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An Experimental Study on the Process Parameters of Incremental Forming of Al-Cu Bimetal

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Formability.

Abstract

Single point incremental sheet metal forming is a process that forms products without the complex dies and tools with low cost. In this study, the incremental sheet metal forming process has been experimentally investigated on the explosively-welded Al/Cu bimetal sheets. Also, the effects of process parameters such as arrangement of layer`s bimetal, tool diameter, and tool path were investigated on the forming force, thickness distribution, formability, and roughness. At first, the bimetals were produced by explosive welding process. Then, two tool diameters, step and spiral tool paths and layer arrangement were chosen as input parameters. The results showed that the forming force increases with increasing the tool diameter and using aluminum as a top layer (contact with tool). Also, using spiral tool path increases the average forming force and decreases the maximum thickness changing. The formability increases with increasing the tool diameter and using the copper as top layer with spiral tool path.

1. Introduction

In the recent years, sheet metal forming industries try to reduce the final product costs and increase the flexibility of the process to manufacture complex geometries. Due to the cost of equipment and set up time, the conventional sheet metal forming processes are not appropriate to produce samples in the quickest way with complex geometries. This process consists of two sub-categories; single point incremental forming (SPIF) and multipoint incremental forming (MPIF) [1]. Measurement the forming force and thickness distribution are the most important challenges in this process. It has been shown that the forming force increases with increasing the vertical pitch, tool diameter, wall angle and initial thickness of sheet [2]. Silva et al. [3] investigated the formability of hole-flanging by SPIF. Montanari et al. [4] compared the relative performance of hole-flanging by incremental sheet forming and conventional press-working. Ambrogio et al. [5] introduced that magnesium has low formability at room temperature. Increasing the temperature up to 300 °C increases the formability of the magnesium sheet. Manco et al. [6] investigated the effects of tool diameter, vertical pitch, thickness and wall angle on the minimum thickness in the incremental forming by controlling and changing the design. The proposed equations showed that tool diameter

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has a significant influence on the minimum thickness and minimum thickness increased with increasing the vertical pitch. Mirnia et al. [7] analyzed the effect of tool diameter and vertical pitch on the thicknesses distribution in a truncated cone. They reported that by increasing the tool diameter the elasticity increases while the thickness decreases; and by increasing the vertical pitch to a specific amount the thinning improves. The surface roughness of parts formed by incremental forming has been analyzed recently [8]. Frattiniet al. [9] compared both traditional and incremental forming by reviewing the effect of some mechanical properties of materials on the formability. They found that the strain hardening is the main parameter on the formability. Iseki et al. [10] provided an approximate analysis to determine the formability of the sheet, strain distribution and forming forces. This analysis was performed using deformation plane strain model and forming limit diagram. Iseki and Naganawa [11] developed a gradual multi-stage forming machine by using spherical and cylindrical rollers to form the vertical wall surfaces of thin rectangular panels. Filice et al. [12] showed an increase in formability due to local plastic deformation in the area around the tool by designing the experiments to determine the forming limit curve. Attanasio et al. [13] tried to optimize the tool path in positive incremental sheet forming process. The purpose of this work was experimental evaluation of the tool path. Young et al. [14] evaluated the wall thickness variations in the single-point incremental forming process. They showed that double-pass forming produces the parts that thin to failure with single-pass techniques. Hussain et al. [15] investigated the formability of pure titanium sheet by using incremental sheet forming. In this study, the effect of step and tool diameter on the formability and tool wear were compared. The results showed that the formability decreases linearly with increasing steps and also it is reduced by increasing the diameter of the tool and feed rate. Hamilton et al. [16] paid to review the effects of feed rate on the incremental forming. Tests on Al3003 sheet with a maximum feed of 8890 mm/min were completed and it was observed that the feed rate does not have a significant effect on the thicknesses distribution. Al-Ghamdi and Hussain [17] examined the effects of annealing on the forming forces and formability in the Cu/steel clad sheet and they showed that forming forces decreased with increasing annealing temperature. It was shown that the surface roughness was highly dependent on the vertical pitch.

Explosive welding process relatively is a new method to join metals together as solid-state [18]. The explosive-welded materials are known as the new industrial materials [19]. The Al/Cu bimetal is one the used explosively-welded products that can be used in industries [20].

