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Investigation of Fracture Depth of Al/Cu Bimetallic Sheet in Single Point Incremental Forming Process

A. Gheysarian and M. Honarpisheh*

Faculty of Mechanical Engineering, University of Kashan, Kashan, Iran

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ABSTRACT

Single point incremental sheet forming (SPISF) has demonstrated significant potential to form complex sheet metal parts without using component-specific tools and is suitable for fabricating low-volume functional sheet metal parts economically. In the SPIF process, a ball nose tool moves along a predefined tool path to form the sheet. This work aims to optimize the formability and forming forces of Al/Cu bimetal sheet formed by the single-point incremental forming process. Two levels of tool diameter, step size, tool path and sheet arrangement were considered as the input process parameters. The process parameters influential in the formability and forming forces have been identified using the statistical tool (response table, main effect plot and ANOVA). Analysis of variance (ANOVA) was used to indicate potential differences among the means of variables by testing the amount of population within each sample, which enabled it to show the effects of input variables on output ones. A multi response optimization was conducted to find the optimum values for input parameters by response surface methodology (RSM), and the confirmatory experiment revealed the reliability of RSM for this approach.

1. Introduction

One of the modern and flexible forming processes is called incremental sheet forming (ISF). This process allows metals to form into complex components with less energy and minimal equipment. An automated forming tool moves along a specified path to assist the process; it forms the sheet into complicated profiles for prototype applications. This process involves two methods, the simplest method of ISF is single-point incremental forming (SPIF), which uses only one forming tool to form components and the other method is double-sided incremental forming (DSIF), which uses two forming tools to form components. In this method, at any moment in time, one of these tools will be forming the component and the other one will act as support. Jesweit et al [1] introduced and described asymmetric single point incremental forming as a new development in asymmetric sheet metal forming. According to the researches, the forming forces increase by increasing the vertical step, tool diameter, wall angle and initial thickness of the 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] stated that magnesium has low formability at room temperature. The formability of the magnesium sheet increased by increasing the temperature up to 300 °C. 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

* Corresponding author
E-mail addresses: honarpishe@kashanu.ac.ir (M. Honarpisheh)

resultant equations showed that tool diameter has a significant influence on the minimum thickness, and that minimum thickness increased by increasing the vertical pitch. Mirnia et al [7] analyzed the effect of tool diameter and vertical pitch on the thickness distribution in a truncated cone. They reported that by increasing the tool diameter, the elasticity increased, while the thickness decreased; besides, they came to the conclusion that increasing the vertical pitch to a specific amount would improve the thinning. The surface roughness of those parts formed by incremental forming has been analyzed recently [8]. Frattini et al [9] compared both traditional and incremental formings by reviewing the effect of some mechanical properties of materials on the formability. They found that the strain hardening is the main parameter affecting 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 et al [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 the formability of the sheet due to local plastic deformation in the area around the tool and determined the forming limit curve by designing the experiments. Attanasio et al [13] tried to optimize the tool path in positive incremental forming process. The purpose of this work was the experimental evaluation of the tool path. Young et al [14] evaluated the wall thickness variations in 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 by increasing the steps, and it also decreases by increasing the diameter of the tool and feed rate. Hamilton et al [16] reviewed 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 thickness distribution. Kurra et al [17] evaluated the effect of process parameters on surface roughness and manufacturing time by using ANOVA and RSM, then a multi-objective optimization, using NSGA-II, was performed on the responses. Wenke Bao et al [18] investigated the influence of electropulse-assisted incremental forming (EAIF) on the formability of AZ31B alloy. The experimental results showed that the electroplastic effect increases with a rise in the root mean square (RMS) current density of the electropulse, and the forming limit angle in EAIF has been up to 72° from the previous 39.6° without the electropulse. It is found that the electropulse can reduce the AZ31B dynamic recrystallization (DRX) temperature and accelerate the DRX progress, and it can also restrain the crack growth of the tested materials, which in turn improves thier formability. Kurra Suresh et al [19] investigated the formability of incremental sheet forming by using finite element simulations and compared the results by experimental values. Senthil et al [20] investigated the formability of AZ61A magnesium alloy by numerical analysis of incremental sheet metal forming process. Mugendiran et al [21] investigated the formability and thickness distribution of AA5052 aluminum alloy by incremental forming process. They showed that a conical cup has a higher forming limit than a square one, and the thickness after forming is better in conical rather than in square cups. McAnulty et al [22] investigated the effect of process parameters such as step down, feed rate, spindle speed and etc. on the formability in the incremental sheet metal forming. Uheida et al [23] investigated the impact of tool velocity on mechanical and thermal process loads in incremental forming of titanium sheets. They showed that higher speeds corresponded to higher temperatures and lower forces. Afonso et al [24] investigated the formability of tunnel type part in incremental sheet metal forming. The goal was to increase the flexibility, maximize part size, and reduce both the material waste and the need for post processing operations. The study finished with manufacturing some more elaborate geometries, plus testing and validating the tunnel incremental forming concept to be used in free form parts.

