Iranian Journal of Materials Forming 10 (1) (2023) 39-52

Online ISSN: 2383-0042

Iranian Journal of Materials Forming

Journal Homepage: http://ijmf.shirazu.ac.ir

Research Article

Investigation of Fracture Depth of Metal-Polymer Three-Layer Sheet in Single-Point Incremental Forming Process

M. Esmailian[1]*, M. Honarpisheh[2] and A. Gheysarian[2]

[1] Faculty of Mechanics, Malek Ashtar University of Technology, Iran
[2] Faculty of Mechanical Engineering, University of Kashan, Kashan, Iran

ARTICLE INFO

Article history:

Received 20 February 2023
Reviewed 26 March 2023
Revised 10 April 2023
Accepted 25 April 2023

Keywords:

Incremental sheet forming
Metal–polymer three-layer sheet
fracture depth
ANOVA
Forming force
Fracture depth

Please cite this article as:

M. Esmailian, M. Honarpisheh, A. Gheysarian, Investigation of fracture depth of metal-polymer three-layer sheet in single-point incremental forming process, *Iranian Journal of Materials Forming*, 10(1) (2023) 39-52.

ABSTRACT

Incremental forming is one of the new forming methods. Single-point incremental forming (SPIF) has shown significant potential for forming complex metal parts. In the single-point incremental forming, a spherical tool head moves along a pre-defined path to form the desired geometry. The aim of this study is to optimize the fracture depth and forming forces of the three-layer metal-polymer sheet by using the single-point incremental forming process. By using response surface methodology (RSM), a series of experiments were designed in which tool diameter, step down and spindle speed were considered as process input parameters. The influencing parameters in fracture depth and forming forces have been identified by using statistical tools (response table, main effect diagram and ANOVA). Analysis of variance was used to show potential differences between the means of variables by testing the population value in each sample, which enables it to show the effects of input variables on output variables. The results show that the forming forces increased and the formability decreased by increasing the step down and the tool diameter. The highest forming force is 1476 N and the lowest value is 1045 N. Similarly, the highest fracture depth is 8.8 mm and the lowest is 7.1 mm. The best conditions are achieved when spindle speed is 2340.9 rpm, tool diameter is 7.51978 mm, and vertical step is 0.329552 mm. In this condition, the fracture depth is 8.50552 mm and the forming force is 776.03 N.

© Shiraz University, Shiraz, Iran, 2023

1. Introduction

Incremental forming is one of the modern and flexible methods in metal sheet forming. In this process the metal sheet is transformed into the most complex geometry at the lowest cost. In this process, the metal sheet is closed in a simple mold and a spherical head tool applies a predetermined path vertically on the sheet to form the desired geometry. This process is done in two ways. The simplest incremental forming method is single-point incremental forming (SPIF). In single-point incremental forming, only one forming tool was used to form the components. Another method is two-point incremental forming, which uses two forming tools. In this method, at any moment in time, one of these tools forms the component and the other acts as a backup.

Jesweit et al. [1] investigated asymmetric single-

* Corresponding author
E-mail address: Mojtaba@Mut-es.ac.ir (M. Esmailian)
https://doi.org/10.22099/IJMF.2023.46874.1249

Published by Shiraz University. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

point additive forming as a new development in asymmetric sheet metal forming. Based on the research studies, the forming forces increase with the increase of the vertical step, tool diameter, wall angle and the initial thickness of the sheet [2]. In another study, a new material modeling technique in single-point incremental formation was introduced with the help of ultrasonic vibration [3]. According to the model, the tool temperature increases rapidly in the early stages of vibration and then reaches a fixed value. Iseki et al. [4] developed a multi-step progressive forming machine using spherical and cylindrical rollers tool to form the vertical wall surfaces of thin rectangular panels. Silva et al. [5] investigated flanging by SPIF. Aluminum and titanium grade 2 sheets were used in this study. Montanari et al. [6] compared the relative performance of hole-flanging by incremental forming and conventional press work. The surface roughness of formed parts that has been recently analyzed by incremental forming and the investigation of this parameter is important [7]. Young et al. [8] evaluated the wall thickness changes in the single-point incremental forming process. They showed that two-pass forming produces parts that are thinned to failure with single-pass techniques.

Mirnia et al. [9] investigated the effect of tool diameter and vertical step on thickness distribution in incremental forming. They reported that the formability increases as the tool diameter increases. Sakhtemanian et al. [10] examined the layers arrangement in the incremental forming of low-carbon St/CP-titanium bimetals. Manco et al. [11] investigated the effect of tool diameter, vertical step, thickness and wall angle on the minimum thickness in incremental forming. The results show that the tool diameter and the vertical step have the greatest effect on the thickness of the sheet. Uheida et al. [12] investigated the effect of tool speed on the mechanical and thermal loads of the process in the gradual forming of titanium sheets. They showed that higher speeds correspond to higher temperatures and lower forces. Saktemanian et al. [13] examined the mechanical and geometrical properties of St/CP-titanium bimetal sheet during the single-point incremental formation process. It is shown that the hardness and tensile properties of the samples increased and surface quality decreased by rising the number of the vertical steps. Hamilton et al. [14] investigated the effects of feed rate on incremental forming. Experiments on Al3003 sheet completed with a maximum feed of 8890 mm/min and it was observed that the feed rate had no significant effect on the thickness distribution. Honarpisheh et al. [15] examined the impact of the process parameters on the formation force, dimensional accuracy and thickness in the incremental formation process of the Al/Cu bimetal sheet. An experimental study was conducted on the parameters of the incremental formation process of Al/Cu explosive welded sheet by Gheysarian et al. [16]. Esmailian et al. [17] investigated the incremental forming of polymer sheets. In this study, the effects of the step down, tool diameter and spindle speed are stated on forming forces and thickness distribution.