Some research has been carried out on the formability of single-layer sheets so far while no research has been done on the explosive welding multilayers sheets. The explosive welding is a solid-state welding process that uses the force of the explosion to create a metallurgical bond between the two layers. In general, these new materials have superior properties such as corrosion and wear resistance with proper mechanical and metallurgical properties. Therefore, the incremental forming process of explosively-welded Al/Cu bimetal has been reported in this study.

2. Principle and equipment of experimental setup

Holder, tools, CNC mill machine, dynamometer, and CMM machine were the used equipment in this experiment. Also, the Al/Cu bimetal sheets fabricated by explosive welding were used in this experiments in 160×160×2 mm. In this process, the tool was used in a cylindrical shape with a hemispherical head. The dynamometer of a KISTLER 9257B model was used and placed under the holder to measure the forming force (Fig. 1). In this process, the tool motion was controlled numerically. Therefore, the required part was modeled in CAD/CAM software (CATIA), and next the model was transferred to the POWERMILL software and tool path was generated. The NC codes were obtained from the generated tool path and transferred to the CNC machine.

In order to form the part with high accuracy, it is important to select the best tool paths. In this study, there were two strategies in the tool path. The first strategy was to step tool path (Fig. 2(a)). In this strategy the tool started to form the desired geometry step by step. The second strategy consisted of spiral tool path (Fig. 2(b)).

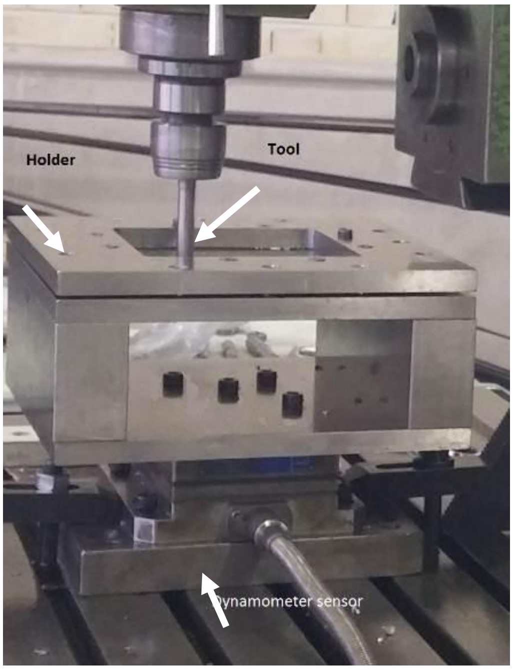
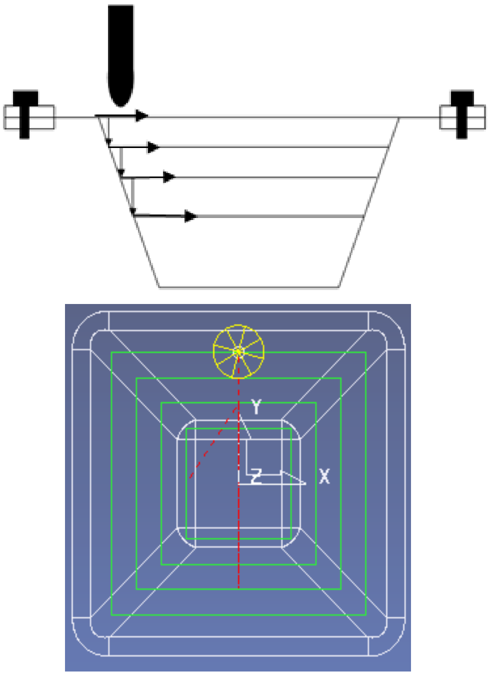


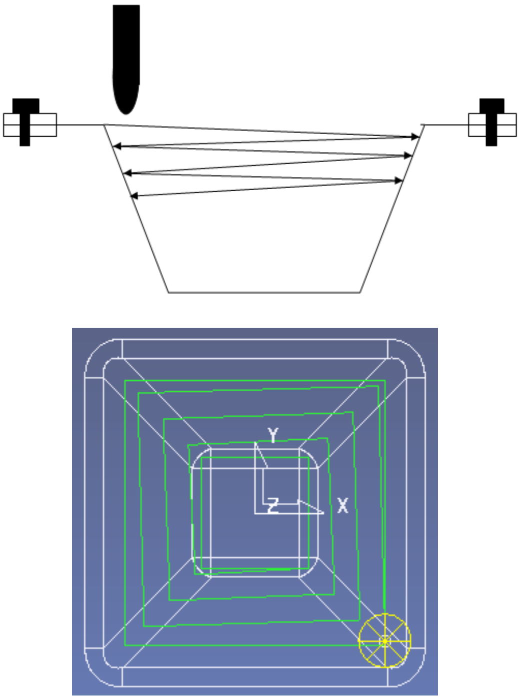
Fig. 1. A general view of holder, dynamometer sensor, and tool.

