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Title: Experimental and FE analysis on spring-back of copper/aluminum

layers sheet for a L-die bending process

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Abstract

This paper is a conduct of experimental tests to investigate different effective parameters of a UNS C10100 copper/aluminum 1100 spring-back on a two-layer L-die bending sheet through finite element simulations. The parameters are the radius and clearance of die, sheet length, thickness of each layer, different lay ups, and sheet annealing. The paper shows that the spring-back decreases with the reduction of the die clearance and radius, similar to the behavior of single-layer sheet and with the increase of the sheet length. The outcome displays a contradiction with 'no significant effect' in the single-layer sheets, previously published in other papers. Furthermore, the thicknesses of copper and aluminum are important roles to evaluate spring-back; however, there is no certain rule to decrease or increase the spring-back through changing the thickness of each layer. Moreover, this work shows the effects of stacking sequence of aluminum and copper layer on the spring-back, because of the different natural axis in each stacking sequence and also different ultimate strength of each layer. Finally, it is concluded that annealing heat treatment significantly reduces the spring-back, where the intermetallic bond hardness in the interface of Cu/Al layers and spring-back increases with the rise of annealing temperature.

Keywords: Spring-back, L-die bending, Two layers sheet, Finite element simulation.

1. Introduction

FCC metals and alloys due to their high ductility use widely in metal forming process [1, 2] . In recent years, the applications of two-layer metallic clad sheets have been increased in manufacturing the products with particular specifications, i.e. high strength, low density, damping covering structures, and corrosion resistibility, used in various industrial fields such as automobile, chemical and electrical industries [3]. In general, clad metallic sheets can be made by several processes, such as adhesive bonding or cold and hot roll bonding [4, 5].

As a fundamental and traditional process in metallic forming technologies, sheet metal bending is widely being employed in almost all industrial fields. In this process, lack of dimension precision is a major concern due to the considerable elastic recovery during unloading, called spring-back. Spring-back is a common phenomenon in sheet metal forming processes, which leads to some geometrical changes in the plate [6, 7].

Several authors studied the forming behavior of layers' clad sheets. Tseng et al. [8] investigated the deformation of Ti/Al-clad metal sheets and discussed several significant parameters in bending process such as holding force, friction, counter pressure history, and blank dimensions to improve the formability of Ti/Al-clad metal sheets. Afshin et al. [9] carried out a comprehensive investigation for warm deep-drawing process on Al 1050/St 304 and Al 5052/St 304-laminated sheets. They concluded that the layer sheet behavior in a forming process differs from the single layer sheet and depends on the layer sequence due to the individual mechanical properties of each layer.

Aghchai et al. [10] predicted the spring-back of Al 3105/ polypropylene/ Al 3105 laminate sheets with numerical and experiment analysis in V-die bending and demonstrated the spring-back increases with increasing the punch radius. Yilamu et al. [11] investigated the stainless steel/aluminum clad spring-back, where the thickness ratios and setting conditions affect sheet bending behavior such as spring-back and sheet thinning.

Gautam and Sharma [12] used experimental and numerical analysis to study the spring-back on U-Bending of 3-Ply cladded metal sheets. They concluded that the maximum and minimum values of the spring-back are in the sample oriented transverse and 45° to the rolling direction, respectively. Parsa et al. [13] experimentally investigated the spring-back on the double-curvature formation of a AA3105/polypropylene/ AA3105 sandwich panel as well as its effects of thickness panel and tool curvature radii on the spring-back.

Furthermore, most of the published works on two-layer copper/aluminum sheets focused on the investigation of formability, forming, and deboning of layers. In a published paper related to the spring-back phenomenon on copper/Aluminum two-layer sheets, Parsa et al. [14] studied the spring-back of cold roll bonded Cu/Al clad sheets in air bending process at the V-die set. Through analyzing the effects of several significant parameters such as die opening, punch radius, and punch stroke on the spring-back, their studies showed that different Al/Cu and Cu/Al setting conditions have no remarkable influence on the spring-back.

Notwithstanding, this paper investigates the spring-back of two-layer sheets consisted of copper/aluminum bended in a L-die. Also, the paper benefits from using the finite element method to verify the results with the acquired experimental tests. Here, Sections 2 and 3 describe the experimental and FE procedure. Through implementation of experimental works and FEM, Section 4 focuses on the effects of die radius, die clearance, and sample length on the spring-back, as well as of thickness and stacking layers on the spring-back with FEM. Finally, the paper experimentally tests the effect of annealing temperature and hardness on the spring-back of the two-layer.

2. Experimental procedures

2.1 Sample Preparation

This study experimentally tests the spring-back of a two-layer UNS C10100 copper / Aluminum 1100 sheet. The sample's total thickness (t) is 1.5 mm, that of copper and aluminum 0.5mm and 1 mm, respectively. The lengths of sample (L) are 40, 60 and 80 mm with its width of 20 mm.

Table 1 shows the chemical composition of Cu/Al sheet determined by metal elements quantimeter. Double layers were fabricated by explosion welding method (EXW), a familiar process to join metal sheets. Created pressures in this method, stabilized metallurgical bond between Cu/Al components. [15].

2.1.1 Mechanical Behavior of Materials

The mechanical and material properties of aluminum and copper were determined by the STM-50 (SANTAM company) electronic tensile machine with a constant velocity of 2 mm/min. Specimens were prepared according to the ASTM-E8 specification. Figures 1a-c shows the prepared sample's dimensions and true stress-strain diagrams for copper and aluminum.

2.1.2 Annealing, metallography and performing micro hardness-test on Sample

In order to investigate the effect of annealing heat treatment on the spring-back and of temperature variations on the annealing process, the sheets were heated at 350° C and 500° C for 2 hours, then cooled in the furnace for 24 hours. . The samples' preparations include sanding, polishing, electro-polishing, etching, and electro-etching. Furthermore, ammonium chloride (NH_4Cl) and barker were used as etch solutions for copper and aluminum, respectively.

Besides, the micro hardness-Vickers test was used to distinguish the hardness variation of the samples, due to variations in the temperature of the annealing. The results have been presented in the section 4.5.