Filice et al. [18] showed that the increase in sheet ductility is due to local plastic deformation in the area around the tool and determined the forming limit curve by designing experiments. Senthil et al. [19] investigated the ductility of AZ61A magnesium alloy by numerically analyzing the incremental sheet metal forming process. Fratini et al. [20] investigated the effect of gender on formability in the modern and traditional forming process. The major strain at fracture in plane strain conditions, determined for different materials and the influence of the main material parameters on formability were accurately investigated through a statistical analysis. Afonso et al. [21] investigated the formability of tunnel-type parts in incremental sheet metal forming. The goal was to increase flexibility, maximize part size and reduce material waste and the need for post-processing operations. This study concluded with the construction of more accurate geometries, plus testing and validation of the incremental tunnel forming concept for use in free-standing parts. Wenke Bao et al. [22] investigated the effect of electropulse assisted incremental forming (EAIF) on the ductility of the AZ31B alloy. The experimental results showed that the electroplastic effects increase with the increase of the root mean square (RMS) current density of the electropulse and the angle of the limit of formation in EAIF was up to 72° from the previous 39.6° without electropulse. It is found that the electropulse can lower the dynamic recrystallization temperature (DRX) of AZ31B and accelerate the progress of DRX, and can also inhibit the crack growth of the tested materials, which in turn improves their ductility. Mugendiran et al. [23] investigated the ductility 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 cups than in squared ones. Hussain et al. [24] investigated the formability of pure titanium sheet using additive sheet forming. In this study, the effects of step and tool diameter on tool ductility and tool wear were compared. The results showed that with the increase of the steps, the ductility decreases linearly, and with the increase of the tool diameter and the feed rate, it also decreases. Ambrogio et al. [25] stated that by using incremental forming magnesium has little formability at room temperature. They also stated that formability increased by rising the temperature up to 300°C. Iseki et al. [26] investigated the amount of sheet formability, strain and forming forces in the incremental forming process for annealed aluminum sheets. In this study, the FEM method was used to predict the stated cases and also validate the results. Kurra Suresh et al. [27] investigated the ductility of sheet incremental forming by using finite element simulation and compared the results with experimental values. McAnulty et al. [28] investigated the effect of process parameters such as step down, feed rate, spindle speed and etc. on ductility in incremental sheet metal forming.

Kurra et al. [29] evaluated the effect of process parameters on surface roughness and fabrication time by using ANOVA and RSM, then a multi-objective optimization using NSGA-II performed on the responses. Attanasio et al. [30] tried to optimize the tool path in a positive incremental forming process. The purpose of this work was to experimentally evaluate the path of the tool. Gheysarian et al. [31] Investigated the incremental forming of bimetal sheet and optimized this process. Esmailian et al. [32] investigated the finite element simulation of a two-point incremental forming.

So far, many studies have been done on incremental forming, and the formability of polymer sheets has not been investigated by direct groove test. The purpose of this study is to evaluate the forming forces and failure depths of the incremental formation process in the metal-polymer three-layer sheet. To achieve this goal, the incremental forming of the metal-polymer three-layer sheet is performed according to design tests (DOE). The studied parameters for this article include tool diameter, rotation speed and vertical step. The maximum failure depth and the formation forces are measured and the ANOVA is used to analyze the results.

2. Experimental Procedure

For this study, direct groove testing is used to measure the maximum height of fracture depth. In this test, the instrument goes down in a predetermined path on the sheet. This process continues to ruin the sheet. After the rupture, the process is stopped and the depth of the rupture is measured and reported. For this experiment, various equipment is required, such as holder, mold, forming tools, computer numerical control (CNC) mill machine and dynamometer (Fig. 1).

The Kistler 9257B dynamometer is used in this article. To measure the forming force, the dynamometer sensor is placed under the holder. The tool movement is controlled numerically in this process. To create the tool's path, first the final geometry is created by using design software. In the next step, the created geometry is transferred to the machining software and the tool path is prepared based on the desired geometry in the NC code.

Fig. 1. Used equipment in this study.

The milling machine moves the forming tool into the mold in a specified path and forms the test sheet. The prepared NC code is transferred to the CNC device controller. The CNC device moves the forming tool based on the created program on the sheet and continues to create a rupture (Fig. 2).

2.1. Material and tools

A press machine, hot molding and 5083 aluminum sheets with a thickness of one millimeter are required to make polymer-metal three-layer sheets. It is important to note that polymer particles do not have polar properties and cannot stick to metal. A layer of propylene maleic was used to create adhesion between metal and polymer. To make this three-layer sheet, the metal sheet is first placed on the mold and a layer of adhesive and a layer of propylene particles are created on the set and a second layer of adhesive and metal sheet is placed on it (Fig. 3) [32].

After the layering, the pressing operation is performed in the heated mold. In order to ensure the accuracy of the made sample, a part of the sheet is reviewed after forming and was magnified by the microscope (Fig. 4). As can be seen in the figure, the layering is done very well.

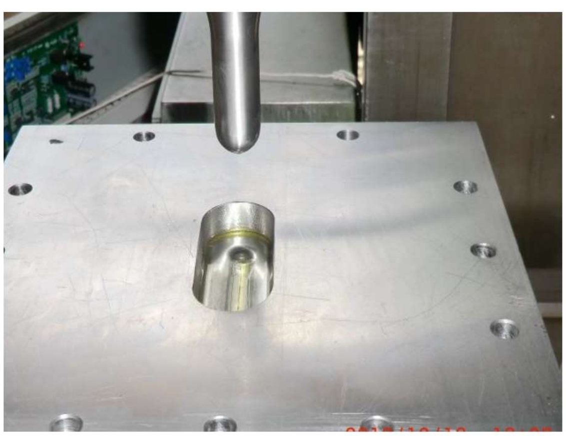

Fig. 2. The effect of tool movement on the sheet.

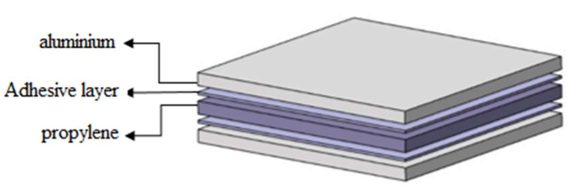

Fig. 3. Sheet laying of metal-polymer three-layer sheet [32].

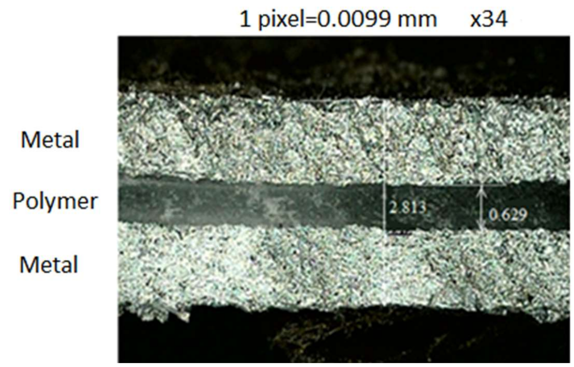

Fig. 4. Observation of the layers of the formed sheet by microscope.

A series of spherical head tools made of MO40 was prepared to perform incremental forming operations. Choosing the right material, machining and heat treatment process is very important in making good tools. The tool must have the necessary hardness and flexibility. The curvature of the tool head should be such that it creates the required angles in the incremental forming process.