Explosive welding process is one of the relatively new welding processes which join similar and dissimilar metals together [25]. Investigation of post process on Al/Cu bimetals and Al/Cu/Al multilayers has been carried out in recent years [26-30]. Incremental forming process of an explosive-welded multilayer is one of the attractive fields which have been used in recent years. Sakhtemanian et al [31] investigated layer arrangement in the incremental forming process of low-carbon steel/CP-titanium bimetals. Experimental study on the process parameters of incremental forming of explosively-welded Al/Cu bimetal was performed by Gheysarian et al [32]. Multi-response optimization on single-point incremental forming of hyperbolic shape Al-1050/Cu bimetal using response surface methodology was also done by Honarpisheh et al [33]. Honarpisheh et al [34] investigated the process parameters on the forming force, dimensional accuracy and thickness variations in the incremental forming process of Al/Cu bimetals, numerically and experimentally. Sakhtemanian et al [35] investigated mechanical and geometrical properties of St/CP-Titanium bimetal sheet during the single point incremental forming process. They showed that by increasing the vertical step down, hardness and tensile properties of the specimens increase, but the thickness reduction in the wall of the pyramidal specimens increases and also the surface quality decreases. In another work, they presented a novel material modeling technique in the single-point incremental forming assisted by the ultrasonic vibration [36]. The presented model was used as the definition of material behavior in the finite element simulation. Based on the provided model, the tool temperature increases rapidly in the early stages of vibration and then reaches a constant value.

The aim of this study is to evaluate the fracture depth in the incremental forming process of the explosive-welded Al/Cu bimetal sheet. To achieve this objective, the incremental forming of the bimetals was performed according to design of experiment (DOE). The effective parameters were tool diameter, tool path, sheet arrangement and step down. Maximum depth of the fracture and forming force were measured, and the ANOVA was used to analyze and extract the forming force and fracture depth model.

2. Principle and Equipment of Experimental Setup

Different equipment is needed for this experiment such as holder, forming tools, CNC mill machine and dynamometer (Fig. 1).

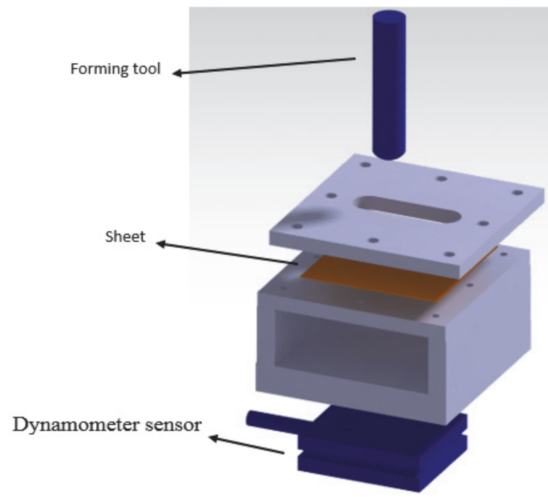


Fig. 1. The equipment used in this study

The dynamometer of a KISTLER 9257B model is used and placed under the holder to measure the forming force. In this process, the tool motion is controlled numerically. Therefore, the required part was modeled in CAD/CAM software (CATIA), and then the model was transferred to the POWERMILL software and the tool path was generated NC codes were obtained from the generated tool path and transferred to the controller of CNC machine by CIMCO software. The milling machine moves the forming tool into the mold and in the specified path and forms the test sheet (Fig. 2).

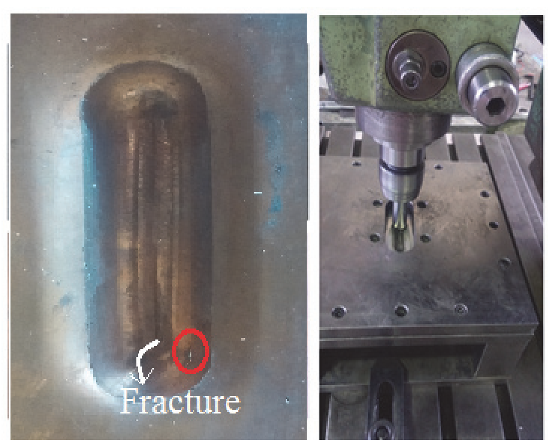


Fig.2. A general view of holder, formed sheet and tool

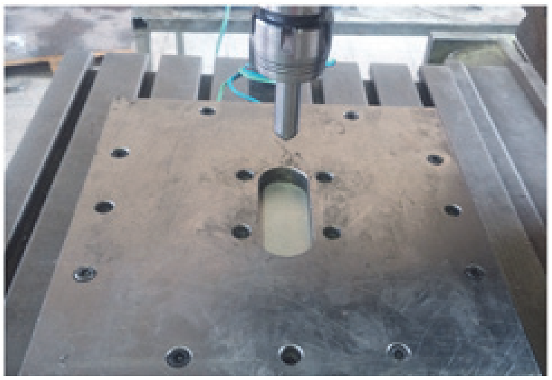


Fig.2. Continue

2.1. Material and tools

The Al/Cu bimetal sheets fabricated by explosive welding process are used in this experiment which are prepared in 12 slides of 100×40×2 mm including six holes in 8 mm diameter around the plate according to the design of the experiments by DESIGN EXPERT software. The welded plate is employed due to the excellent corrosion resistance of copper and the mechanical properties of aluminum (i.e. higher strength with lower weight). To ensure that the welding has been done correctly between the layers, a part of the used sheet is observed with microscope at different levels of magnification. One of the results is shown in the (Fig. 3).

In this process a two-head forming tool is used with hemispherical heads which have the diameters of 10 mm and 16 mm, and it is placed in the 3-axis CNC mill machine. The fixture, shown in (Fig. 1), is machined from CK 45 steel blank by the CNC milling machine. SAE-40 liquid oil is used as lubricant to reduce friction between the forming tool and the plate during the incremental forming.