2.2 Die description

Fig.2 shows the schematic of the designed L-die set which contains upper and lower shoes, a punch, spring, holder, keeper, die, and pin. With the die set up, it's possible to investigate the effect of radius and clearance of die on the sample's spring-back. In such a way, for a radius examination, it is sufficient to rotate the die part with its three corners with different radius and in the desired radius. Also, to investigate the clearance, different gaps have been placed by embedding the washer with different thickness between the keeper and die parts.

2.3 The experiment test

Hydraulic press machine was used to bend the sample. The tests were performed at a constant velocity 2 mm/min. The bending process was divided into two stages: in the first stage, called loading, the punch moved down to the point of its stroke reaching to a specific value. All of the samples bend from middle. In the second stage, named unloading, the punch moved up and elastic strains were released. Figure 3 shows the mechanism of bending.

After ending second stage, a Baty profile projector was used to measure the bending angle and the spring-back of the samples. Figure 4 shows the measurement of the spring-back angle with the profile projector. Baty profile projector is a regular machine to measure spring-back with different die-bending [16, 17]. Baty profile projector includes holder to keep the sample and plate that the image of sample reflects on it. Selecting and matching two lines by machine, on the legs of sample, measuring of angle between two lines is possible. Spring-back evaluates with decreasing the measured angle from 90^0 (the angle of L-die bending).

3. Finite-Element Method

Abaqus software was used to validate the results of FE simulations and experimental tests. The two-dimensional plane strain modeling was used to both decrease computational cost and simplify simulation and to investigate the spring-back of a two-layer Cu/Al sheet. A punch, die, and holder were set as rigid bodies along with the sample modeled as an elastic-plastic type. Elastic-Plastic material properties, obtained from the tensile tests (Fig.1), were inputted in the material model of software. The surface to surface contact was selected to model the interaction between die and sample, punch and sample, keeper and sample, and holder and sample. Also, a tie interaction was used to attach the layers, and aluminum and copper sheets. The quadrangle 4 node S4R shell elements were used for the two-layer sheet modeling, repeatedly used in nonlinear problems with large deformations [18]. FE simulation details were listed in Table 2. Figure 5 shows FE simulations of the presented L-die bending problem.

The FE simulation divided three steps: in step 1, the holder moves with constant velocity v_h =1 mm/min in y- direction until contacts to the sample. In step 2, during loading process, punch moves down with the constant velocity of v_p=2 mm/min similar to experimental tests and bends the sample. Finally in step 3, during unloading process, punch moves up. Table 3 shows applied boundary conditions in two steps.

To achieve an optimum mesh to calculate the spring-back in the two-layer sheet, first, an element size with 0.5mm dimension was selected for the layer sheet and then it gradually reduced. Figure 6 shows the calculated spring-back according to the approximated element size. According to Figure 5, because no significant change exists in the amount of the spring-back in lower than element size of 0.1mm.As a result, a 0.1 mm element size was chosen for FE simulation. The foresaid optimum mesh method was used by Safikhani and Etemadi [19, 20].

In this paper, the thickness of aluminum and copper were 1mm and 0.5mm, respectively for the entire FE simulation except section 4-3, which the effect of layer thickness investigated by FE simulation.

To measure the spring-back angle, one of the nodes on the meshed two-layer sheet in Figure 5 was selected and its position history was plotted during the two-step loading-and-unloading. Then, the spring-back was evaluated by calculating the difference between the sample angles at the end of the loading step and unloading process. As the spring-back measurement was repeated for the selected nodes, a very good agreement was found among the spring-back results.

4. Results and discussions

4.1. The effect of length sample, radius die and clearance die on spring-back

Figure 7 (a-c) and Table 4 show the results of the spring-back angle related to the variations of die radius (R), die clearance (C), and sample length (L), respectively. For the foresaid tests, the aluminum and copper layer thicknesses are constants (h_{Al}=1mm, h_{cu}=0.5mm). To investigate the effect of radius on the spring-back, tests were implemented on the constant sample length and die clearance (L=60mm and

C=0.2mm). Furthermore, to investigate the die clearance, the radius and sample length are constants and R=5 mm and L=60 mm, respectively. Furthermore, to investigate the effect of sample length on the spring-back, the die radius and die clearance are R=5 mm and C=0.2 mm, respectively. For the foresaid tests, the aluminum and copper layer thicknesses are constants (h_{Al}=1mm, h_{cu}=0.5mm). According to Figures 7 and Table 4, there was a good agreement between experimental tests and FE simulations. Maximum error percentage was 9.30 % for R=5mm, C=0.2mm, and L=40mm. Furthermore, the spring-back reduces with decrease of die radius and clearance as well as increase of sheet length. It also should be noted that the spring-back decreases from 4.3^0 to 3.7° as the length of samples increases from 40 mm to 80mm.

4.2. Effect of layer stacking sequence on spring-back

Figure 8 is a comparison between the spring-back of the sample in two layouts of Cu/Al and Al/Cu. The spring-back of Cu /Al layer sheet are 3.8° and 3.7° for experimental works and FEM, Respectively. Furthermore, for stacking layer of Al /Cu it decreases to 3.4° and 3.35°, for experimental works and FEM, respectively. The spring-back differences are explained below:

1. Different lay-up effects on natural axis. In general point of view, the natural axis shifts to the stiffer layer, which is copper in this case. Besides, the bending radius has a direct relation with the natural axis and spring-back, as well (see section 4-1). Therefore, in the Al/Cu lay-up, the spring-back is smaller than Cu/Al, because of its smaller natural axis.

2. When the two-layer sheets bend according to Figure 8, the bottom and top of the natural axis are under compression and tensile loading, respectively. In the two-layer sheet with different strengths, the top face starts to be thinner and sharper due to the

high tensile force and this phenomenon is more severe when the lower strength sheet placed on top. As a result, the radius and spring-back of the two layer Al/Cu decrease more than those of Cu/Al.

4.3. Effect of Layer Thickness on spring–back

This section investigates the thickness effect of each layer. The sheet's total thickness is 1.5mm for all cases. Furthermore, the effect of layer thickness on the spring-back was evaluated for the constant die's radius (R=5mm), clearance (C=0.2mm), and sample length (L=60mm). Table 5 shows the aluminum and copper percent thicknesses evaluated with FE simulation. Furthermore, the spring-back angles of No. 1, 7, and 10 were also measured by experimental tests to verify the FE results. The results in foresaid cases were close to that of the finite element method, which indicates a good agreement between them. The maximum error percentage is 10.71 for test No. 10.

