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Al-Cu Composite's Springback in Micro Deep Drawing

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Abstract

With the recent technological trend of miniaturization in manufacturing industries, the rise of micro forming operations such as micro deep drawing (MDD) is inevitable. On the other hand, the need of more advanced materials is essential to accommodate various applications. However, a major problem are size effects that make micro scale operations challenging. One of the most important behaviors affected by size effects is the springback phenomenon, which is the tendency of a deformed material to go back to its original shape. Springback can affect dimensional accuracy, which is very important in micro products. Thus, this paper investigated the springback behavior of Al-Cu composite in MDD operations. Micro cups were fabricated from blank sheet specimens using an MDD apparatus with variation of annealing holding time. The springback values were measured and compared to each other. The results showed that different grain sizes lead to variation in the amount of springback. However, unlike in single-element materials, the amount of springback in Al-Cu composite is not only related to the thickness to grain size (t/d) ratio. Another factor, i.e., the existence of an interfacial region between layers, alters the mechanical behavior of the composite.

Keywords: *Al-Cu composite; micro deep drawing; micro forming; micro manufacturing; springback.*

Introduction

Micro deep drawing (MDD) is a metal forming process that involves punching a blank sheet into a die to form the desired shape on a micro scale. Deep drawing at normal sizes is a well-established technology that is used in various industries but performing it on a micro scale is still challenging.

On a micro scale, material forming faces challenges related to variation in material behavior, especially mechanical properties [1] due to size effects. Size effects come from physical and structural sources [2]. Thus, theories of material deformation in macro forming cannot be directly applied to micro forming operations [3].

The study on formability and stress of down-sized pure aluminum and brass by Gau *et al.* in [4] is a good example of size effects. It describes that when a material has a much larger thickness than its grain size, as is the case at normal size, the yield stress and tensile stress increase as the thickness increases. However, when the thickness is smaller than the grain size, the thickness itself cannot be used to define the material behavior. On a micro scale, another parameter, called the t/d ratio (the ratio between thickness and grain size), takes over. Due to the size effects, the yield stress and tensile stress increase as the t/d ratio decreases.

The size of grain by itself can influence the operation repeatability that is the culprit for difficulties in controlling product dimensions. A larger grain size leads to scatter in deformation behavior [5]. Since the number of grains is limited, each grain that has different properties contributes significantly to the inhomogeneity of the material [3].

Size effects can be related to various forming behaviors during micro forming processes, i.e., forming force, friction, scattering dimension, flow stress [6], and springback. In operations that involve bending, springback is the tendency of the formed material to return to its original shape. This phenomenon is caused by residual elastic recovery [7]. This unwanted recovery leads to deviation in the final product shape and dimensions. Many

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studies have investigated springback on a macro scale, yet knowledge on this phenomenon on a micro scale is still limited.

In micro bending operations, investigation of brass material confirmed that for thicknesses less than 350 µm, the amount of springback depends on the t/d ratio instead of the thickness only [8]. Here, the amount of springback increases as the t/d ratio decreases. Similar results have also been found for the same operation using copper (Cu) [9]. On the other hand, when the t/d ratio is small, which implies that the material has a limited number of grains involved in the operation, variation in forming behavior occurs. Thus, the amount of springback is scattered [9,10].

Up to now, investigation of forming behavior, especially springback, mostly involved micro bending. While this basic operation is sufficient to illustrate springback, the context needs to be expanded to more complex forming processes. MDD is a potential process in the micro forming field. This technique is suitable for mass production and has a short operation time and needs less material.

Some studies have been conducted for MDD with various materials, such as aluminum alloys [11], stainless steel [12,13], copper and its alloys [14,15], TWIP steel [16,17], and titanium [18], which are single-layered materials. Other researchers applied simulation of MDD to predict the relationship between springback and holder pressure [19], drawn radius [20], and surface roughness [21]. Most of the studies focused on single-layered material models and experimental results. Meanwhile, two-layered materials such as Al-Cu composite, fabricated with MDD promises eminent characteristics, i.e., light weight and good conductivity, that are suitable for electronic and biomedical applications [22].

Utilization of Al-Cu composite sheet metal in MDD has been tested and micro cups with good quality could be obtained [22,23]. However, these two studies focused on the deformation behavior to fabricate defect-free products. The contribution of springback remained unexplained. Thus, the objective of this research was to understand the springback behavior of Al-Cu composite so that the final shape of the MDD product can be predicted more accurately and the desired dimensions can be obtained.