The deformation mechanism in incremental forming is caused by stretching. Local bending has occurred at the point of contact between the tool and the sheet, but the overall deformation is due to stretching. In order to check the properties of the studied sheet, the tensile test must be performed according to ASTM E9 and the bending test according to ASTM E290. The dimensions of the samples were prepared and tested based on these standards. The tensile test is one of the destructive tests in which the sample is subjected to a one-dimensional tensile force until the breaking point. This is while the increase in length is recorded simultaneously with the applied force (applied load). Test results are typically used to select a material for quality control purposes and to predict how a material will react under other types of forces. A bending test is a test that evaluates the mechanical properties of materials in which the resistance of the part to bending and breaking is tested. This test is a simple and cheap way to evaluate the quality of materials. As can be seen in Fig. 5, the multi-layer sheet has a lower tensile strength than the single-layer sheet. In the event that the bending strength of the multi-layer sheet is higher than the single-layer sheet.

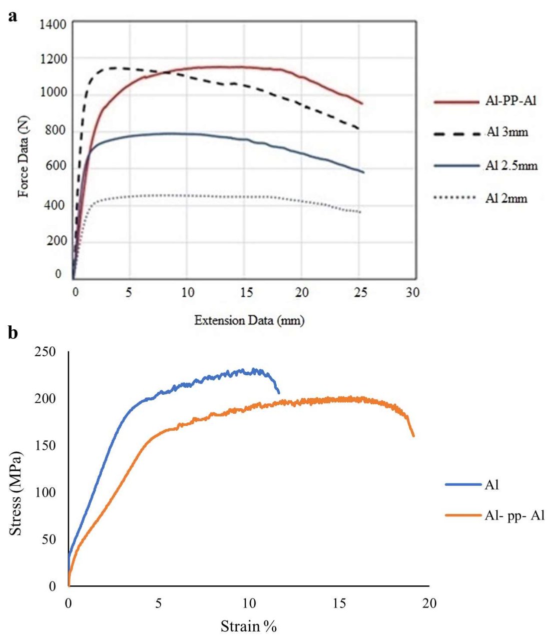

Fig. 5. (a) bending test and (b) tensile test results.

Most of the parts that are subjected to incremental forming, are shells. Shell parts are placed under the bending loads. Choosing multi-layered sheets for incremental forming is very suitable due to their high bending strength and low tensile strength. In the incremental forming of a multi-layer sheet that has the same bending strength as a single-layer sheet, due to the lower tensile strength of the multi-layer sheet, less forming force is required. During the forming operation, the sheet cannot move from the sheet holder to the middle space. Therefore, due to the strong contact between them, significant tensile stress is created in the material. The created tensile stress causes the sheet to stretch on the mandrel. On the other hand, when the tool head moves down a vertical step, a small area of the sheet is drawn on the mandrel. At this time, a part of the metal sheet that previously had a completely flat surface now sticks to the surface of the mandrel; In other words, a kind of local bending occurs in a very small area of the sheet. The radius of the created local bend is equal to the radius of the tool. Local bending causes tensile stress along the tangent to the mandrel. This phenomenon is called bending under tension; At the same time as the sheet is stretched on the mandrel, due to the circumferential movement of the tool, the material elements slide on each other in the circumferential direction; Therefore, a kind of shear stress is created in the direction parallel to the movement of the tool in the area of contact between the tool and the sheet.

In these diagrams, AL represents aluminum and PP represents propylene. These tests were done in Isfahan University of Technology.

2.2. Design of part

As stated earlier, the direct groove test is used in order to obtain the maximum forming depth (Fig. 6). The tool moves until the sample is torn in a similar path to Fig. 6. The length of the tool movement path is 50 mm and the amount of down in each step is called a vertical step.

2.3. Design of experiments and process parameters

It is important to make a design for the required tests in carrying out engineering processes. This design of experiments (DOE) shows the appropriate distribution of each parameter and its effects. Designing tests save time and reduce the cost of operations. The Minitab software is used to conduct the experiment. The response surface method (RSM) is used, and in this method, tool diameter, vertical step and spindle speed are introduced as input parameters (Table. 1). A central composite design (CCD) is used to determine the number of needed tests to study the responses. The software designed and presented a series of tests according to the chosen method and the number of input parameters (Table. 2).

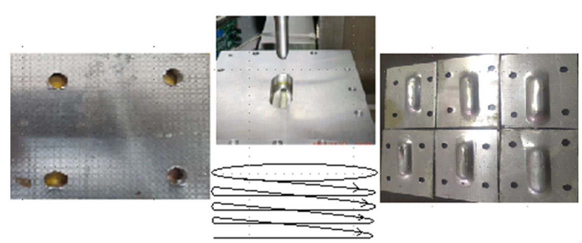

Fig. 6. Direct groove test.

Table 1. Parameters of the experiment and used level

Level	Step down (mm)	Rotational speed (rpm)	Tool diameter (mm)
L1	0.5	1000	8
L2	1	2000	12

Table 2. Designed experiments

Row	Step down (mm)	Rotational speed (rpm)	Tool diameter (mm)
1	0.75	1500	10
2	1	2000	8
3	0.75	1500	6.6364
4	0.5	2000	8
5	0.75	1500	10
6	0.75	659.1	10
7	0.32955	1500	10
8	0.75	1500	10
9	0.5	1000	12
10	1.17045	1500	10
11	1	1000	8
12	0.75	1500	10
13	0.75	1500	13.3636
14	1	2000	12
15	1	1000	12
16	0.5	2000	12
17	0.75	1500	10
18	0.5	1000	8
19	0.75	1500	10
20	0.75	2340.9	10

3. Results and Discussion

3.1. Fracture depth and forming force measurement

The direct groove test is used in this article for the purpose and the measurement of the maximum depth sheets fracture depth reach before tearing. This tear will be visible by observation or by examining the force diagram. The force diagram has a sudden drop at the moment of sheet tearing according to which a maximum depth of plasticity can be calculated (Fig. 7). This graph is obtained by a dynamometer and shows the applied vertical force to the forming tool. As long as the sheet is not torn, the graph is in an ascending state and after tearing, it will become descending.

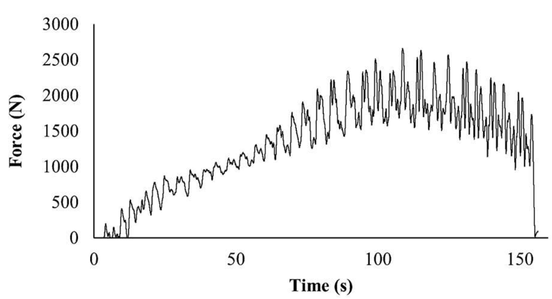

Fig. 7. Force diagram.

The maximum depth of plasticity is measured by visual measuring machine (VMM) or by using a depth gauge. The results of the maximum fracture depth and forming forces measuring for the designed experiments are given in Table 3. In Fig. 8, the effect of the input parameters on the results is determined by examining the performed tests. The results show that by increasing the tool diameter, the forming forces increase and the amount of fracture depth decreases. Increasing the vertical pitch also shows the same results as the tool diameter. Increasing the spindle speed causes heating of the contact area between tool and sheet and improves the machining conditions. Improving the machining conditions means reducing the forming forces and increasing the fracture depth.