Figure 9 shows the spring-back according to the thickness percent of each layer. As Figure 9 shows, the spring-back decreased linearly when the percent thickness of copper layer decreased where it reached to the minimum value of 1.74° in the copper thickness of 50%, then increased to reach the maximum value of 3.70° in copper thickness of 33.33%, and then it decreased again. According to Figure 9, the main changes of the spring-back are ranging from 1.74^0 to 3.70^0 which is 112.64%. Therefore, the thickness of each layer is a very significant parameter on the two-layer sheet's spring-back. Furthermore, considering Figure 9 and Table 5, due to the complicated behavior of foresaid samples, no certain behavior between effects of each layer's thickness on sample's spring-back is expected to happen.

4. 4. Effect of Annealing on spring-back

To investigate effect of annealing on spring-back, Figure 10 shows the spring-back of samples according to the different die radius (R3, R5 and R7), which are annealed at 350° C and 500° C as well as compared to fabricated state (25 ° C- no annealing). According to Figure10, the spring-back decreased using annealing heat treatment, because annealing heat treatment significantly improved the sheet formability and reduced the spring-back.

On the other hand, the layer sheets used in this paper were manufactured by a rolling technology which increases strain hardening and yield strength [21]. Beside, strain hardening and yield strength of layers increase again with welding process to bond the sheets [22]. Effects of strain hardening and yield strength are to increase the spring-back which makes the annealing heat treatment an appropriate method to decrease spring-back.

4.5. Effect of hardness on spring-back of two layers sheet

Hardness of copper and aluminum layers and especially intermetallic interface, effect on the spring-back [22-24]. Figure11 shows the results of the micro Vickers hardness test with respect to different regions of aluminum, copper and interface bonding. As it can be observed, in the fabricated state samples (25^{0}C), the hardness of the copper, interface bonding, and aluminum are 170 ±3 HV, 190 ±3 HV and 80 ±3 HV, respectively. The higher value of hardness for interface bonding is due to the interface hardening [23]. Furthermore, annealing at 350° C reduced the hardness of copper, intermetallic bond, and aluminum from 85 ±3, 70 ±3, 30 ±3, respectively.

Considering Figure 11, hardness variations, especially in the intermetallic bond, decreases spring-back. Also, the annealing process at 500 ° C did not have much effect on the hardness of the copper (90 ±5 HV) and aluminum (30 ±5) layers. But the hardness of intermetallic bond increased and reached 230 HV. In conclusion, the hardness of the intermetallic bond was one of the major factors which increased the spring-back in annealed sample at 350 ° C in comparison with the other at 500 ° C.

Conclusion

This paper studied the experimental and numerical spring-back prediction of two copper/aluminum clad layers sheet in the L-die bending process as well as its effective decreasing parameters. The following results were obtained from the research:

1. Spring-back decreases with the decrease of the die's radius and clearance as well as increase of the sample length.

2. Stacking sequence layer effects on the spring-back and for the Al/Cu spring-back is less than that of Cu/Al.

3. The layers' thickness is a very significant parameter. With changing thickness from 100% copper to 100% aluminum, spring-back significantly alters. Furthermore, minimum value of spring-back is in 50% Aluminum- 50% copper. Also, due to the complicated behavior of the Cu/Al two-layer sheet, the effect of layer thickness has no certain behavior on the spring-back.

4. The rolling manufacturing process improves strength and decreases formability and forming ability of metal layers and therefore increases the spring-back.

5. Increase of annealing temperature does not significantly affect the hardness of the aluminum and copper layers, but it increases that of the intermetallic bond in the interface of Cu/Al layers as well as the spring-back of the sample.

Also, it is ideal for the future work of this paper's writers to focus on the spring-back of laminated sheets annealed at different times and temperatures and on the effects of inter metallic bonding hardness on the spring-back in several annealed temperatures.

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Table 1 Chemical composition (wt.%) of aluminum 1100 and copper C10100.

Table 2 FEM simulation conditions

Table 3 Applying boundary conditions in FE simulation (u_x: displacement in x-direction, u_y: displacement in y-direction)

Table 4 Result of experimental test and FEM simulation for effective parameters (radius, clearance and sample length)

Table 5 Aluminum and copper percent thicknesses

Table 1

element	Al layer	Cu layer
Al	99.49	0.0007
Cu	0.02	99.8
Si	0.12	0.00065
Fe	0.28	0.0044
Mn	0.02	0.00039
mg	0.02	0.00019

Table 2

Simulation model	Plane strain model
Object types	Sample: Elastic-plastic Punch/Die/Holder: Rigid
Element type	Cu , Al: Rectangular elements
Number of work piece elements	Cu: L_{80}* =4000, L_{60}=3000, L_{40}=2000 elements Al: L_{80}=8000, L_{60}=6000, L_{40}=4000 elements
Friction coefficient (μ)	0.1
Simulation method	Bending: explicit Spring back: implicit
Constrain type	Tie

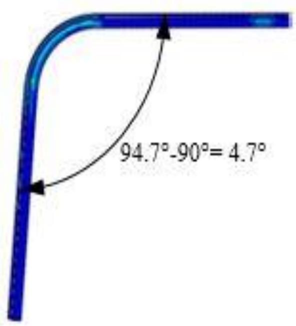
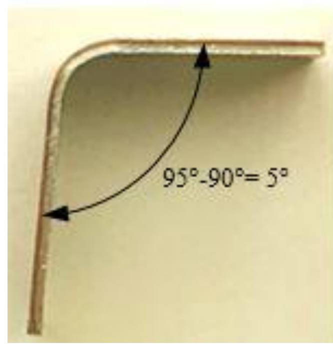
* L_{80} =4000 means the length of sample is 80mm with 4000 elements.