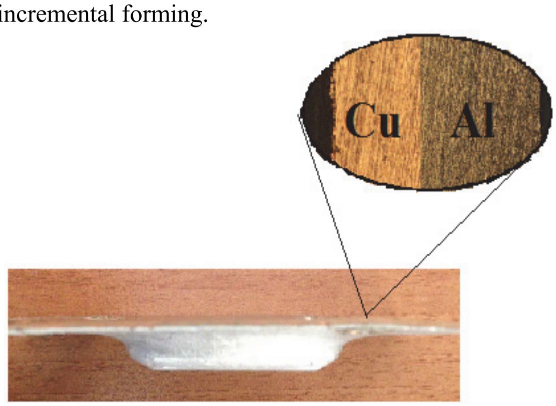


Fig. 3. Observation of the layers of the sheet by microscope

2.2. Design of part

In the current work, direct groove testing (Fig. 4) is used to obtain the maximum shaping height. The tool moves along the displayed path until the sheet is broken and deflected. The tool path (G codes) is extracted from CAD model by POWERMILL software and transferred to the controller of CNC machine by CIMCO software. Z parameter in the figure represents the vertical step.

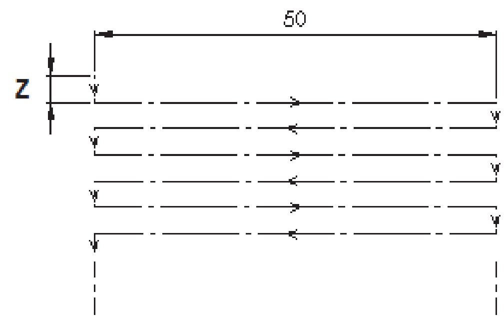


Fig. 4. Direct groove test

2.3. Design of experiments and process parameters

At the beginning of each process, an appropriate design is needed to carry out the required tests that determine and investigate the proper distribution of each parameter. Design of Experiment (DoE) methods are the ways that help researchers to track the impact and amount of each parameter and prevent the waste of time and cost. In this study, the design is constructed using RSM method with tool diameter, step down, sheet arrangement and tool path in two levels (i.e. L1 and L2) as input factors by DESIGN EXPERT software, which are shown in Table 1 and it is seen that there are 12 different states which should be performed by SPIF process (Table 2).

Table 1. Parameters of the experiment and used level

Input parameters	Level 1	Level 2
Tool diameter	10	16
Tool path	Spiral	Step
Sheet arrangement	Al	Cu
Step down	0.25	1

Table. 2. Design experiments

No.	Tool diameter	Step down	arrangement	Tool path
1	10	0.25	Al	Spiral
2	10	1	Cu	Step
3	10	0.25	Cu	Step
4	10	1	Al	Spiral
5	10	1	Cu	spiral
6	10	0.25	Al	Step
7	16	1	Al	Step
8	16	0.25	Al	Spiral
9	16	0.25	Cu	Spiral
10	16	1	Al	Spiral
11	16	1	Cu	Step
12	16	0.25	Cu	Step

As mentioned in the previous sections, an explosive welded Al/Cu bimetal sheet is used in this experiment and the effects of input parameters on the forming force and ductility of this sheet are investigated. The sheet arrangement refers to the side where the bimetal plate touches the forming tool, as instance sheet arrangement of Al means that the aluminum side of the blank plate is on the top and the forming tool touches only this side of the plate.

2.4. Fracture depth and forming force measurement

Maximum forming height is achieved by direct groove testing, which indicates the degree of sheet shape ductility. In this way, the tool starts moving in a straight line, based on the defined path, until the sheet is torn. This tear is detectable by observing the sheet or using the force chart. This rupture is clearly visible by pouring oil from a torn sheet or a sudden drop in the force chart (Fig. 5). A sudden change occurs in this chart when it reaches its maximum height and failure occurs. This chart has been obtained by the dynamometer and represents the vertical force input into the forming tool. This chart increases ascendency until the duct leaves or fails, and hereafter, the chart draws the downside due to a failure in the sheet.

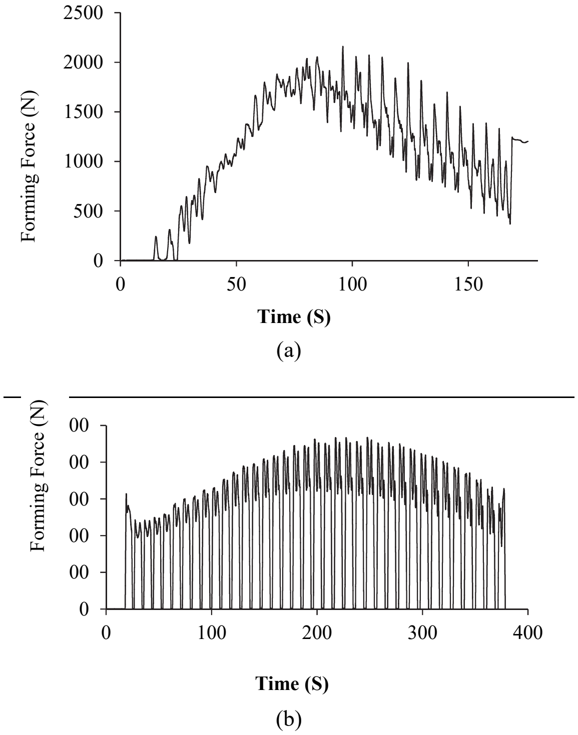
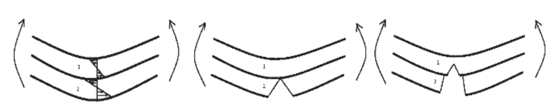


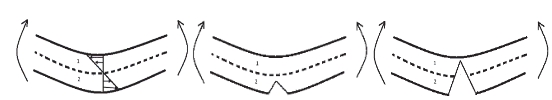
Fig. 5. Forming force variations for (a) Spiral tool path (b) Step tool path

According to the principles of resistance, the highest stresses in bending are introduced into the outer layer of the sheet. When two sheets are placed together without any mechanical and chemical bonding and are shaped with incremental sheet metal forming, first the outer layer and then the inner layer are torn, which is due to the greatest stress on the outer layers (Fig. 6), while in sheets with explosive-welding, the thickness is reduced until both sheets are torn at the same time (Fig. 7). In these materials, the strength of the material increases due to the explosive welding and the tear depth is greater than the time that sheets are placed on one another without any connection.