3.2. RSM and optimization

Designing experiments and using the RSM is a useful method for investigating the relationships between results and input parameters. In this study, the effect of step down, tool diameter and spindle speed are investigated on the forming force and maximum fracture depth. This method examines the effectiveness of each

Table 3. Forming forces and fracture depth measurement results

Row	Forming force (N)	Fracture depth (mm)
1	1309	8.3
2	1428	7.7
3	1187	7.7
4	1045	8.4
5	1339	8.2
6	1258	7.9
7	1059	8.5
8	1324	8.2
9	1353	7.9
10	1411	7.5
11	1329	7.5
12	1328	8.3
13	1430	7.4
14	1422	7.6
15	1377	7.5
16	1266	8.2
17	1335	8.2
18	1049	8.1
19	1332	8.1
20	1311	8.3

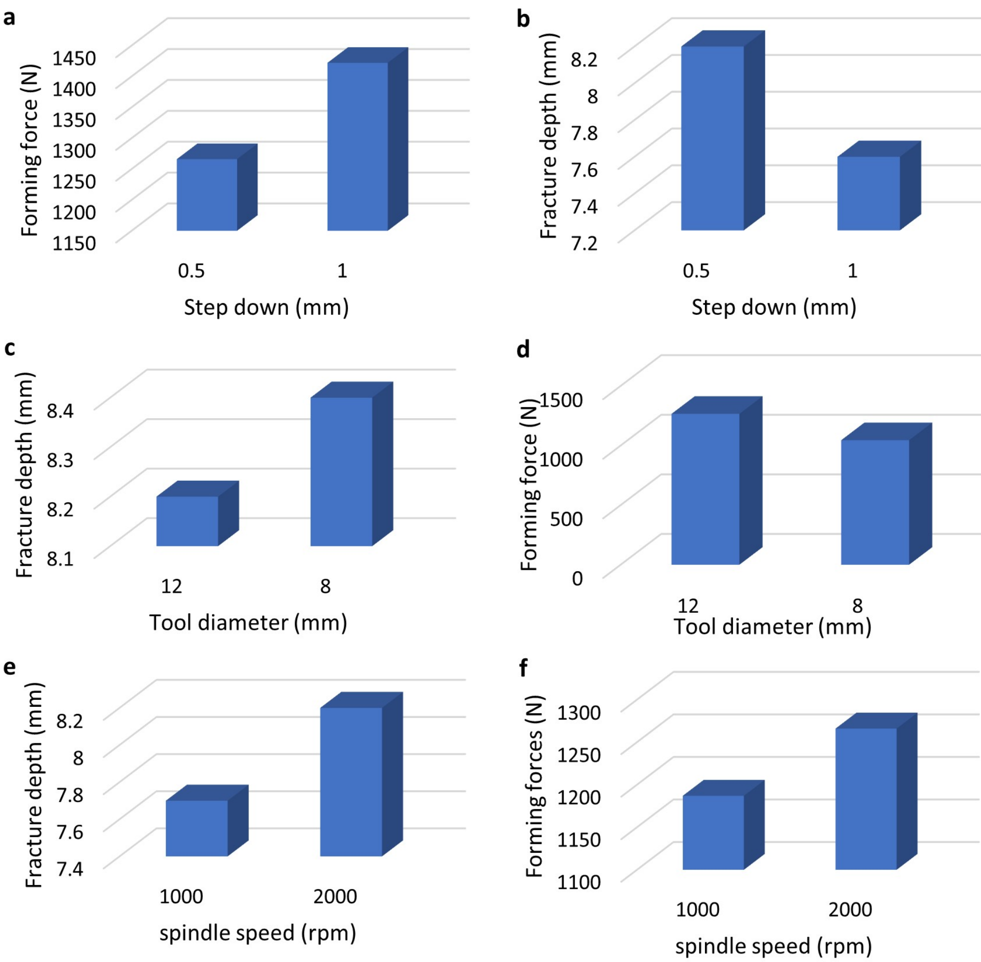

Fig. 8. Effects of input parameters on the forming forces and fracture depth:
(a) effects of step down on the forming forces, (b) effects of step down on the fracture depth,
(c) effect of tool diameter on the fracture depth, (d) effect of tool diameter on the forming force,
(e) effect of spindle speed on the fracture depth, and (f) effect of spindle speed on the forming force.

parameter and optimizes the process by using regression tests.

3.2.1. Response surface modeling

The RSM examines the relationship between inputs and outputs. The goal is to express the best relationship between inputs and outputs. Minitab provides a model by using the obtained results from the designed experiments and examining the relationship between these results and the input data, which can be used to predict the results without conducting experiments.

3.2.2. Analysis of variance

The analysis of variance of the applied forming forces and fracture depth is shown in Tables 4 and 5. The importance of each variable is determined by the P-value, which is a measure of the deviation of the data from the mean value. Significant parameters of the model that have a P-value less than 0.05.

The study of P-value for forming forces and fracture depth indicates the validity of the proposed model in this research. In this model, all the main factors are significant. In this step, the pareto diagram is examined for the proposed model. According to the diagram in Figs. 9 and 10, the step down and tool diameter have the greatest effect on the forming forces and fracture depth, respectively. It is also important to note that, among the interactive effects, the interactive effect of the tool diameter and step down are effective in the forming forces and fracture depth.

Table 4. Analysis of Variance for forming forces

Source	DF	Adj SS	Adj MS	F-value	P-value
Model	9	275290	30588	231.26	0.000
Linear	3	221965	73988	559.39	0.000
Step down (mm)	1	150781	150781	1139.99	0.000
Rotational speed (rpm)	1	1479	1479	11.18	0.007
Tool diameter (mm)	1	69704	69704	527.01	0.000
Square	3	14915	4972	37.59	0.000
Step down×Step down	1	13449	13449	101.68	0.000
Rotational speed×Rotational speed	1	2454	2454	18.55	0.002
Tool diameter×Tool diameter	1	300	300	2.27	0.163
2-Way Interaction	3	38410	12803	96.80	0.000
Step down×Rotational speed	1	6903	6903	52.19	0.000
Step down×Tool diameter	1	29161	29161	220.47	0.000
Rotational speed×Tool diameter	1	2346	2346	17.74	0.002
Error	10	1323	132		
Lack-of-fit	5	760	152	1.35	0.375
Pure error	5	563	113		
Total	19	276613			