Table 3

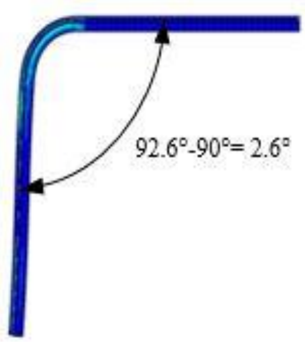
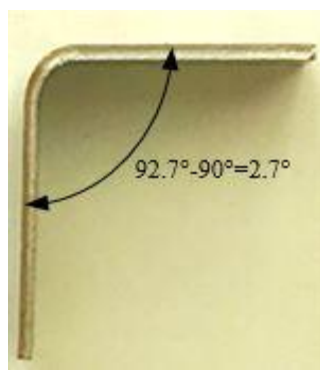
		Step 1	Step 2	Step 3
Boundary Condition	Punch	$u_x = u_y=0$	$u_x =0, v=-v_p$	$u_x =0, v=v_p$
	Die	$u_x= u_y=0$	$u_x= u_y=0$	$u_x= u_y=0$
	Holder	$u_x =0, v_y= -v_h$	$u_x= u_y=0$	$u_x= u_y=0$

Table 4

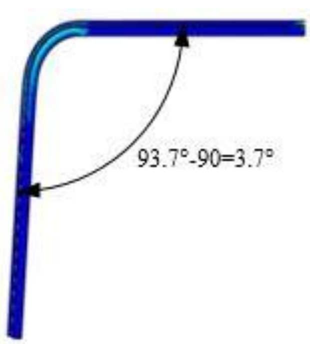
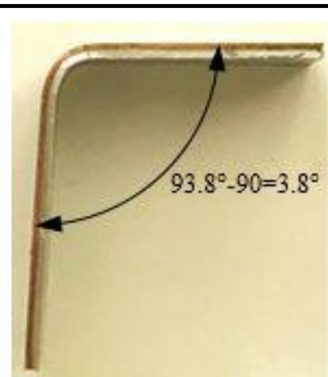
Variations of die radius(L=60mm, C=0.2mm)

FEM simulation	Experimental test	Result			
		Radius	Spring back		Error
		R	FEM	EXP	%
		3	1.55	1.5	3.33
		5	3.7	3.8	2.63
		7	4.7	5	6.00

Variations of die clearance(L=60mm, R=5mm)

FEM simulation	Experimental test	Result			
		clearance	Spring back		Error
		C	FEM	EXP	%
		0.1	2.6	2.7	3.70
		0.2	3.7	3.8	2.63
		0.3	4.53	4.8	5.62

Variations of sample length(R=5mm, C=0.2mm)

FEM simulation	Experimental test	Result			
		length	Spring back		Error
		L	FEM	EXP	%
		40	4.7	4.3	9.30
		60	3.7	3.8	2.63
		80	3.6	3.7	2.70

* The highlighted rows are the captured image's specifications of experimental test and FE simulation.

Table 5

Sheet thickness (%)			Spring back (°)		Error (%)
NO	Cu	Al	FEM	EXP	
1	100	0	3.18	3.20	0.62
2	88	12	2.94	…	…
3	75	25	2.86	…	…
4	66.66	33.33	2.72	…	…
5	55	45	2.55	…	…
6	50	50	1.74	…	…
7	45	55	2.00	…	…
8	33.33	66.66	3.70	3.80	2.63
9	25	75	3.63	…	…
10	12	88	3.30	…	…
11	0	100	3.10	2.80	10.71

Fig. 1. Stress–strain diagrams of copper and aluminum sheets.

Fig. 2. Schematic for L bending

Fig3. Bending process with hydraulic press machine

Fig. 4. Measuring spring back angle.

Fig. 5. FE simulation model.

Fig.6. Spring back of selected element to achieve optimum mesh size.

Fig.7. Diagrams of spring-back with respect to the change of effective parameters a) radius (L=60mm, C=0.2mm) b) clearance (L=60mm, R=5mm) c) length (R=5mm, C=0.2mm)

Fig.8. Layer stacking sequence

Fig.9.Spring back according to thickness percent of each layer

Fig.10. Spring back according to different die radius for different sample heat treatment.

Fig. 11. Hardness profile across the aluminum, copper and welded interface of sample

