Investigation of Springback Angle in Single Point Incremental Forming Process on Explosive Welded Cu/St/Cu Multilayer

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Abstract
Nowadays, the role of light weight materials has grown up in important industries such as aerospace and biomechanics, but before the appliance, their strength should be increased. A modern way to increase this factor along with the lightweight factoris using bimetal sheets, hence, the design of multilayer sheets has been very much considered recently. In this study, explosive welded Cu/St/Cu multilayer sheets were used in the incremental forming process to determine the springback phenomenon on different layers. The results indicated that rotational speed, feeding rate, and vertical step parameters can affect spring back in single point incremental forming process (SPIF).Three levels of vertical step size, tool rotational speed, and feed rate have been considered as the input process parameters and spring back as the output.In order to design a better experiment and analyze the data, the Taguchi method was selected on the basis of DOEin Mini-Tab software andthe results have been analyzed by two states. In the first state,the value which was closest to the nominal value is considered to be the optimal result which obtained for spring back angles with parameters of 0.75 mm for the vertical step down, 200 rpm for the rotational speed and 500 and 1000 mm/min for the feeding rate. In the second state, the least amount is considered as the optimal result in which the values of 0.5 and 1 mm of the vertical step down, 150 and 100 rpm of the rotational speed, and 1500 and 500 mm/min of the feeding rate formed the optimal outcome.

Keywords
Incremental Sheet Forming, Spring Back, Taguchi Method, Optimization

1. Introduction

In the incremental sheet forming (ISF) processes, metal sheet is deformed by tool or tools in a gradual way to create the final shape of the product. Complicated shapes can be formed by a simple tool without the need for special molding.The upper mold is equipped for clamping and holding the sheet in its position during the single point incremental forming (SPIF) process. The backing mold supports the sheet and its open part defines the working area of the single point forming tool.

The SPIF is one of the incremental forming branches in which during the forming process, no backup die supports the back surface of the sheet and the name SPIF has been chosen becauseof the tool concerns with the sheet at a single point at any moment. This method is really useful for rapid prototyping in a low production rate. The tool is designed to form the sheet into a component progressively, and its path is generated by a CNC machine. The ISF is a flexible process in which the metal sheet gradually is formed by the movement of the instrument in free space. The free space means the absence of matrix in the mold, which makes the process flexible to produce complex geometry shapes. Due to the local formation of the sheet and the focus of the forces on the contact area between the sheet and the instrument, the formability in this process increases and this phenomenon advances the flexibility of the process used. The geometry in these experiments is a frustum with a variable wall angle, schematically presented in Figure 1 [1].