(a) (b) (c)

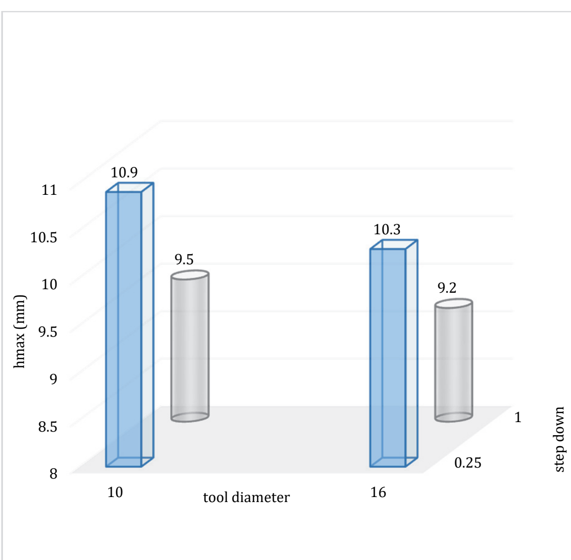
Fig. 6. Rupture of unconnected sheets



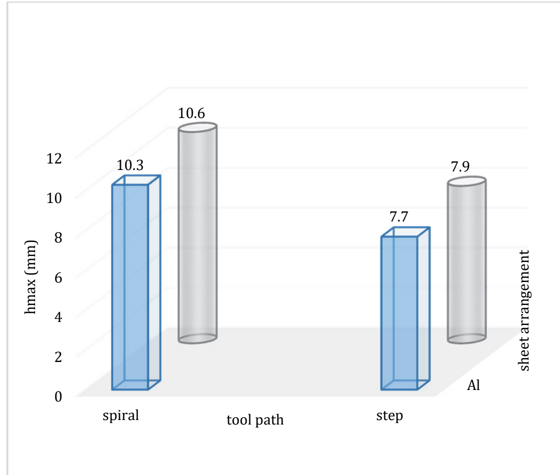
(a) (b) (c)

Fig. 7. Tearing of explosive welding sheets

The resulting tear depth can be obtained by the VMM or from the existing CNC program. In Fig. 8, the effects of the input parameters on the results are shown. The results indicate that by increasing the tool diameter, the level of the engagement of the sheet and tool increases, and a higher level of the sheet is formed by the tool, which increases the force and decreases the formability. Increasing the vertical step such as increasing the tool diameter increases the forming force and decreases the formability because of increases in the shaping volume. The use of the stepped tool path, due to the separation of the tool and the re-engagement with the sheet at each step, reduces the average shaping forces. Using spiral tool path improves the condition of ductility, due to the fact that the tool is not detached being continuously in contact with the sheet; besides, fewer shocks are introduced into the sheet, and also, the thickness variation is uniform compared to step tool path. When copper is the underside of the sheet, the forming forces increase. This is because copper yield stress is higher than that of aluminum, copper is harder and most tensions come to the outer layer. Moreover, using copper as the top layer improves the formability of the substrate due to the better formability of aluminum as the underside layer and because most stresses come to the underside layer.



(a)



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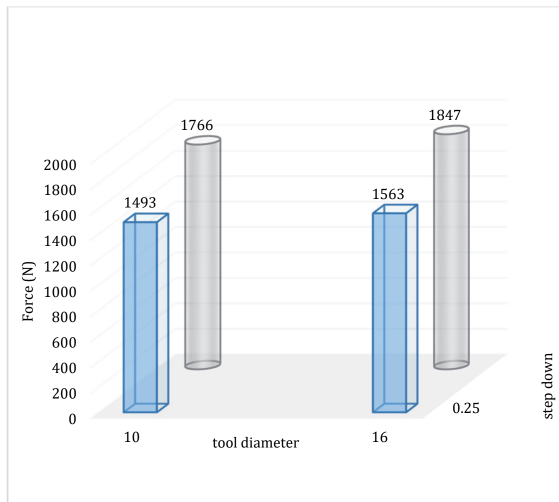
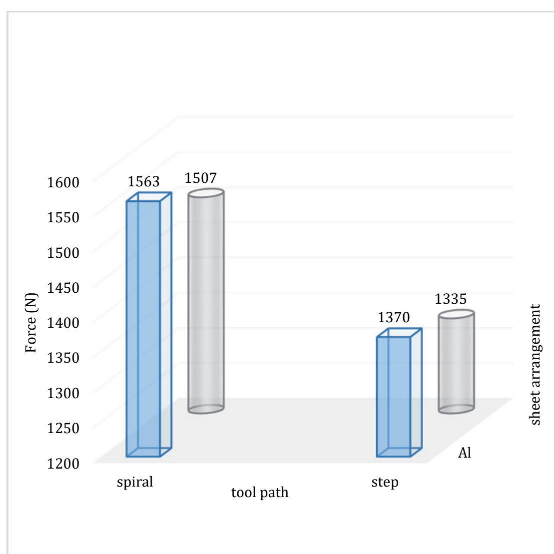


(c)



(d)

Fig. 8. Effects of input parameters on the results

3. Finite Element Analysis

Finite element analysis is one of the suitable methods for examining a variety of processes, including incremental sheet metal forming, which saves costs and finds key factors in this process. In the current study, the 3D model of Al/Cu bimetal was developed as shown in Fig. 9 in ABAQUS/explicit platform. The element type in the modeling was C3D8R element and the total number of elements of this modeling was 2896. One of the ways to inject a tool path to ABAQUS software is using subroutines, but this method does not provide reliable answers because this path is not used in reality. In this study, the taken G-codes were inserted to ABAQUS software from the Power Mill software, which makes the movement path of the forming tool exactly the same as its path in reality, as in the simulation with the best results. In this process, the forming takes place until the sheet is broken. At the corners of the tested geometry, the amount of stress increases due to the concentration of stress at these places from which the tear begins and then extends.