Figure 1

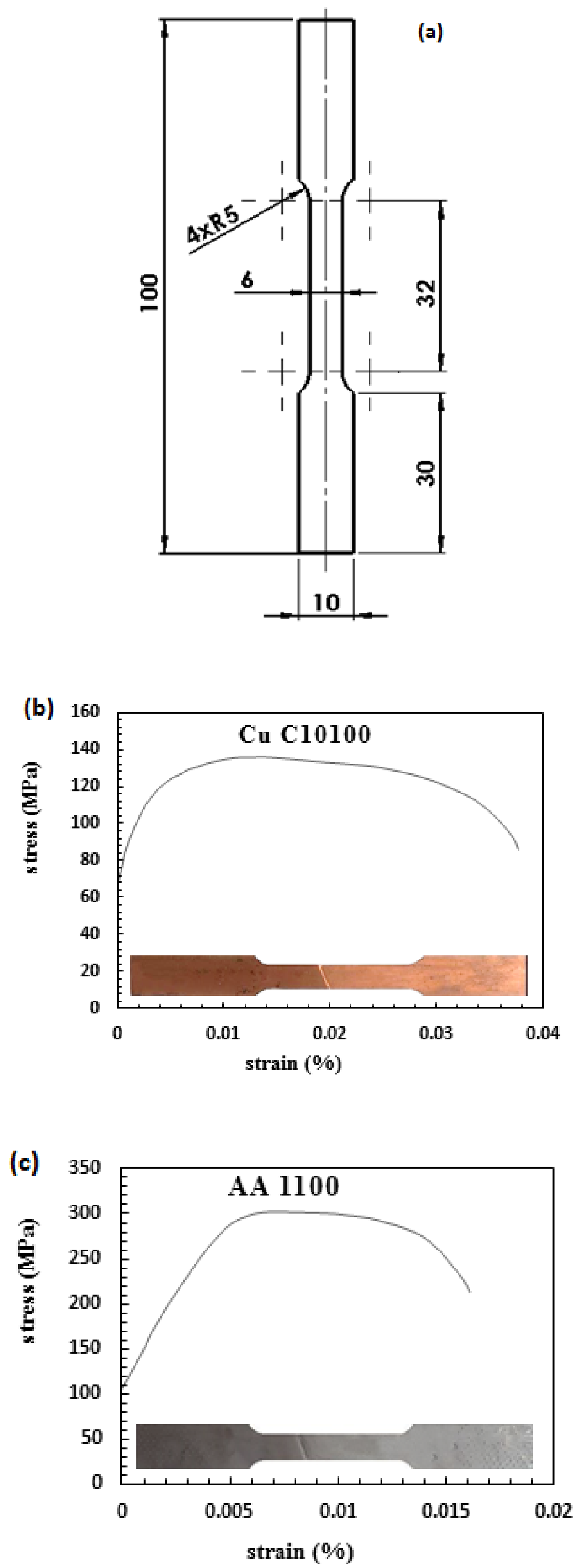

(a)
100
4xR5
6
32
30
10
(b)
Cu C10100
stress (MPa)
strain (%)
(c)
AA 1100
stress (MPa)
strain (%)