The explosively-welded bimetals sheets were consisted of Al and Cu sheets. In the present study, layer arrangement was a parameter that can be considered. In order to investigate the layer arrangement, the experiments were performed in two states; the Cu layer as the top layer (contact with tool) (Fig. 3(a)) and the Al layer as the top layer (Fig. 3(b)).

One of the most important parameters in the incremental sheet metal forming is tool diameter. The contact zone between the tool and sheet increases with increasing the tool diameter. Increasing the contact zone increases the forming forces and maximum thickness changing and decreases formability of the sheet. Two tool diameters, 10 and 16 mm were used in this study, according to the literature. The tools were made from Mo40. The effect of the tool diameters were investigated on the forces and thickness change. The input parameters and the design of experiments are shown in Table 1.



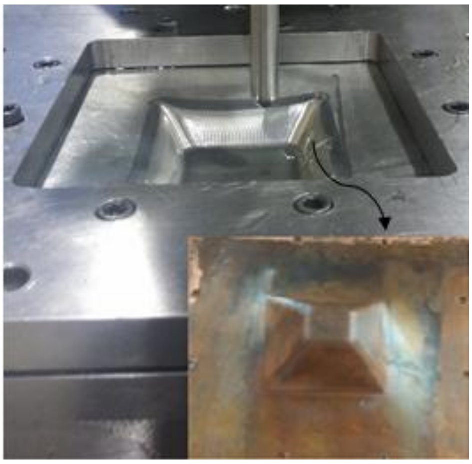
(a)



(b)

Fig. 2. (a) Step tool path and (b) Spiral tool path.

(a)



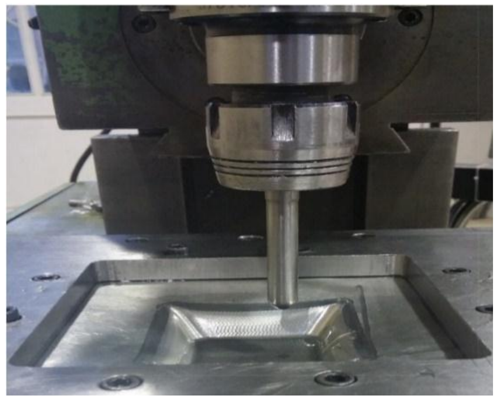
(b)

Fig. 3. (a) Cu as top layer and (b) Al as top layer.

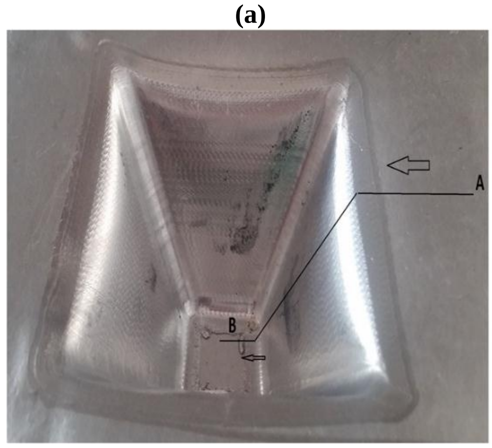
Table 1. The input parameters and their values.

Parameters	Tool diameter	The contacted layer with tool	Tool path
1	10	Al	Spiral
2	16	Cu	Step

The aim of this study was to investigate the effect of the forming parameters on the maximum thickness reduction, roughness, formability and forming forces. Tool diameter, layer arrangement, and tool path were studied and for each factor, two values were selected (Table 2). For this experiment, the truncated pyramid (Fig. 4(a)) with an opening dimension of 73×73×60 mm height and 60 degrees wall angle was used.



(a)



(b)

Fig. 4. (a) The truncated pyramid test and (b) Defined path.

3. Results and discussion

In this section, the effects of parameters such as tool diameters, motion strategy and the contacted layer with the tool have been experimentally investigated on the forming force, roughness, formability, and thickness reduction of formed samples.

Table 2. Design of experiments.