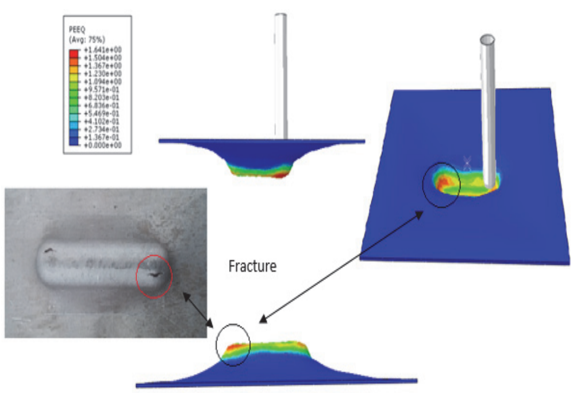


Fig. 9. 3D model of incremental forming in the ABAQUS

Tool and plate support were assumed analytically rigid. The forming tool moves along the defined path and forms the plate. The procedure is actually quite simple: while the tool incrementally forms the blank plate, the deformation continues until the first crack appears. The results of forming force measurement indicate the appropriate matching between the experimental and numerical results (Fig. 10).

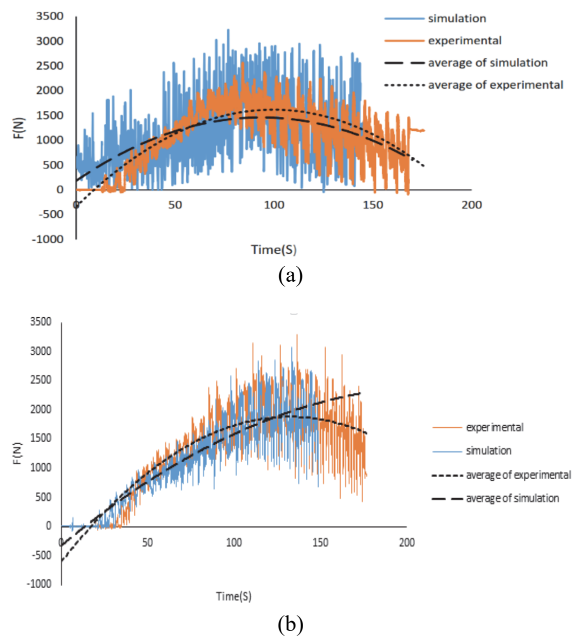


Fig. 10. Numerical and experimental results of forming force
(a) Tool diameter: 10, step down: 0.25, sheet arrangement: Al, tool path: spiral
(b) Tool diameter: 16, step down: 0.25, sheet

4. RSM and Optimization

Response surface methodology (RSM) is a helpful method to investigate the relationships between the measured and the input parameters. In this study, we investigated the effect of step down, tool diameter, tool path and arrangement as input parameters on the forming force and formability. Calculating regression coefficients has been done by DESIGN EXPERT software. Among the input parameters, the tool path and sheet arrangement are non-numeric and therefore, the software provides a model for each mode of these two parameters.

4.1. Response surface modeling

Response surface methodology (RSM) explores the relationships between the input and output parameters. central composite design (CCD) tool is used to determine the number of experiments required to study the responses. The forming and response parameters were modeled using RSM method. The aim is to obtain the optimal response of the input parameters to the output ones through a quadratic model. This design consists of the following three portions:

a) A complete 2k factorial design, where k is the number of variables whose factors' levels are coded as -1 and 1

b) Axial portion of 2k points arranged in such a manner that two points are chosen at a distance of α from the design center

c) No center points

Thus the total number of the design points in a CCD is $n = 2\^k+2k+no$. The minimum possible number of experiments (N) can be determined from the following equation

$$N = nf + na \quad (1)$$

where $nf = 2\^k$ and $na = 2k$, nf defines the number of factorial points and na defines the number of axial points or star points.

Design Expert provides prediction equations in terms of actual units and coded units. The coded equations are determined first, and the actual equations are derived from the coded ones. The experimental results from the forming trials performed according to the matrix by central composite full factorial design are tabulated in Table 3. These results are given as input in Design Expert software for further analysis.

RSM offers two models for each of the formability and forming forces by using the results obtained from the designed experiments and examining the relationship between these results and the input data of the first model which includes a coded formula. The second model also includes a formula that is consistent with the fact that the second model can be used to obtain the parameter in the future without having to redo the tests (Table. 4a to b). The models provided in Tables 4a and 4b indicate that the step down and then the tool path have the greatest impact on h_{max} and the forming force.

Table. 3. Design experiment and results.

No.	Tool diameter	Step down	Arrangement	Tool path	F_{mean}	h_{max}
1	10	0.25	Al	Spiral	1493	10.9
2	10	1	Cu	Step	1296	8.1
3	10	0.25	Cu	Step	992.1	9.3
4	10	1	Al	Spiral	1766	9.5
5	10	1	Cu	spiral	1668	9.7
6	10	0.25	Al	Step	1033	9.1
7	16	1	Al	Step	1370	7.7
8	16	0.25	Al	Spiral	1563	10.3
9	16	0.25	Cu	Spiral	1507	10.6
10	16	1	Al	Spiral	1847	9.2
11	16	1	Cu	Step	1335	7.9
12	16	0.25	Cu	Step	975.2	8.9

Table. 4 Final equation in terms of coded factors (a) Forming forces (b) h_{max} model.