Table 5. Analysis of variance for fracture depth

Source	DF	Adj SS	Adj MS	F-value	P-value
Model	9	2.28510	0.25390	78.36	0.000
Linear	3	1.41593	0.47198	145.67	0.000
Step down (mm)	1	1.16093	1.16093	358.31	0.000
Rotational speed (RPM)	1	0.18111	0.18111	55.90	0.000
Tool diameter (mm)	1	0.07389	0.07389	22.81	0.001
Square	3	0.84542	0.28181	86.98	0.000
Step down×Step down	1	0.08485	0.08485	26.19	0.000
Rotational speed×Rotational speed	1	0.02467	0.02467	7.62	0.020
Tool diameter×Tool diameter	1	0.80151	0.80151	247.38	0.000
2-Way Interaction	3	0.02375	0.00792	2.44	0.124
Step down×Rotational speed	1	0.01125	0.01125	3.47	0.092
Step down×Tool diameter	1	0.01125	0.01125	3.47	0.092
Rotational speed×Tool diameter	1	0.00125	0.00125	0.39	0.548
Error	10	0.03240	0.00324		
Lack-of-fit	5	0.00407	0.00081	0.14	0.974
Pure error	5	0.02833	0.00567		
Total	19	2.31750			

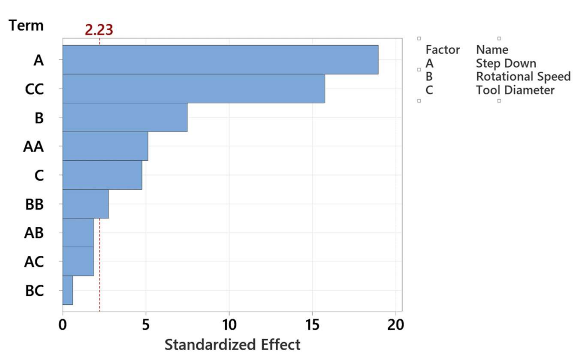

Fig. 9. Pareto chart for fracture depth.

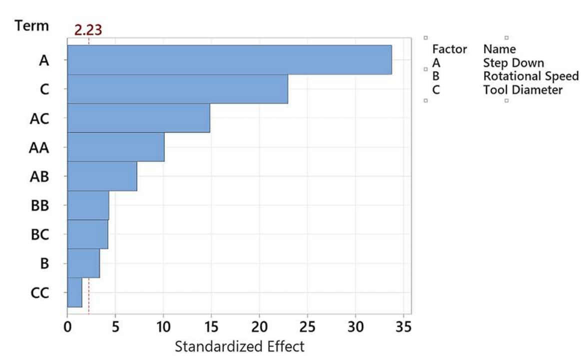

Fig. 10. Pareto chart for forming force.

Another used item for statistical analysis validation is the residual graphs that are shown in Figs.11 and 12. The graphs show the normality of the test data and also indicate that the residuals do not follow a specific trend.

3.2.3. Regression equation

A regression equation is given to predict the values of forming forces and fracture depth based on effective parameters. The values and coefficients of the variables in the model equation show the amount and effect of these variables, respectively. The desired force and fracture depth results can be obtained without performing experiments and by using these models. By using these models, the necessary predictions can be made to perform experiments.

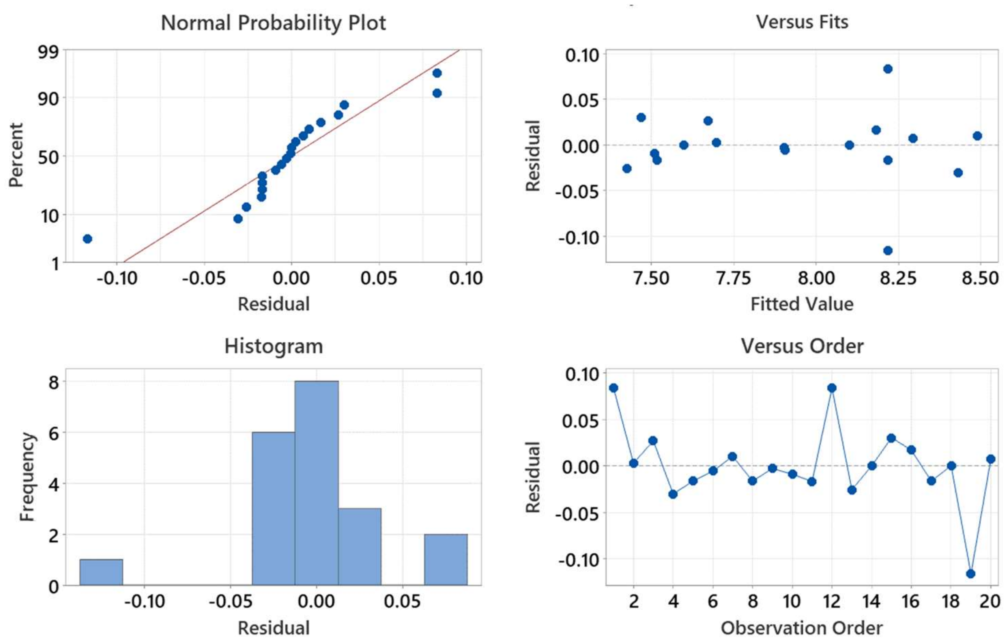

Fig. 11. Residual plots for fracture depth.

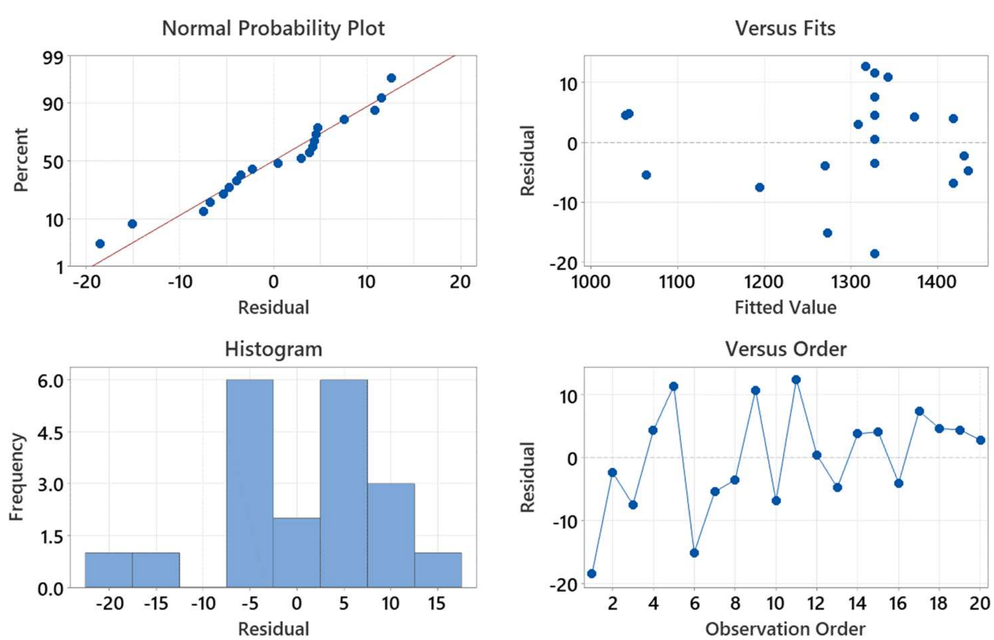

Fig. 12. Residual plots for forming forces.