No.	Tool diameter	Layer Arrangement	Tool path
1	10	Al	Step
2	10	Al	Spiral
3	10	Cu	Step
4	10	Cu	Spiral
5	16	Cu	Spiral
6	16	Cu	Step
7	16	Al	Spiral
8	16	Al	step

3.1. Forming Force

In this section, the effects of tool paths, tools diameter and layer arrangements have been studied on the forming forces (Fig. 5). The results of forming forces show that because of the strain hardening during the tool movement, sheet resistance increases which lead to increase in the force diagram. In addition, due to the increasing tool contact area with the sheet in the corners, the amount of force was partially large. These results show that the maximum average force occurs in the case where the tool diameter was 16; Al was used as the top layer and the tool path was spiral.

3.1.1. Arrangement

The effect of arrangements on the forming forces were examined. The results of forming force are shown in Fig. 6. The results indicate that the average force decreases when the copper is used as the top layer. The average difference between the force results is about 5%. According to the way of this process, yielding starts from outer layer to inner one. The Al naturally has lower yield stress than copper. Therefore, as Al is the outer layer, plastic deformation or in other words moving of dislocations is started sooner and as a result, the lower force is needed in order to deformation starts.

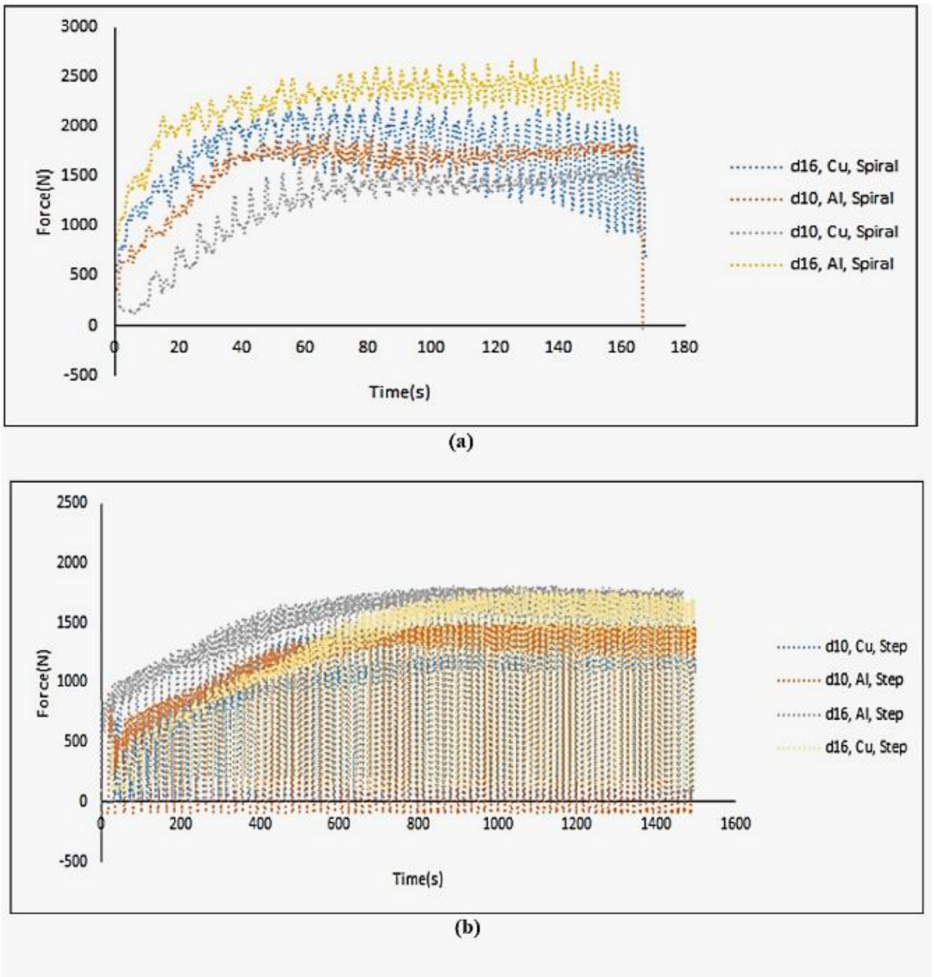


Fig. 5. (a) Effect of spiral tool path on the forming forces (b) the effect of step tool path on the forming force.