F_{mean}=1333.00+ 39.33 * A+ 123.50 * B- 19.06 * C+ 143.81* D		
Final equation in terms of actual factors:		
Sheet	Machining	Equation
Al	Step	F_{mean}= 831.97222+ 13.11111* tool diameter+ 329.33333 * step down
Cu	Step	F_{mean}= 793.84722+ 13.11111* tool diameter+ 329.33333* step down
Al	Spiral	F_{mean}= 1119.59722+ 13.11111* tool diameter+ 329.33333* step down
Cu	Spiral	F_{mean}= 1081.47222+ 13.11111* tool diameter+ 329.33333* step down

(a)

h_{max} =+9.27-0.18*A-0.59 * B+0.11*C+0.82*D+0.063 * A* B-0.031 * A * D-0.044 *B* D		
Final equation in terms of actual factors:		
Sheet	Machining	Equation
Al	Step	h_{max} = 10.34722+ -.084722* tool diameter-2.422 * step down
Cu	Step	h_{max} = 10.57222 + -.084722 * tool diameter-2.422 * step down
Al	Spiral	h_{max} =12.41389+ -.084722 * tool diameter-2.422 * step down
Cu	Spiral	h_{max} = 12.63889 + -.084722 * tool diameter-2.422 * step down

(b)

The validity of this model is checked by using the analysis of variance (ANOVA). It can be concluded from this analysis that the obtained model is complete enough to predict the desired results. This analysis states the significance of variables by using F- value parameter and that any primary parameter with a higher F- value is more effective in the model. In this analysis the confidence level is 95 %; therefore, factors with P- values of less than 5% are certainly impressive in the desired result.

The results of the ANOVA are shown in Tables 5 and 6. These results indicate the significance of the model terms (sheet arrangement, tool diameter, step down and tool path) with regard to the forming forces and formability. Among these factors, the step down is the most significant one with a high F-value for the response of the surface to the results followed by the tool path. The high F-value for this model shows that the presented model is meaningful and significant for forming forces, and formability and the use of this model can lead to meaningful conclusions which are in accordance with reality.

Table. 5. ANOVA for forming forces model.

Response 1: forming force Analysis of variance table						
Source	**Sum of squares**	**df**	**Mean square**	**F value**	**p-value prob > F**	
Model	1.084E+006	10	1.084E+005	37630.47	0.0040	significant
A-tool diameter	6204.98	1	6204.98	2154.51	0.0137	
B-step down	1.903E+005	1	1.903E+005	66070.42	0.0025	
C-arrangement	71877.36	1	71877.36	24957.42	0.0040	
D-tool path	2.196E+005	1	2.196E+005	76256.52	0.0023	
AB	36.98	1	36.98	12.84	0.1733	
AC	21809.16	1	21809.16	7572.63	0.0073	
AD	14322.78	1	14322.78	4973.19	0.0090	
BC	30294.91	1	30294.91	10519.07	0.0062	
BD	17344.53	1	17344.53	6022.41	0.0082	
CD	49704.20	1	49704.20	17258.40	0.0048	
Residual	2.88	1	2.88			
Cor Total	1.084E+006	11				

Table. 6. ANOVA for h_{max}.

Response 1: h_{max} Analysis of variance table						
Source	**Sum of squares**	**df**	**Mean square**	**F value**	**p-value prob > F**	
Model	11.60	7	1.66	1591.20	<0.0001	significant
A-tool diameter	0.35	1	0.35	336.40	<0.0001	
B-step down	3.76	1	3.76	3610	<0.0001	
C-arrangement	0.10	1	0.10	97.20	0.0006	
D-tool path	5.44	1	5.44	5227.20	<0.0001	
AB	0.031	1	0.031	30	0.0054	
AD	0.010	1	0.010	10	0.0341	
BD	0.020	1	0.020	19.60	0.0114	
Residual	4.167E-003	4	1.042E-003			
Cor Total	11.61	11				

In this test the stepwise method is used. This method removes those values which are not significant, i.e. with a confidence level of 95%. The results of the ANOVA for forming forces indicate that the F value of the tool path is the highest, followed by the step down, arrangement and tool diameter as the most effective input parameters for the forming forces (Table 5), and as for the h_{max} , they indicate that the F value of the tool path is the highest, followed by the step down, arrangement and tool diameter as the most effective input parameters for the h_{max} (Table 6).

In order to ensure the proper linear output data, the normal test is used. Normal test results of the answers are shown in Fig. 11 to Fig. 12 indicating that the answers are acceptable. In case of non-normality of this data, it will be required to normalize the data before evaluation.

