation of Al-Cu composite significantly in MDD forming.
4. By analysis of both experiment and simulation results, TiO_2 nanolubricant has better effect on the forming with Al-Cu blank in terms of drawing force, thickness distribution and surface quality of the drawn cups, followed by oil lubricant condition.

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