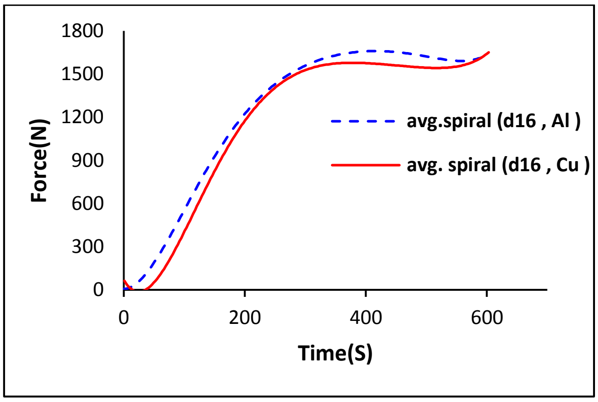


Fig. 6. The variation of forming force as different sheet arrangement (Diameter: 16 mm, tool path: spiral).

3.1.2. Tool path

Forming, in the incremental sheet metal forming, is done gradually with tool movement, so that the desired shape is achieved at the end of the process by tool movement and for this reason it was important to determine the tool path. The effect of tool path (Fig. 7) on the forming forces was examined.

The results show that the average force decreases about 45% in case of using step tool path. This is because of separating the tool from the sheet after the forming a certain height at each step. According to Fig. 8, at the A and B, the tool separates from the sheet and the vertical force increases in the positions 1,2, 3, and 4 because of the increases in the mentioned points in the contact zone between the tool and sheet.

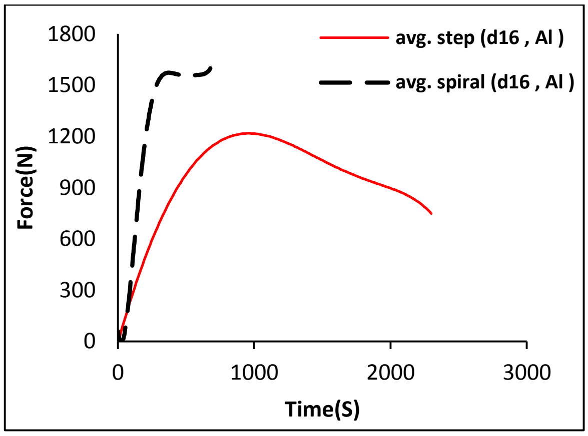


Fig. 7. The variation of forming force as different tool path (Diameter: 16 mm, top layer: Cu).