$$\begin{aligned} Fracture\ depth\ (\mathrm{mm}) = {} & 2.192 + 0.375\, Step\ down + 0.001077\, Rotational\ speed \\ & + 1.1049\, Tool\ diameter - 1.228\, Step\ down \times Step\ down \\ & - 0.000000\, Rotational\ speed \times Rotational\ speed \\ & - 0.05896\, Tool\ diameter \times Tool\ diameter \\ & - 0.000300\, Step\ down \times Rotational\ speed \\ & + 0.0750\, Step\ down \times Tool\ diameter \\ & - 0.000013\, Rotational\ speed \times Tool\ diameter \end{aligned} \tag{1}$$

$$\begin{aligned} Forming\ Force\ (\mathrm{N}) = {} & -781 + 2008\, Step\ down + 0.1724\, Rotational\ speed \\ & + 174.8\, Tool\ diameter - 488.8\, Step\ down \times Step\ down \\ & - 0.000052\, Rotational\ speed \times Rotational\ speed \\ & - 1.141\, Tool\ diameter \times Tool\ diameter \\ & + 0.2350\, Step\ down \times Rotationalspeed \\ & - 120.75\, Step\ down \times Tool\ diameter \\ & - 0.01712\, Rotational\ speed \times Tool\ diameter \end{aligned} \tag{2}$$

3.2.4. Investigating the effect of main factors on results

The effects of the main factors on the results are shown diagrammatically in Figs. 13 and 14. According to the diagrams, the forming forces increase due to an increase in the length of the engagement of the tool with the workpiece by increasing the cutting depth. As can be seen in the figures, forming forces increase by increasing the tool diameter as a result of lengthening the contact between the tool and the sheet. According to Fig. 14 fracture depth decrease by increasing step down caused as a result of increasing the length of engagement of the tool with sheet and increasing forming forces. Increasing the spindle speed increases the heat and improves the machining conditions and fracture depth. As can be seen, spindle speed has very little effect on forming forces and can be ignored compared to other parameters. In addition, increasing the tool diameter as a whole, reduces the fracture depth due to an increase in the contact surface and forming forces.

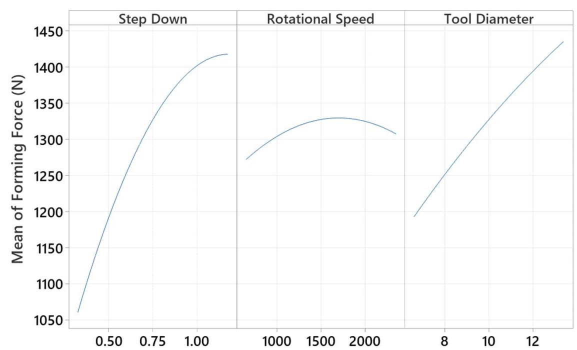

Fig. 13. The effects of each parameter on forming forces.

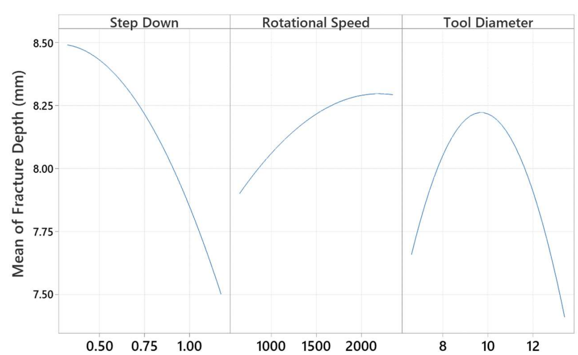

Fig. 14. The effects of each parameter on fracture depth.

3.2.5. Interaction between the main factors

The interaction between the parameters can be seen in Figs. 15 and 16. These diagrams show effects of the interaction between parameters on the forming forces.

The results of the study of the input parameters and their effect on the forming forces and fracture depth are as follows: Examining the graphs shows that the forming forces increase by increasing the step down and this is due

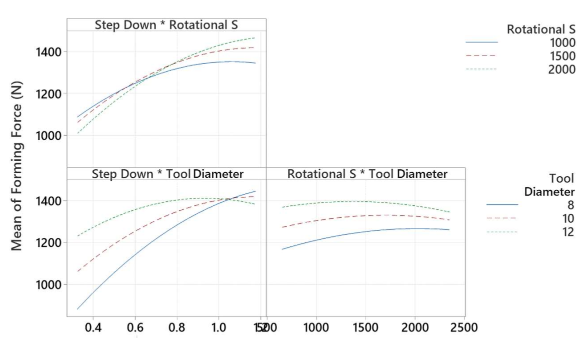

Fig. 15. Diagram of the parameters interaction on the forming forces.

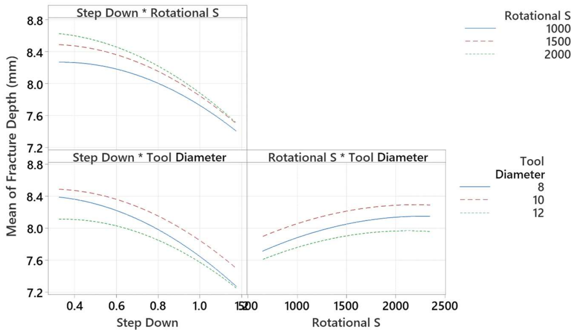

Fig. 16. Diagram of the parameters interaction on the fracture depth.

to the increase in the length of the engagement between tool and sheet and the amount of chips in front of the tool. The graphs show that the forming forces decrease with increasing spindle speed due to heat generation at the contact point between the tool and sheet. Additionally, increasing the diameter of the tool increases the contact surface of the tool and sheet and increases the forming forces. Examining the graphs shows that the increase in forming forces reduces the machinability as well as the fracture depth of the sheet. It is important to note that the most effective parameter is the vertical step. As can be seen in the above diagrams, in large step downs, the effect of the tool diameter and the spindle speed is very limited. While in small vertical steps, the effect of the tool diameter and the spindle speed is significant.

3.2.6. Optimum point

Multi-response optimization based on the desirability of the goals was employed in order to find the optimum point which gives the maximum fracture depth and minimum forming forces possible during the SPIF. The purpose of optimization is to find the individual utility for each response separately, to combine the individual utilities in order to evaluate the combined utility, and to find the maximum combined utility and the final expression of the best modes for selecting each parameter. The optimized objectives are stated in Table 6. Table 7 shows the best condition of each parameter in order to achieve optimal results. Fig. 17 shows the process of changing the results based on the change in the input parameters. It can also be seen that by changing these parameters, what changes have been made in the desired desirability.