Approach

Springback Interpretation

Springback was measured by two approaches as illustrated in Figure 1. In MDD, the initial material is a flat blank sheet, while the expected final product is a 3D U-cup (Figure 1 (a)). Due to springback, there will be a deviation from the 3D shape (Figure 1 (b)). The value of the cup corner angle (α) will be larger, which can be used to measure the amount of springback, as employed by Cho *et al.* [24]. The second interpretation is based on the common sense understanding that when α is bigger, cup height (h) will be shorter, which can also be a measurement of springback.

Thus,

$$\%Sp_{\alpha-\text{based}} = \frac{\alpha_{actual}-\alpha_{ideal}}{\alpha_{ideal}} \times 100\% \quad (1)$$

$$\%Sp_{\text{h}-\text{based}} = \frac{h_{ideal}-h_{actual}}{h_{ideal}} \times 100\% \quad (2)$$

where α_{ideal} is equal to 90° and h_{ideal} is assumed to have the same value as the drawing depth.

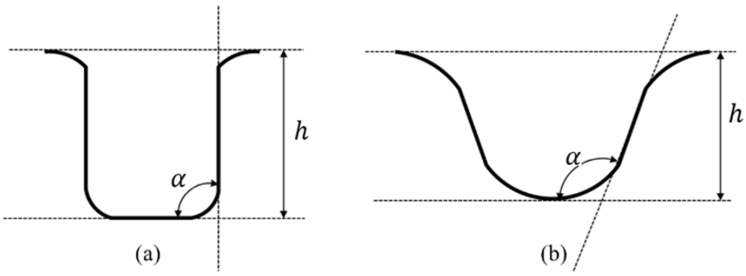

Figure 1 Illustration of cup formed by MDD: (a) before unloading, (b) after unloading.

Material

The material was a two-layered metal composite blank sheet consisting of aluminum and copper with a thickness ratio of 4:1. The composite was micro-rolled from a thickness of 234 µm to 50 µm, which gave 40-µm and 10-µm layer thicknesses to the Al and the Cu, respectively. Material preservation was done following Jia *et al.* [23]. An illustration of the material composition is presented in Figure 2.

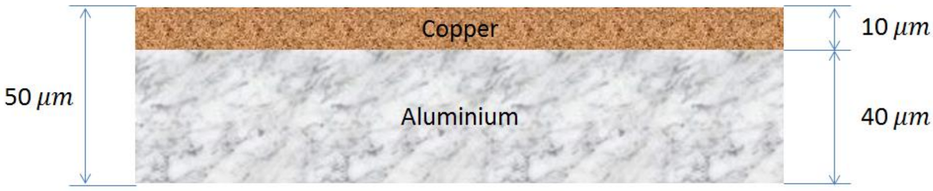

Figure 2 Material composition.

For the purpose of gaining variation in grain size, three different annealing conditions were performed in a KTL 1,400-tube furnace with an argon environment. The annealing temperature was 400 °C with a heating rate of 10 °C per minute. The holding times for each specimen were 5, 10, and 30 minutes before the furnace was cooled down. Then the specimens were left inside the furnace tube for further cooling down to room temperature. The average grain size was then measured under a digital microscope using the Aztec software.

Micro Deep Drawing Experiment

The micro deep drawing machine employed in this experiment was a Desktop Servo Press Machine DT-3AW; a schematic diagram of the MDD is presented in Figure 3. Before the operation, the specimens and tool sets that come into contact with the material were cleaned using ethanol. The Al-Cu composite blank sheet was then placed with the Cu layer on top.

The initial punch position was 1.6 mm above the blank sheet. It was then moved relative to the die with a speed of 3 mm/s during the first step of the operation. After the punch contacted the specimen, the drawing process was commenced with a speed of 0.1 mm/s until the drawing depth was reached. Several drawing depth values were applied for each specimen. Each drawing depth was performed twice for each specimen. After the drawing depth was reached, the punch moved back to its previous contact point with the specimen at a speed of 1 mm/s.

The product (micro cup) was ejected from the die and visually inspected right after the MDD operation to determine its quality. A KEYENCE VK-X100 laser microscope was utilized to observe the product quality as well as to measure the amount of springback.