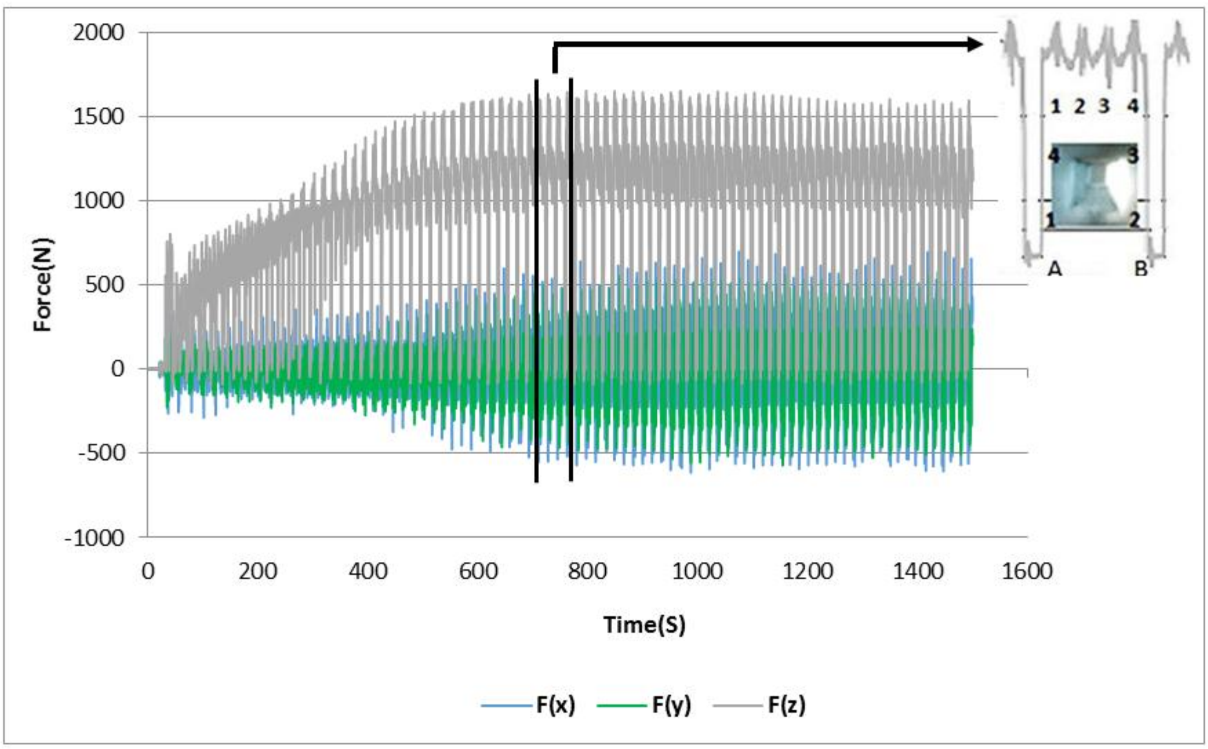


Fig. 8. Obtained forces diagram by dynamometer in case of step tool path (Diameter: 10, arrangement: Cu**).**

3.1.3. Tool diameter

The effect of tool diameter on the forming forces was examined. The results of average force are shown in Fig. 9. Results indicate that the average force increases about 33% by increasing the tool diameter. Due to increasing the contact zone between tool and sheet, the forming force increases.

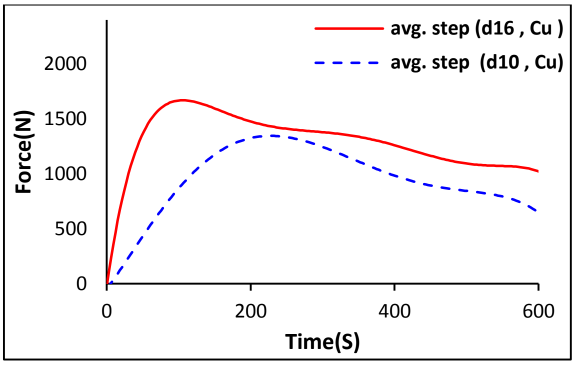


Fig. 9. The variation of forming force as different tool diameter (top layer: Cu and tool path: step).

3.2. Effects of process parameters on the thickness changing

In this section, the effects of tool paths, tool diameters, and arrangements have been investigated on the thickness distribution. It is necessary to mention that the defined path is A-B and presented in Fig 4(b). The results showed that the maximum thickness changing occurred in the case where the Al used as the top layer and tool diameter and tool path were 16 mm and step, respectively. Since the final geometry was identical in all samples, the maximum thickness changing happened at almost near the line 2 (Fig. 10).

Also, Fig. 11 presents the thickness distribution at the samples in different conditions.

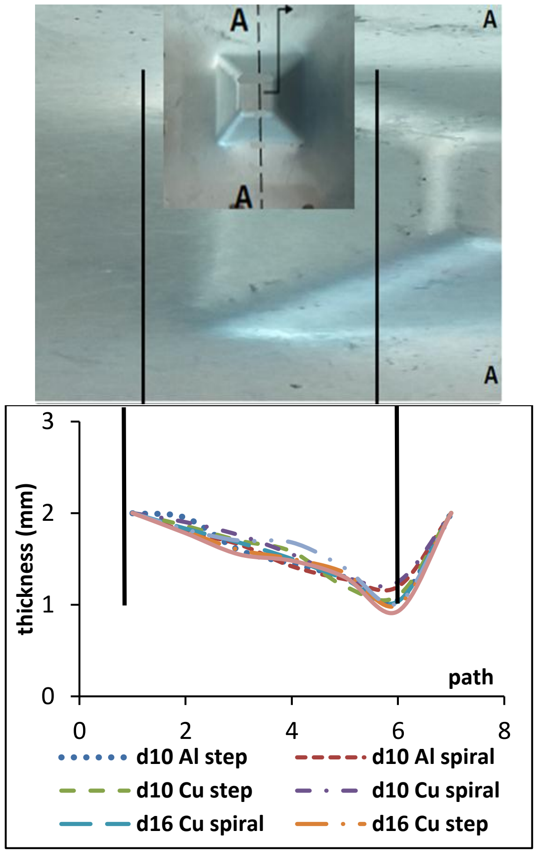
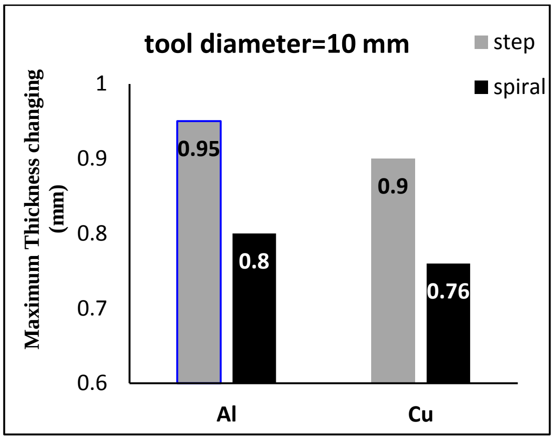
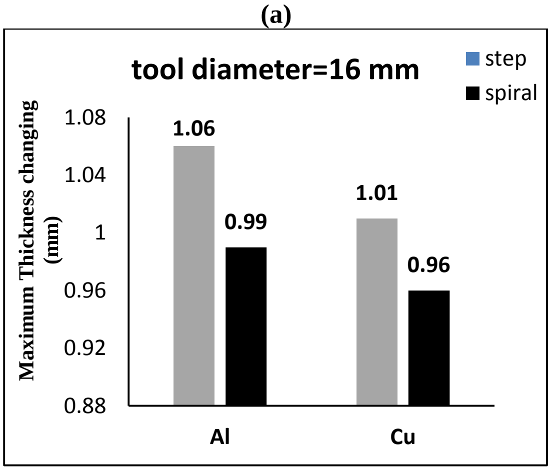