Figure 2

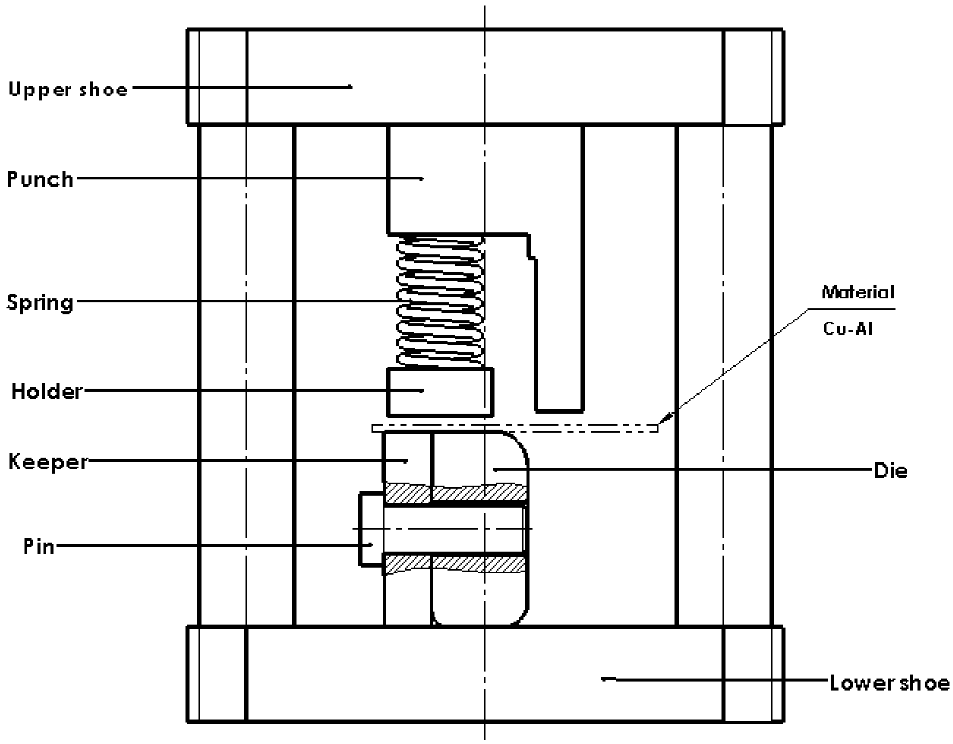

Upper shoe
Punch
Spring
Holder
Keeper
Pin
Material
Cu-Al
Die
Lower shoe

Figure 3

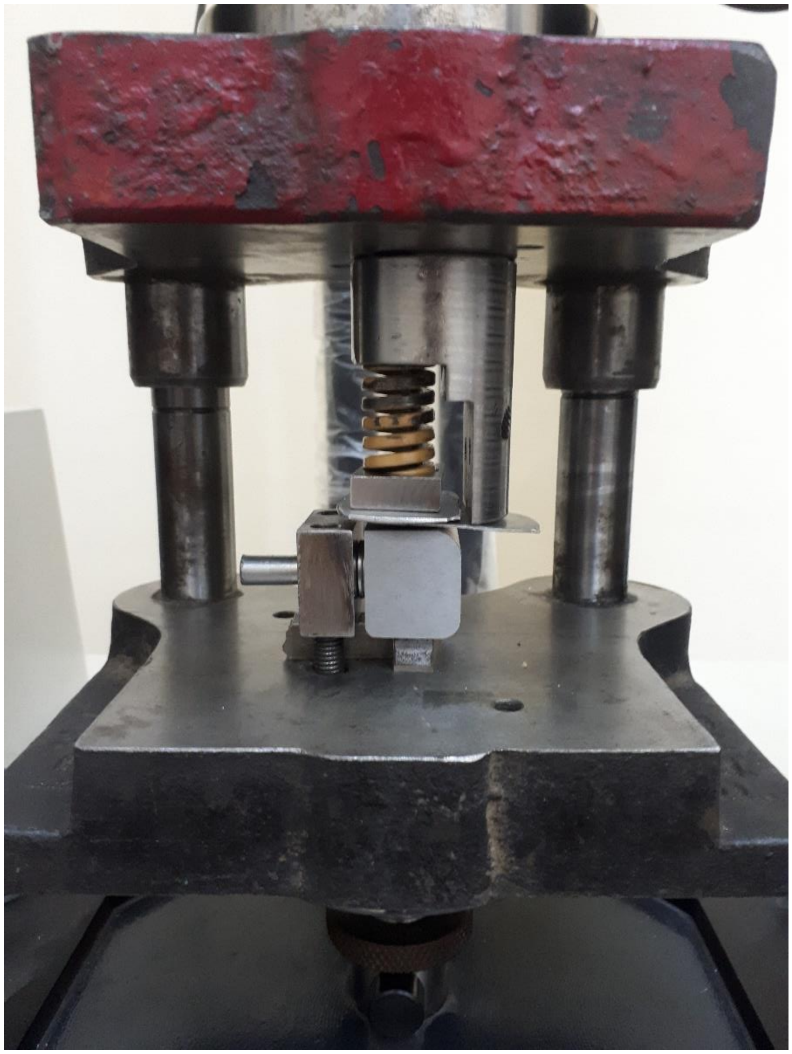


Figure 4

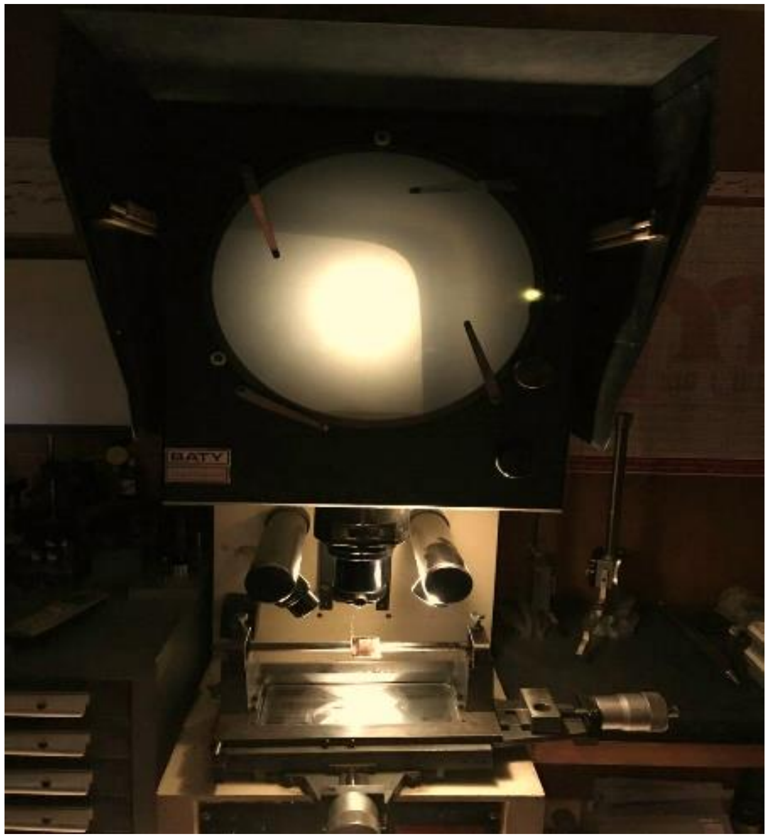


Figure 5

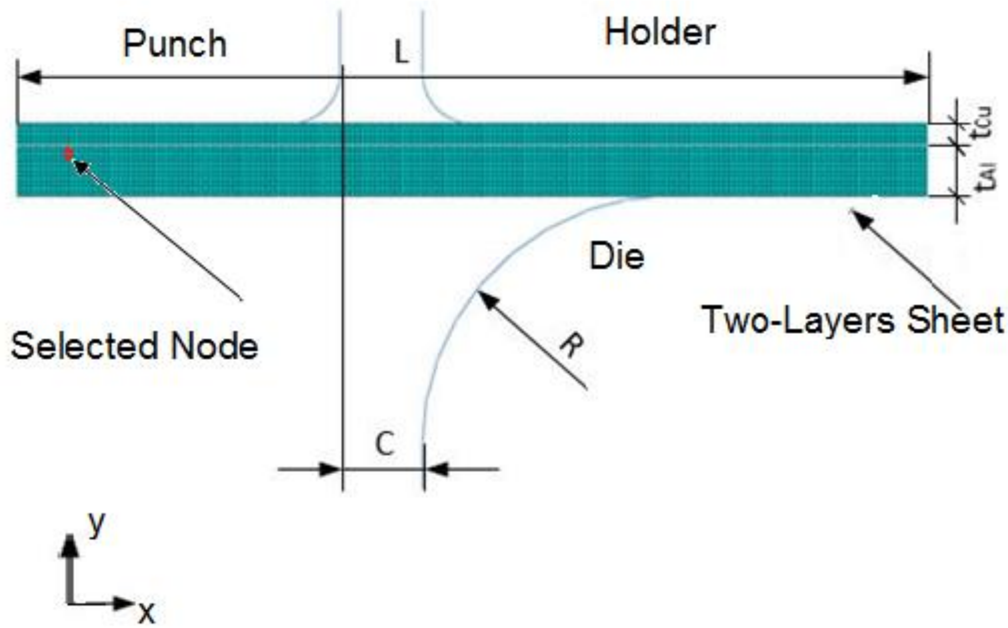
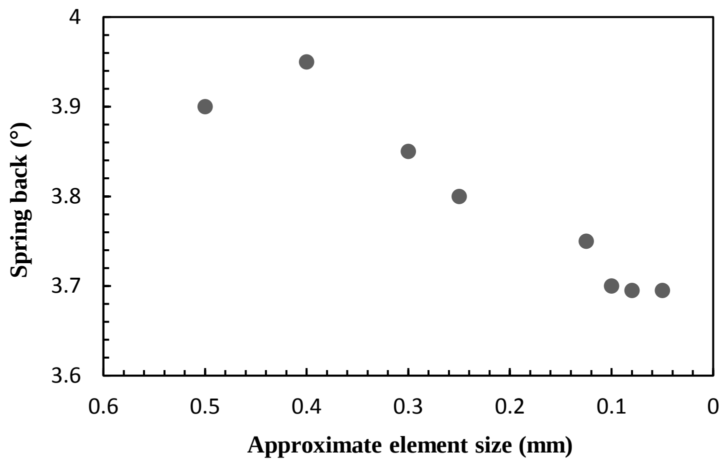

Punch
L
Holder
tCu
tAl
Die
Two-Layers Sheet
Selected Node
R
C
y
x

Figure 6



Spring back (°)
4
3.9
3.8
3.7
3.6
0.6
0.5
0.4
0.3
0.2
0.1
0
Approximate element size (mm)