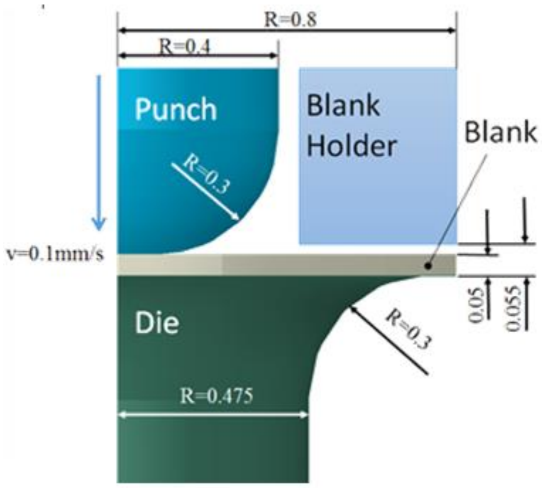

Figure 3 Schematic diagram of the MDD operation.

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Results and Discussion

Variation in annealing time resulted in different grain sizes for each layer. Since the thicknesses were uniform, the ratio of thickness and grain size could be calculated, as presented in Table 1. Note that some grain sizes were bigger than the layer thickness. This was because the composite was a product of micro-rolling, which flattens the microstructure as shown by the composite's electron backscatter diffraction (EBSD) image in Figure 4.

Table 1 Average grain size & t/d ratio.

Specimen	Layer	Thickness (µm)	Avg. grain size (µm)	t/d ratio
Specimen 1	Al layer	40	15	2.67
	Cu layer	10	80	0.13
Specimen 2	Al layer	40	20	2.00
	Cu layer	10	82	0.12
Specimen 3	Al layer	40	50	0.8
	Cu layer	10	65	0.15

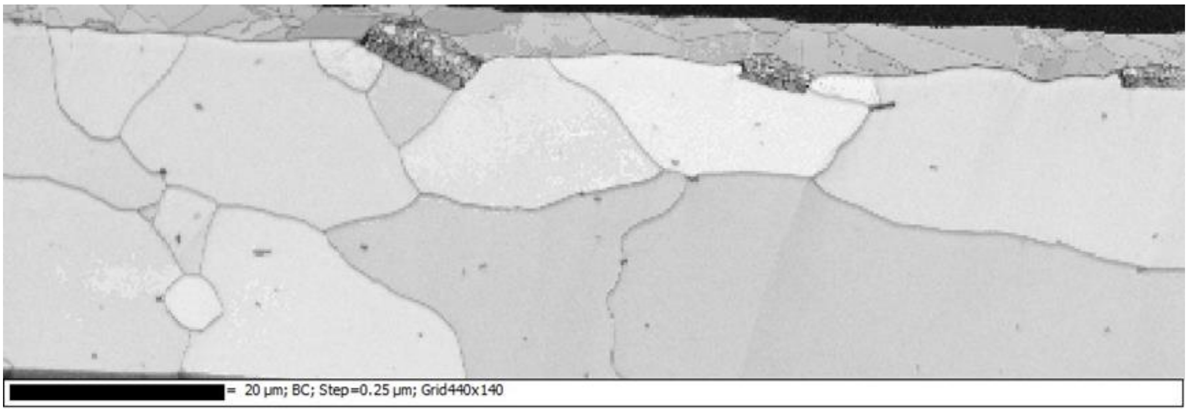


Figure 4 EBSD image of the Al-Cu composite.

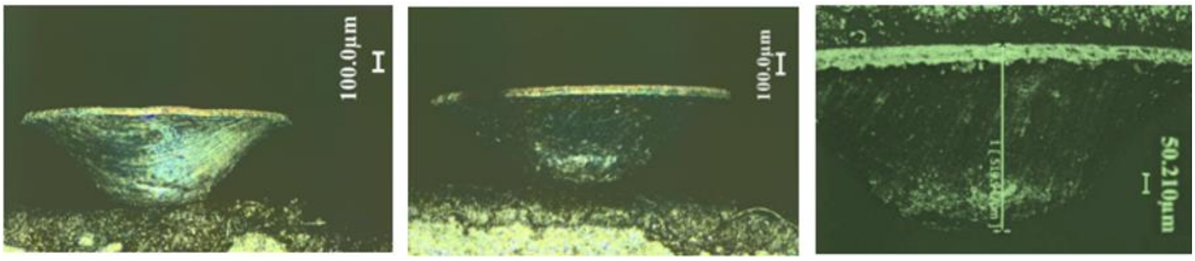
MDD was performed for each specimen with different drawing depths. Prior heat treatment was expected to refine the microstructure, which helps to improve the formability.[1] Table 2 presents the drawing depth that produced the cup with the best quality for each specimen.

Table 2 Best drawing depth for each specimen.