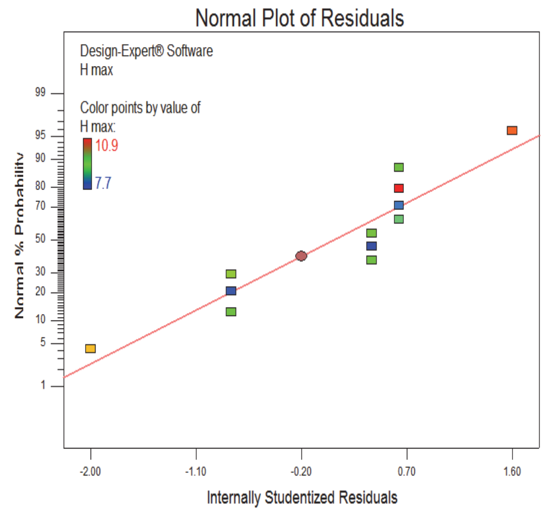


Fig. 11. Normal test result for h_{max}

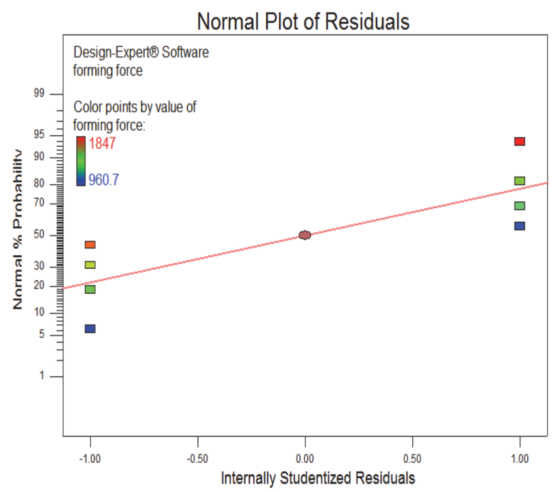


Fig. 12. Normal test result for forming forces

4. 2. Optimum point

Multi-response optimization, based on the desirability of goals, was employed in order to find the optimum point which gives the maximum fracture depth and minimum forming forces possible during the SPIF. Optimization tool bar provided by MINITAB gives the researcher the capability to find the optimum point of the experimental processes. The headlines of the optimization process by the software are [24]:

1. Finding the individual desirability for each response separately

2. Combining those individual desirabilities in order to evaluate the desirability of the composite

3. Searching for maximum composite desirability and the respecting input variables.

Table 7 depicts constrains of the process parameters and the responses; furthermore, the weights of the responses are equal to 1.

Table. 7. Optimized factors.

No.	Tool diameter	Step down	Arrange ment	Tool path	Forming force	h_{max}	Desirabi lity	
1	12.36	0.25	Cu	Spiral	1090.82	10.9	0.942	Selected
2	11.39	0.25	Cu	Spiral	1112.37	10.9889	0.932	
3	11.36	0.25	Cu	Spiral	1113.12	10.992	0.932	
4	11.16	0.25	Cu	Spiral	1117.61	11.0105	0.930	
5	10	0.25	Al	Spiral	1490.25	10.8917	0.710	
6	10	0.25	Al	Spiral	1491.7	10.8844	0.708	
7	10	0.25	Cu	Step	959.15	9.31667	0.653	
8	10	0.25	Al	Step	1033	9.09167	0.576	
9	10	0.25	Al	Step	1034.6	9.07043	0.570	
10	10	0.25	Al	Step	1038.1	9.02401	0.557	

According to Table 8, the best conditions for forming forces can be achieved when the tool diameter is 12 mm, the step down.25 mm and copper is used as the top layer. For formability, conditions are similar to forming forces, except for the tool path. Suitable tool path for forming forces is step and for formability is spiral and in this case, the utility of the presented model is maximum and the forming force is minimum.

RSM optimization method is based on the utility of the parameters and results, and the range of desirability is from 0 to 1. If the answer equals the purpose, then the utility is equal to 1, and if the answer is outside the acceptable range, then the utility is zero. Relatively high level of utility function (1) for tool diameter, vertical step, sheet arrangement and tool path variables as independent factors of each output parameter, demonstrates the effectiveness of each one and equals the value of the target. (Fig. 13).

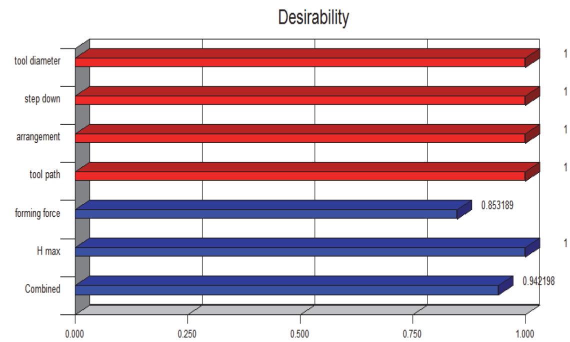
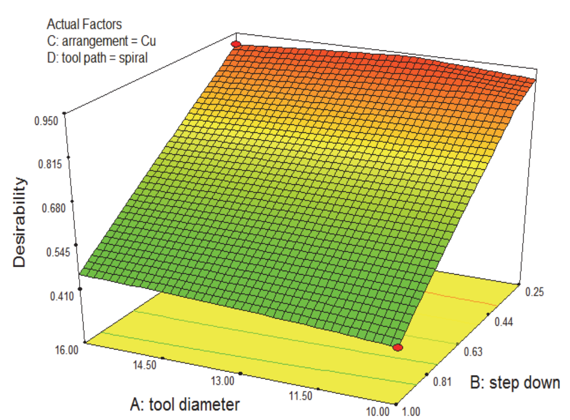


Fig. 13. Desirability of the input and output parameters

4. 3. 3D response surface plot

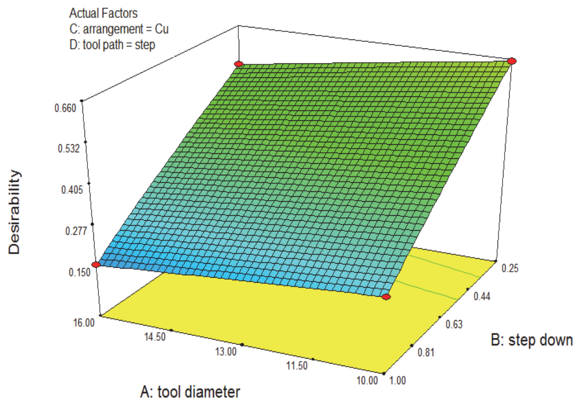
3D response surface plots, which are the graphical representations of the regression equation, are useful to understand the interaction properties between the input and output parameters. The ultimate aim of the plot is to predict the optimum values of the variables whether the responses are maximized or minimized. Each contour represents an infinite number of combinations of two input variables with the response maintained at zero level.