Fig. 10. The thickness changing at the all models (according to the defined path in the Fig. 4(b)).

The effects of arrangement on the thickness distribution showed that the maximum thickness changing increases when Al is used as the top layer. This phenomenon is due to the formability of Al and its sticking to the tool in the forming operations. Also, using the spiral tool path decreased the thickness changing rather than the step tool path. According to the other works [21], these results are acceptable. This is because of the more uniform thickness distribution and less thinning occur in the spiral tool path. According to the Fig. 9, the thickness changing increases by increasing the tool diameter. There is a good agreement between these results and other works [11, 14]. This is because of increasing the contact zone between the tool and sheet.

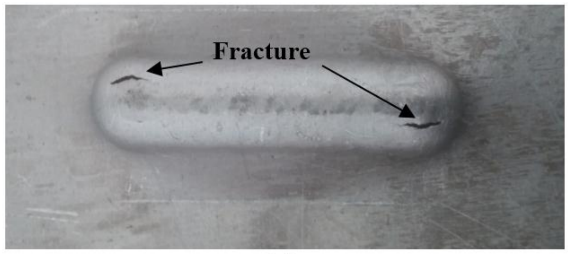


(a)



(b)

Fig. 11. The variation of thickness changing at different conditions.



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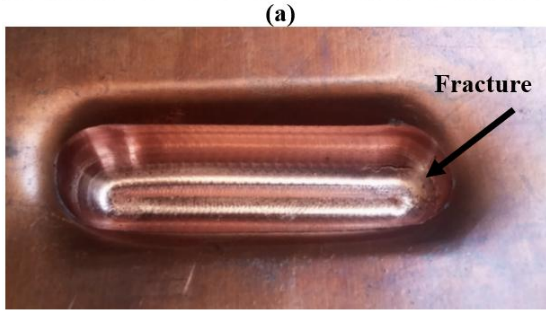


(b)

Fig. 12. The failure in the sheet (a) Cu as a top layer (b) Al as a top layer.

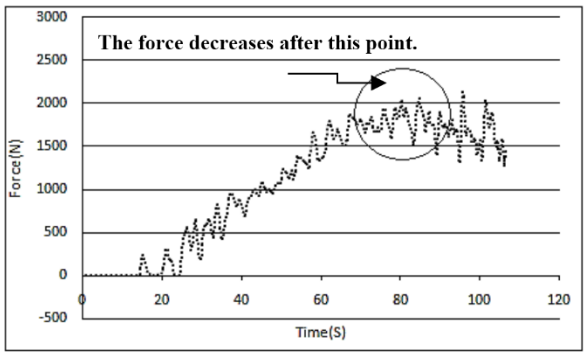
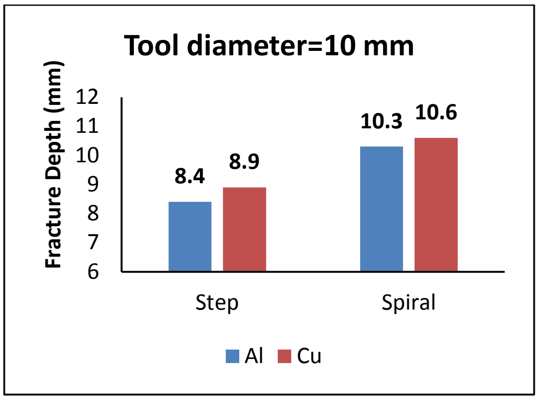


Fig. 13. Using the force diagram to obtain the fracture depth (Diameter: 16 mm, tool path: spiral, top layer: Al).