3.3. Finite element analysis

Finite element analysis is one of the suitable methods for checking all kinds of processes, including incremental sheet metal forming. Using simulation saves costs and finds key factors in the incremental forming process. In the present study, as shown in Fig. 18, the three-dimensional model of the incremental forming process is developed in the ABAQUS/explicit platform. The C3D8R element type is used in this model with total number of 3266 elements. In this study, the tool path is entered according to the taken G-codes from the Power Mill software, which shows the movement path of the forming tool exactly like its real with the best results. In this process, forming takes place until the sheet breaks. As can be seen, tears are created in the corners due to stress concentration. The simulation results show a very good match with reality.

Table 6. Goals for forming forces and fracture depth

Response	Goal	Lower	Target	Upper	Weight	Importance
Fracture depth (mm)	Maximum	7.4	8.5	-	1	1
Force tool (N)	Minimum	-	1045	1430	1	1

Table 7. Best conditions for each parameter

Solution	Step down (mm)	Rotational speed (rpm)	Tool diameter (mm)	Fracture depth (mm) Fit	Force tool (N) Fit	Composite desirability
Fracture depth (mm)	Maximum	7.4	8.5	-	1	1
Force tool (N)	Minimum	-	1045	1430	1	1

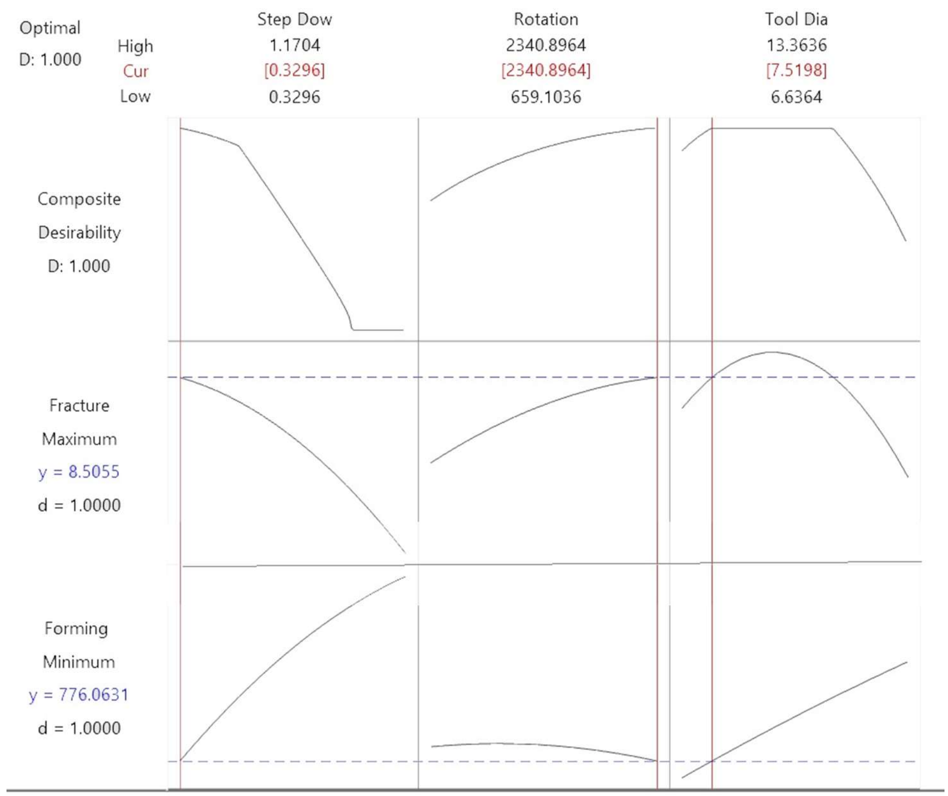

Fig. 17. Desirability of the input and output parameters and effects of input parameters changing in the results and desirability.

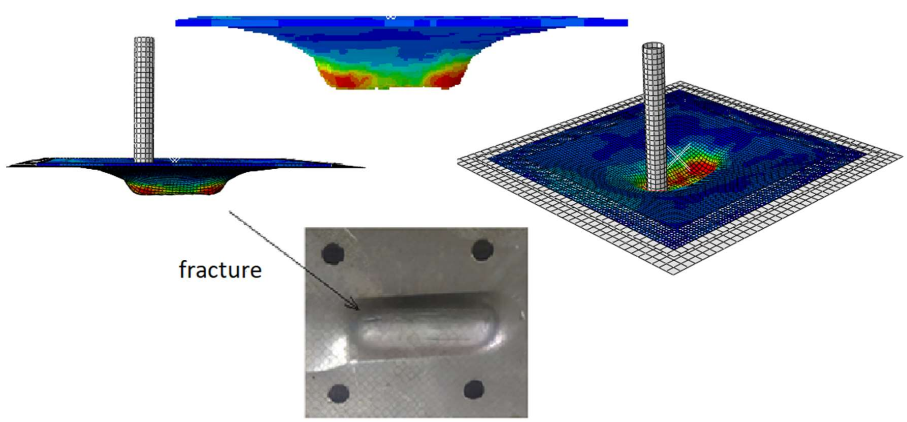

Fig. 18. Simulation results.

The forming tool moves along the defined path and forms the sheet. On the other hand, while the sheet forms incrementally, the deformation continues until the first crack appears.

4. Conclusion

Forming forces and maximum fracture depth of metal-polymer three-layer sheets have been analyzed during the incremental sheet metal forming and the conclusions have been given below.

- The forming forces increase by increasing the tool diameter and the step down.
- The fracture depth of this sheet increases by decreasing the tool diameter and decreasing the step down because the strain on the sheet decreases at each stage by doing this.
- Increasing the spindle speed causes heating of the

contact point between the sheet and the tool, which improves the forming conditions.

- In this process, forming continues until tearing, according to the specified path. Due to the fact that stress is concentrated in the corner, tearing occurs in the corners. The simulation results also show the same issue.
- 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.
- The best forming conditions are created when the forming forces are the lowest and the fracture depth is the highest.
- The maximum plasticity value is 8.5 mm and the minimum forming force is 1045 N.

Conflict of Interests

The authors Mojtaba Esmailian, Mohammad Honarpisheh and Ahmad Gheysarian, have no financial or proprietary interests in any material discussed in this article. The authors declare that they have no conflict of interest.

Funding

This research did not receive any specific funding.

5. References

[1] J. Jeswiet, D. Adams, M. Doolan, T. McAnulty, P. Gupta, Single point and asymmetric incremental forming, *Advances in manufacturing*, 3(4) (2015) 253-262.