Elliptical contour is considered as a measure of perfect interactions among independent variables. The response surface models for h_{max} and forming forces are given in Figs. 14a to 14d. The figures show the estimated h_{max} and forming forces as a function of input variables.

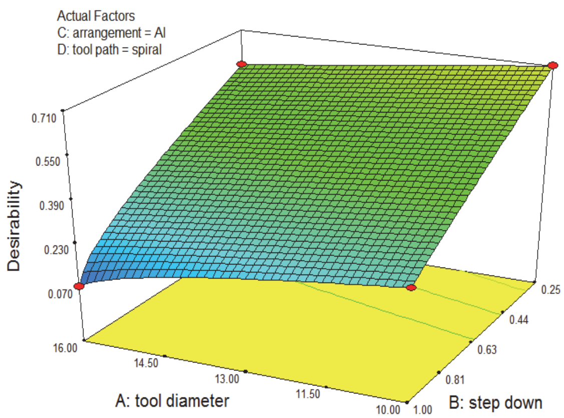


(a)

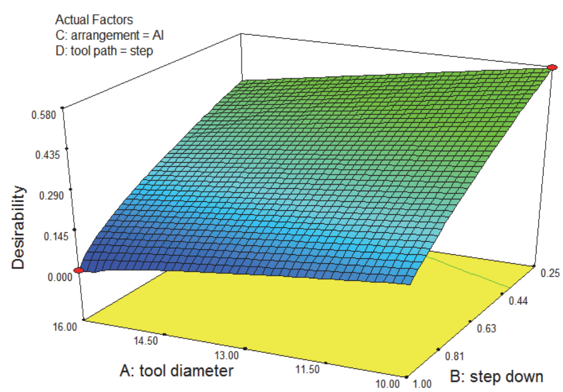
Fig. 14. Interaction charts



(b)



(c)



(d)

Fig. 14. Continue

5. Conclusions

Forming forces and maximum formability of Al/Cu multilayer sheet fabricated by explosive welding have been analyzed during the incremental sheet metal forming and conclusions have been given below.

- The forming forces increase about 5% by increasing the tool diameter about 15% and the step down about 30% by using the spiral tool path and about 3% by using Al as the top layer.
- The formability of this sheet increases by decreasing the tool diameter about 5% and by decreasing the step down about 12% because the strain on the sheet decreases at each stage by doing this and about 16% by using spiral tool path due to the fact that the tool is not detached being continuously in contact with the sheet and fewer shocks are introduced into the sheet, and also, the thickness variation is more uniform compared to the step tool path, which improves the condition of ductility and also using copper as the top layer improves the formability of the substrate about 3% because most stresses come to the underside layer (Al).
- The results of ANOVA confirm that the developed empirical models for the output responses show an excellent fit, and provide the predicted values of these response factors that are close to the experimental values, at 95% confidence level.

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بررسی عمق شکست در ورق دولایه آلومینیوم/ مس در فرآیند شکل‌دهی افزایشی یک نقطه‌ای

احمد قیصریان، محمد هنرپیشه

دانشکده مهندسی مکانیک، دانشگاه کاشان، کاشان، ایران.

چکیـــده

شکل‌دهی افزایشی ورق‌های فلزی پتانسیل قابل توجهی برای شکل‌دهی قطعات فلزی پیچیده بدون نیاز به ابزار خاصی را دارا بوده و برای ساخت قطعات فلزی با کاربردهای اقتصادی مناسب و مقرون به‌صرفه می‌باشند. در فرآیند شکل‌دهی افزایشی تک نقطه‌ای، یک ابزار سر کروی بر روی یک مسیر از پیش تعیین شده حرکت نموده و به شکل‌دهی ورق می‌پردازد. هدف از این مطالعه بهینه‌سازی میزان شکل‌پذیری و نیروهای شکل‌دهی ورق دولایه شکل داده شده توسط فرآیند شکل‌دهی افزایشی می‌باشد. دو قطر ابزار، دو گام عمودی، دو مسیر حرکت ابزار و چینش ورق به عنوان پارامترهای ورودی در این فرآیند مورد توجه قرار گرفتند. پارامترهای تأثیرگذار بر توانایی شکل‌گیری و نیروهای شکل‌دهی با کمک ابزارهای آماری (جدول پاسخ، نمودار پارامترهای اصلی و تأثیرات آن‌ها و ANOVA) شناسایی شدند. تجزیه و تحلیل واریانس (ANOVA) برای نشان دادن تفاوت‌های بالقوه در میان ابزارهای متفاوت با تست کردن میزان ارتباط بین نمونه‌ها مورد استفاده گردید، که این‌کار آن‌ها را قادر می‌سازد تا اثرات متغیرهای ورودی را بر روی خروجی‌ها نشان دهند. یک روش بهینه‌سازی چند پاسخ برای پیدا کردن مقادیر بهینه پارامترهای ورودی، با استفاده از روش پاسخ‌دهی سطح و آزمایش تأییدیه برای نشان دادن قابل اطمینان بودن پاسخ‌های به‌دست آمده توسط روش RSM مورد استفاده قرار گرفت.

واژه‌های کلیدی: شکل‌دهی افزایشی، ورق دولایه، عمق شکست، ANOVA ، نیروی شکل‌دهی