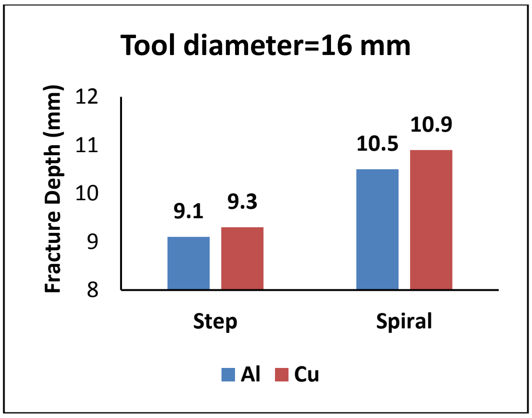
3.3. Effects of process parameters on the formability

Direct groove test is one of the methods to evaluate the formability of the sheets in the incremental sheet metal forming. In this test, the tool moves along a linear path and goes down as much as vertical step and comes back the same path. This operation continues until the sheet failure. It can be observed visually (Fig. 12) or by force curve. In case of using the force diagram, at the time of failure, severe drop can be seen in the force graph (Fig. 13).

In this section, the effects of tool paths, tool diameters and layer arrangements have been investigated on the formability of the Al-Cu bimetals (Fig. 14). It is necessary to mention that the formability of this sheet because of explosive welding is different with Al and Cu. The results showed that the maximum formability occurs in the case where Cu is used as the top layer, and tool diameter and tool path are 16 mm and spiral, respectively.



(a)



(b)

Fig. 14. Effects of tool path and arrangement on the formability at tool diameter (a) d=10 mm (b) d=16 mm.

The effects of arrangement on the formability show that this parameter increases when Cu is used as the top layer. This phenomenon is due to the formability and flexibility of Al as the downer layer. Also, using the spiral tool path decreases the thickness changing rather than the step tool path and this makes, in this case better formability. According to the Fig. 14, the formability increases by increasing the tool diameter. There is a good agreement between these results and other works [3]. This is due to reduced stress concentration in the contact zone between the tool and sheet at the tools with larger diameter.

3.3. Effects of process parameters on the surface roughness

In this section, the effects of input parameter have been studied on the surface roughness (Table. 3). The results of surface roughness measurement showed that by increasing tool diameter, because of the increased contact zone and using Cu as the top layer to reduce adhesion to the tools in comparison with Al sheets and using spiral tool path because of no single treatment effect compared to the step tool path, the amount of Ra and Rz decreases and conditions improve. These results show that the minimum surface roughness occurs in the case where the tool diameter is 16 mm, Cu is used as the top layer, and the tool path is spiral.

Table 3. Effects of tool path, tool diameter and arrangement on the surface roughness.

No.	Tool diameter (mm)	Layer Arrangement	Tool path	R_a (µm)	R_z (µm)
1	16	Al	Step	0.739	3.96
2	16	Al	Spiral	0.686	3.53
3	16	Cu	Step	0.670	3.39
4	16	Cu	Spiral	0.569	2.50
5	10	Cu	Spiral	0.710	3.46
6	10	Cu	Step	0.728	3.77
7	10	Al	Spiral	0.776	4.08
8	10	Al	step	0.780	4.12

4. Conclusions

In this study, layer arrangement of explosive-welded Al/Cu bimetal was investigated in the incremental sheet metal forming process. The following conclusions can be drawn:

1. Using copper as a surface layer reduces the forming forces due to the lower yield strength and better formability of aluminum. This arrangement increases the maximum height of formability because of the different behavior of layers in terms of formability.
2. Using the step tool path reduces the average forces of forming rather than the spiral tool path.
3. Spiral tool path decreases the maximum sheet thickness changing. The maximum thickness changes increases by using aluminum as the top layer. Also, the thickness changing increases by increasing the tool diameter.

4. The maximum fracture depth is obtained when tool diameter is 16 mm, Cu is used as the top layer and spiral tool path is used. Also, the best roughness occurs at these conditions.
5. The best surface roughness is obtained when the tool path, tool diameter and arrangement are spiral, 16 mm and Cu, respectively.
6. The maximum thickness changing occurs when tool path, tool diameter and arrangement are step, 16 mm and Al, respectively.

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