Best depth (µm)	Specimen	Layer	Avg. grain size (µm)	t/d ratio
550	Specimen 3	Al layer	50	0.80
		Cu layer	65	0.15
600	Specimen 1	Al layer	15	2.67
		Cu layer	80	0.13
650	Specimen 2	Al layer	20	2.00
		Cu layer	82	0.12

The experiment by Lee *et al.* in [12] revealed that higher t/d ratio is expected to produce a deeper drawing due to more grains being involved in the process. However, this was not the case for the Al-Cu composite. The relationship between the t/d ratio and the drawing depth for the Cu layer was even exactly the opposite, as shown in Table 2: when the t/d ratio decreased, the drawing depth increased.

Figure 5 presents a micro cup formed by the MDD process under a digital microscope at the best drawing depth for each specimen.



(a) (b) (c)

Figure 5 Micro cups under a digital microscope: (a) specimen 1 with drawing depth at 600 µm, (b) specimen 2 with drawing depth at 650 µm, and (c) specimen 3 with drawing depth at 550 µm.

The shapes of the cups were relatively flat compared to for example the micro cup formed by Vollersten & Hu [25]. However, defects like fractures, a rough end wall, or wrinkling were absent. This flat shape resulted from the small drawing depth that was set for the operation due to the limitation in formability. An excessive drawing depth resulted in severe defects that could be seen immediately. There were sloping cup walls that could be clearly identified by the large difference between the top and bottom cup diameters. This slope is an early indication that the springback phenomenon occurred during operation.

In order to measure the springback, a straight line was drawn from the center point of the cup top to the center point of the cup bottom. This line, which is equal to the cup height (h), was divided by the drawing depth to calculate the h-based springback value. The α-based springback was measured by extending the previous line and drawing another line that aligned with the cup wall. The angle formed by the two lines added by 90° gave the α value. This measurement is illustrated in Figure 6. Table 3 presents the values of h, α, and the amount of springback, which was calculated by Eqs. (1) and (2).

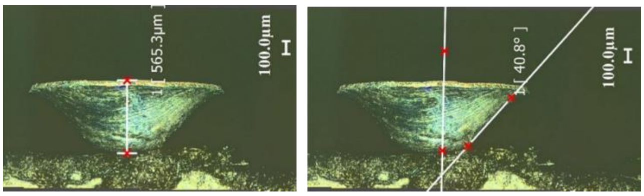


Figure 6 Figure lines for springback measurement.

Table 3 Springback values.

Specimen	h (µm)	α (degree)	Springback	
			h based	α based
Specimen 1	537.8	132.7°	10.37%	47.44%
Specimen 2	565.3	130.8°	13.03%	45.33%
Specimen 3	524.1	126.7°	4.71%	40.78%

To simplify things, by disregarding different properties between the Al and the Cu layer, the t/d ratios were combined to obtain the t/d ratio of the composites. This combined t/d ratio of the Al-Cu composites is presented in Table 4 along with the springback values.

Table 4 Combined t/d ratio and springback value.

Specimen		t/d ratio	Combined t/d ratio	Springback	
				h based	α based
1	Al layer	2.67	2.79	10.37%	47.44%
	Cu layer	0.13			
2	Al layer	2.00	2.12	13.03%	45.33%
	Cu layer	0.12			
3	Al layer	0.80	0.95	4.71%	40.78%
	Cu layer	0.15			

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Previous research revealed that the amount of springback was smaller with a higher t/d ratio [8-10, 15,26]. In other words, the t/d ratio actually depicts the number of grains in the thickness direction. This number is very important since it determines how many grains are involved in micro forming. The material becomes more homogenous with more grains, which allows it to weaken the size effects [3].

As shown in Table 4, for α-based springback, the amount was smaller following the decrease of the combined t/d ratio. This relationship contradicts the results studies mentioned previously. On the other hand, the α-based springback values were relatively higher. Three-point micro bending operation conducted by Liu *et al.* [9] obtained a springback angle range between 4° and 20°, while that from Gau *et al.* [8] was between 9.45° and 20.42°. For comparison, using the same approach, the springback angles obtained by the experiment in the present study were 42.7°, 40.8°, and 36.7°.

A different relationship was shown by the h-based springback value. While the t/d ratio for Specimens 1, 2, and 3 were descending, Specimen 2 had the biggest amount of springback compared to Specimens 1 and 3. The relationship was still not consistent with previous studies.