Figure 7

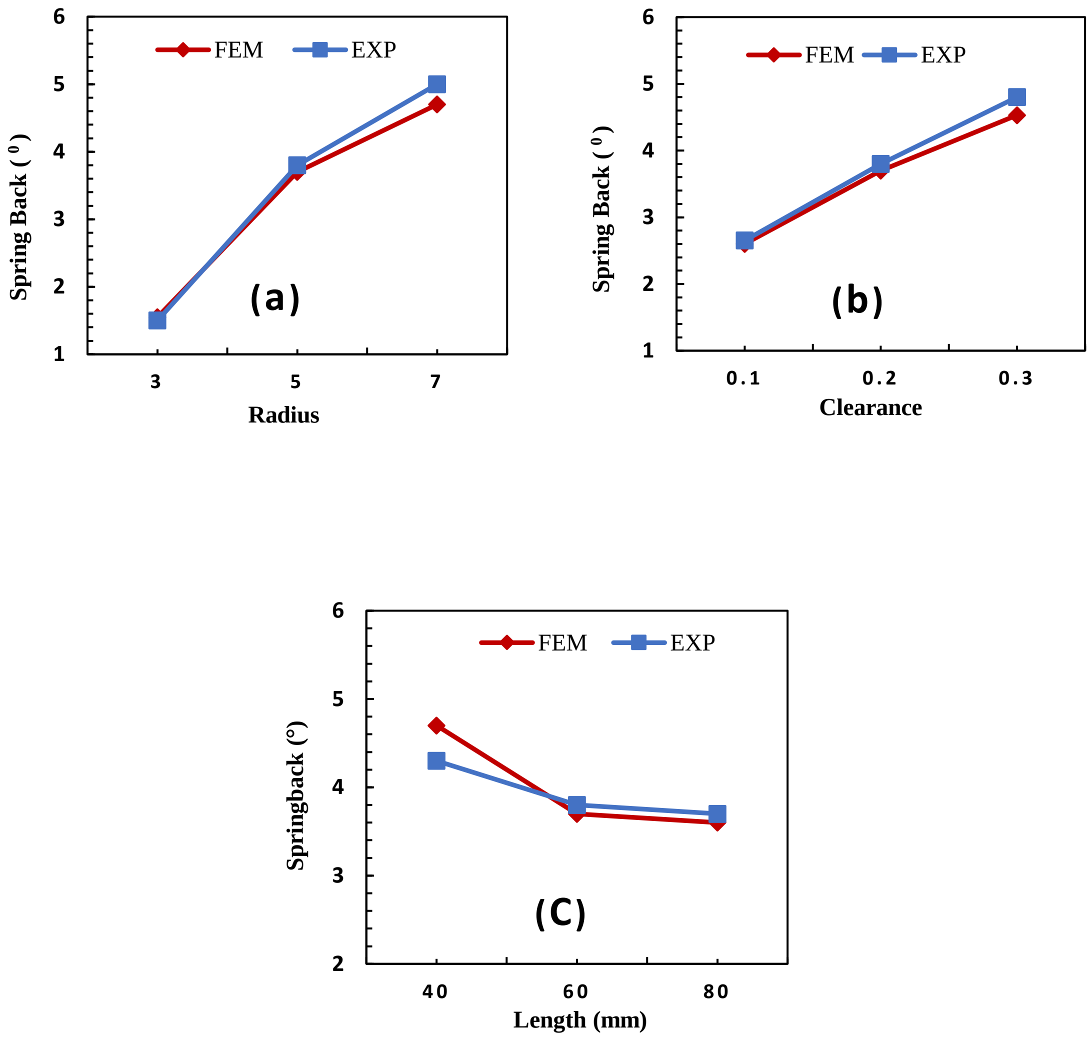

6
5
4
3
2
1
FEM
EXP
Spring Back (⁰)
(a)
3
5
7
Radius
6
5
4
3
2
1
FEM
EXP
Spring Back (⁰)
(b)
0.1
0.2
0.3
Clearance
6
5
4
3
2
FEM
EXP
Springback (°)
(C)
40
60
80
Length (mm)