[2] J. Jeswiet, E. Hagan, A. Szekeres, Forming parameters for incremental forming of aluminium alloy sheet metal, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 216(10) (2002) 1367-1371.

[3] M.R. Sakhtemanian, M. Honarpisheh, S. Amini, A novel material modeling technique in the single-point incremental forming assisted by the ultrasonic vibration of low carbon steel/commercially pure titanium bimetal sheet, *The International Journal of Advanced Manufacturing Technology*, 102(1) (2019) 473-486.

[4] H. Iseki, T. Naganawa, Vertical wall surface forming of rectangular shell using multistage incremental forming with spherical and cylindrical rollers, *Journal of Materials Processing Technology*, 130 (2002) 675-679.

[5] M.B. Silva, P. Teixeira, A. Reis, P.A.F. Martins, On the formability of hole-flanging by incremental sheet forming, *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, 227(2) (2013) 91-99.

[6] L. Montanari, M.B. Silva, V.A. Cristino, P.A.F. Martins, On the relative performance of hole-flanging by incremental sheet forming and conventional press-working, *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, 228(4) (2014) 312-322.

[7] E. Hagan, J. Jeswiet, Analysis of surface roughness for parts formed by computer numerical controlled incremental forming, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 218(10) (2004) 1307-1312.

[8] D. Young, J. Jeswiet, Wall thickness variations in single-point incremental forming. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 218(11) (2004) 1453-1459.

[9] M. J. Mirnia, B. Mollaei Dariani, H. Vanhove, J.R. Duflou, An investigation into thickness distribution in single point incremental forming using sequential limit analysis, *International Journal of Material Forming*, 7(4) (2014) 469-477.

[10] M.R. Sakhtemanian, M. Honarpisheh, S. Amini, Numerical and experimental study on the layer arrangement in the incremental forming process of explosive-welded low-carbon steel/CP-titanium bimetal sheet, *The International Journal of Advanced Manufacturing Technology*, 95(9) (2018) 3781-3796.

[11] G.L. Manco, G. Ambrogio, Influence of thickness on formability in 6082-T6, *International Journal of Material Forming*, 3(1) (2010) 983-986.

[12] E.H. Uheida, G.A. Oosthuizen, D. Dimitrov, Investigating the impact of tool velocity on the process conditions in incremental forming of titanium sheets, *Procedia Manufacturing*, 7 (2017) 345-350.

[13] M.R. Sakhtemanian, S. Amini, M. Honarpisheh, Simulation and investigation of mechanical and geometrical properties of St/CP-titanium bimetal sheet during the single point incremental forming process, *Iranian Journal of Materials Forming*, 5(1) (2018) 1-18.

[14] K. Hamilton, J. Jeswiet, Single point incremental forming at high feed rates and rotational speeds: surface

and structural consequences, *CIRP Annals*, 59(1) (2010) 311-314.

[15] M. Honarpisheh, M. Keimasi, I. Alinaghian, Numerical and experimental study on incremental forming process of Al/Cu bimetals: influence of process parameters on the forming force, dimensional accuracy and thickness variations, *Journal of Mechanics of Materials and Structures*, 13(1) (2018) 35-51.

[16] M. Honarpisheh, A. Gheysarian, An experimental study on the process parameters of incremental forming of explosively-welded Al/Cu bimetal, *Journal of Computational & Applied Research in Mechanical Engineering (JCARME)*, 7(1) (2017) 73-83.

[17] M. Esmailian, K. Khalili, Two-point incremental forming of metal–polymer three-layer sheets, *Iranian Journal of Science and Technology, Transactions of Mechanical Engineering*, 45(1) (2021) 181-196.

[18] L. Filice, L. Fratini, F. Micari, Analysis of material formability in incremental forming, *CIRP Annals*, 51(1) (2002) 199-202.

[19] R. Senthil, A. Gnanavelbabu, Numerical analysis on formability of AZ61A magnesium alloy by incremental forming, *Procedia Engineering*, 97 (2014) 1975-1982.

[20] L. Fratini, G. Ambrogio, R. Di Lorenzo, L. Filice, F. Micari, Influence of mechanical properties of the sheet material on formability in single point incremental forming, *CIRP Annals*, 53(1) (2004) 207-210.

[21] D. Afonso, R.A. de Sousa, R. Torcato, Incremental forming of tunnel type parts, *Procedia Engineering*, 183 (2017) 137-142.

[22] W. Bao, X. Chu, S. Lin, J. Gao, Experimental investigation on formability and microstructure of AZ31B alloy in electropulse-assisted incremental forming, *Materials & Design*, 87 (2015) 632-639.

[23] V. Mugendiran, A. Gnanavelbabu, Comparison of FLD and thickness distribution on AA5052 aluminium alloy formed parts by incremental forming process, *Procedia Engineering*, 97 (2014) 1983-1990.

[24] G. Hussain, L. Gao, Z.Y. Zhang, Formability evaluation of a pure titanium sheet in the cold incremental forming process, *The International Journal of Advanced Manufacturing Technology*, 37(9) (2008) 920-926.

[25] G. Ambrogio, L. Filice, G.L. Manco, Warm incremental forming of magnesium alloy AZ31, *CIRP Annals*, 57(1) (2008) 257-260.

[26] H. Iseki, An approximate deformation analysis and FEM analysis for the incremental bulging of sheet metal using a spherical roller, *Journal of Materials Processing Technology*, 111(1-3) (2001) 150-154.

[27] K. Suresh, S.P. Regalla, Analysis of formability in single point incremental forming using finite element simulations, *Procedia Materials Science*, 6 (2014) 430-435.

[28] T. McAnulty, J. Jeswiet, M. Doolan, Formability in single point incremental forming: a comparative analysis of the state of the art, *CIRP Journal of Manufacturing Science and Technology*, 16 (2017) 43-54.

[29] S. Kurra, N. HR, S. Regalla, A. K. Gupta, Parametric study and multi-objective optimization in single-point incremental forming of extra deep drawing steel sheets, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 230(5) (2016) 825-837.

[30] A. Attanasio, E. Ceretti, C. Giardini, Optimization of tool path in two points incremental forming, *Journal of Materials Processing Technology*, 177(1-3) (2006) 409-412.

[31] M. Honarpisheh, M. Mohammadi Jobedar, I. Alinaghian, Multi-response optimization on single-point incremental forming of hyperbolic shape Al-1050/Cu bimetal using response surface methodology, *The International Journal of Advanced Manufacturing Technology*, 96(9) (2018) 3069-3080.

[32] M. Esmailian, K. Khalili, Finite element simulation of two-point incremental forming of free-form parts, *Iranian Journal of Materials Forming*, 5(2) (2018) 26-35.