The α-based springback value is relatively more difficult to measure than the h-based one. This is due to the difficulty of drawing a line that aligns with the cup wall. On the other hand, there is also the possibility that the α angle does not fully come from the springback phenomenon in the first place. There is a gap between the die and the punch that naturally generates a slope. The slope could be incorrectly identified as a springback angle, especially when the drawing depth is small.

Agreement with previous studies was achieved when comparing the h-based springback value with the t/d ratio of the Cu layer. For the Cu layer, the amount of springback decreases as the t/d ratio increases. Although only 20% volume of the composite was Cu, it may have contributed significantly to the springback value. This is reasonable, since Cu has a higher yield stress and elastic modulus than Al, which makes it harder to form and drive composite formability. Cu also has a larger elastic region, which is closely related to springback behavior. Recall that the springback phenomenon is caused by residual elastic behavior after plastic deformation. Changes in the mechanical behavior of Al-based composite reinforced by a harder material has been reported in other studies, including hardness increase [27], strength increase [28], and force required to perform machining operations [29].

Nevertheless, assuming the Cu t/d ratio as the only parameter to determine the springback behavior of the composite is likely inappropriate. Certainly, the Al layer contributed as well to a degree that could not be determined yet. There is also the possibility that another factor significantly influenced the phenomenon.

The discussion so far was conducted under the assumption that the composite only consists of two layers. However, what if this is not the case?

Peng [30] studied a roll bonded Al-Cu metal laminate to figure out the development of an interface between layers. It was called a laminate because the volume ratio between the two elements was 95% Al and 5% Cu. The laminate was produced by hot rolling and sintering. Cross-sectional observation using a scanning electron microscope (SEM) showed that intermetallic compounds were present between the layers. The compounds, commonly $CuAl_2$ and Cu_9Al_4, were mixed with pure Al and pure Cu at various compositions, forming additional regions that were either Cu-rich or Al-rich. This region is called the interface region, which grows with increasing sintering time.

Interaction between the Cu and the Al layer in Cu Clad Al (CCA) thin wire was studied by Hug and Bellido [31]. The 300-µm diameter thin wire, which was the product of drawing from an initial diameter of 20 mm was annealed at 300 °C with various holding periods. It was found that while annealing improved the ductility of Cu and Al, it also created an intermetallic compounds at the interface region. These compounds, which were identified as Al_2Cu, AlCu + Al_3Cu_4, and Al_4Cu_9, have brittle properties.

The intermetallic interface region is able to provide an explanation for the deformation properties of the micro deep drawn cups made of Al-Cu composite, particularly springback. The interfacial region is developed during the rolling operation, which contributes to material brittleness. This region expands as the annealing time increases. For Specimens 1 and 2 with holding times of 5 and 10 min, the regions were not large enough to oppose the pure materials' ductility. The interfacial region grew significantly larger at 30 min of annealing time and drove the composite's mechanical behavior. Specimen 3 became more brittle, which led to a smaller amount of springback. This explains why the h-based springback value for Specimen 3 decreased.

Conclusion & Future Works

An MDD experiment was performed on an Al-Cu composite sheet with three different annealing holding times to fabricate micro cups. The heat treatment affected the formability of the Al-Cu composite, which was indicated by variation in the drawing depth that produced a good quality cup. The cups were investigated under a digital microscope and the amount of springback was measured.

A difference in the deformation behavior of the Al-Cu composite in terms of springback was observed due to the variation in grain size under different annealing conditions. However, this behavior was not consistent with previous findings. According to the experimental results, the increase of the t/d ratio did not make the amount of springback decrease, as commonly stated in other studies. Comparison of the springback values with the t/d ratio of the Al layer, the Cu layer, and the composite as a unity resulted in different patterns. Only the springback in the Cu layer decreased with an increase of the t/d ratio, which agrees well with previous research. The cause of the discrepancy was the existence of an interfacial region between the layers, which had brittle compounds.

Following the present research, there is plenty of room for improvement that can be addressed to further understand the springback phenomenon in MDD. Thus, potential works in the near future may include:

1. Since the research deals with micro operation, which always has to deal with repeatability challenges, scatter in the amount of springback needs to be investigated as well.
2. The assumption that the interfacial region between the layers in the Al-Cu composite influences the springback needs to be confirmed. Investigation into composition, size, and mechanical properties needs to be performed to determine its degree of contribution to the springback value.
3. Manufacturing proper micro cups from Al-Cu composite is still a challenge. Optimization of the annealing temperature and holding time need to be addressed to obtain properties that are appropriate for MDD.

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