Figure 8

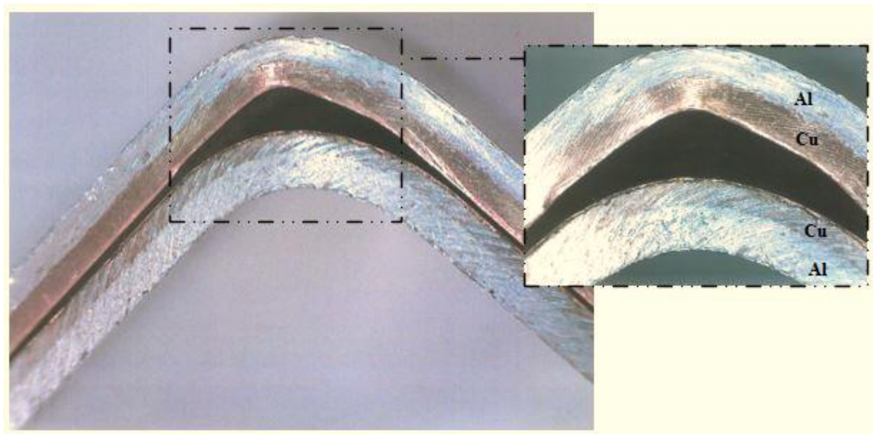


Figure 9

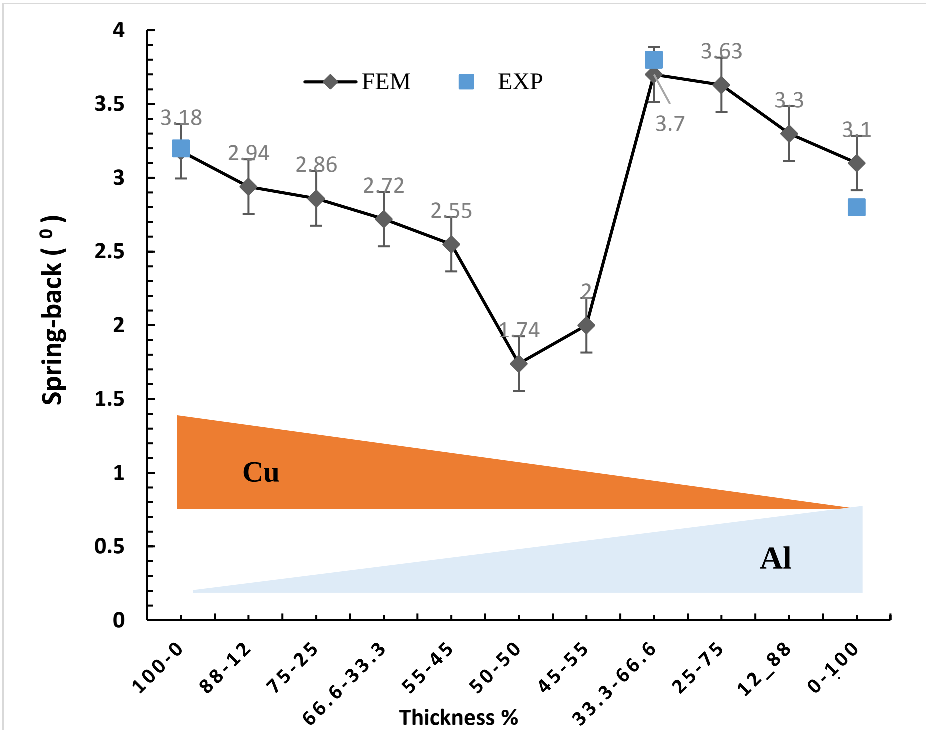

FEM
EXP
Spring-back (0)
Thickness %
Cu
Al
3.18
2.94
2.86
2.72
2.55
1.74
2
3.7
3.63
3.3
3.1
100-0
88-12
75-25
66.6-33.3
55-45
50-50
45-55
33.3-66.6
25-75
12_88
0-100

Figure 10

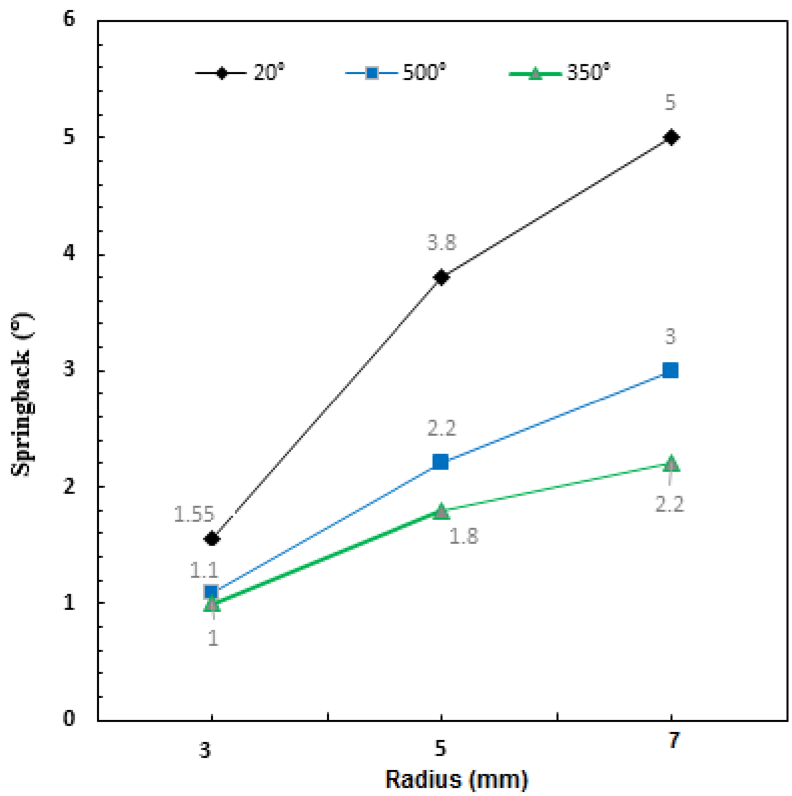
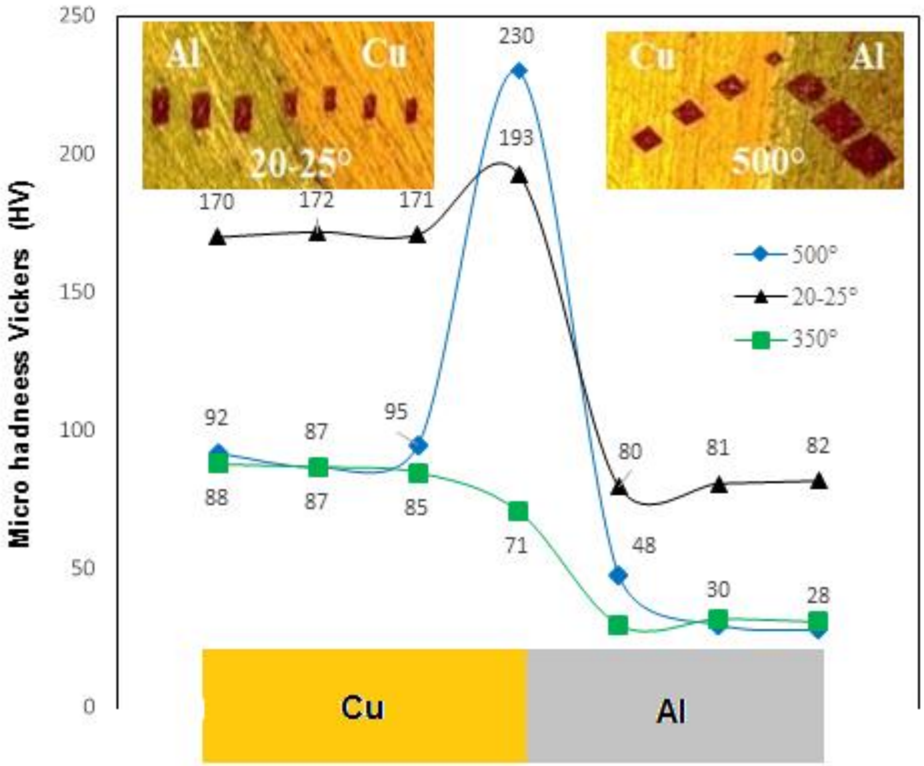

20°
500°
350°
Springback (°)
Radius (mm)
0
1
2
3
4
5
6
3
5
7
1.55
3.8
5
1.1
2.2
3
1
1.8
2.2

Figure 11



Micro hadneess Vickers (HV)
250
200
150
100
50
0
Al
Cu
20-25°
Cu
Al
500°
230
193
170
172
171
92
87
95
88
87
85
71
80
81
82
48
30
28
500°
20-25°
350°
Cu
Al