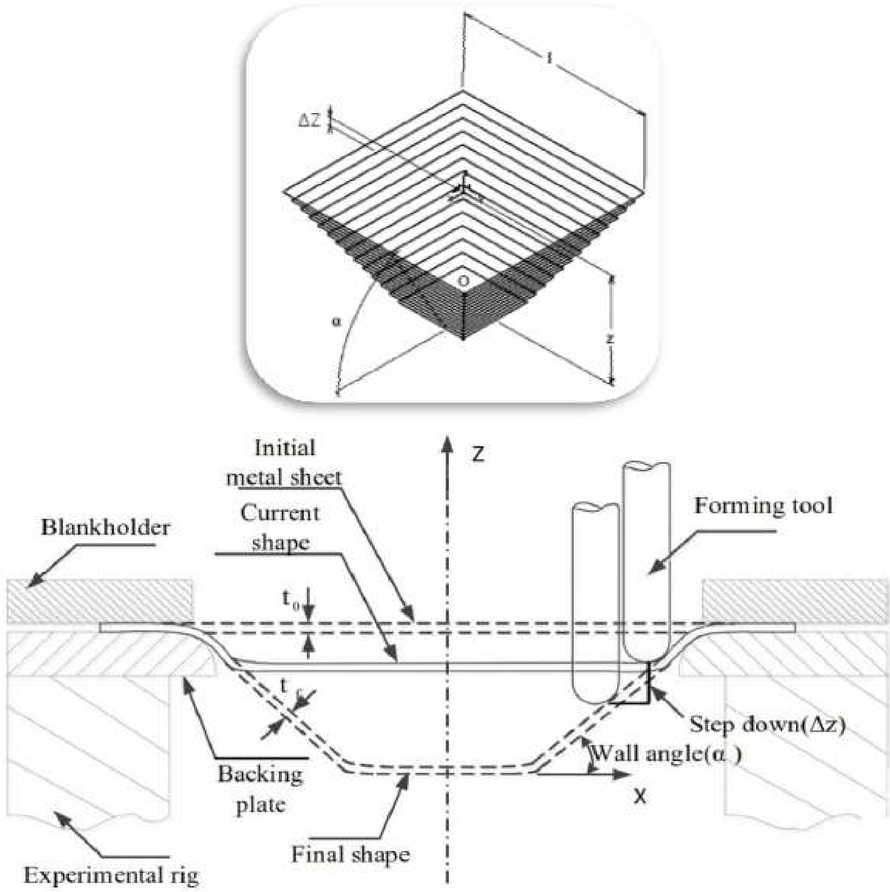

Figure1. Details of incremental forming and illustrating incremental steps [1]

For the first time, the SPIF method was assessed for circular and elliptical frustum by Iseki in 1993 [2]. Later in 2003, Kim et al. investigated formability of cones by both single point and two points incremental forming (TPIF) methods [3]. They found that it is impossible to form both “Stainless Steel/ Stainless Steel fiber/ Stainless Steel” and “Aluminum/ Aluminum foam/ Aluminum” sandwich panels by ISF process without compression and possible shear strength reduction of their core layer. In a study, Contorno et al. investigated the formability of the aluminum foam sandwich through experimental and numerical simulations. Obtained results indicated the possibility of developing simple forming processes on such composite parts as the aluminum foam sandwiches [4]. By the year 2008, Jackson et al. [5] had research on sandwich panels and found that 3D sandwich shells with aluminum foam core can be produced by using the ISF and the ISF can be used to form impressions on one surface of metal foam core sandwich panels. In another study, eight forms of fracture were recognized by Zenkert et al. in 1995 [6]. They werefractures in the surface of the core, the core shear failure, wrinkled surfaces (inside or out), buckling, shear wrinkles, surface dimples, and local wedges. With an assumption of plane stress shear and local wedges to be the only possible forces in incremental forming, Zenkert's list was decreased to three items which they werefractures in the surface of the core, the core shear failure, and local wedges. In 2009 Fu et al. numerically investigated the incremental forming process and their results showed that the mean dimensional error for the work-piece was in the range of 0.38-0.74 [7]. By the year 2010,Dejardin et al. analyzed the shape distortion and springback effects arising in SPIF in order to study the use of a finite element model to perform a simulation of the ISF process [8]. In 2012, Chao et al. numerically and experimentally investigated tensile test on frustum made through the incremental forming process and studied mechanical properties and thickness distribution [9]. In addition, they discussed the relationship between the tool path and the minimum thickness, as well as the location of it, which the results from experiments and simulations showed that the minimum thickness is greatly related to the diameter of the instrument.Honarpisheh et al by 2015 investigated the electric hot incremental forming (EHIF) process experimentally and numerically on the Ti-6Al-4V sheet [10]. The results demonstrated that the incremental forming force increased with increasing the step size and decreasing the tool diameter. Also, the thickness of the formed samples is decreased with increasing the wall angle and decreasing the step size.By the year 2018,Sakhtemanian et al. investigatedmaterial modeling technique in the single point incremental forming assisted by the ultrasonic vibration of low carbon St/CP-Ti bimetal sheet [11]. The experimental results showed the reduction of the amount of force and coefficient of friction under the influence of vibration. In 2018 Sakhtemanian et al.used ultrasonic vibrations on a tool to improve the mechanical properties of the sample made bythe ISF process [12]. The results showed that hardness and tensile strength increased by 50% and 30% respectively, due to the applying ultrasonic vibration. Microstructural studies on the samples showed that due to the temperature increase of the samples as a result of the conversion of ultrasonic vibration into the heat, the continuous dynamic recrystallization process occurred in the microstructure of the samples, which resulted in the grain refinement and improvement in the mechanical properties.

The explosive welding process is relatively a new solid-state method to join metals together. Today, due to the creation of double-layer composite properties such as favorable mechanical and combined electrical properties, the use of bimetals has been developed as well as achieving low-weight structures with proper corrosion resistance, reduced spring back in bending process and cost reduction of components, uniform distribution of temperature, and increasing of sound and vibration absorption in various industries. In recent years, researches have been done on forming of these bimetal sheets. Post-processing on the explosively welded materials has been an interesting field. In recent years, some researches with post-processes have been executed on explosively welded Al/Cu, Al/St, Ti/St multi layers which indicate the enthusiasm of researchers to investigate on these kinds of materials [13-16]. Gheysarian et al. investigated incremental sheet metal forming process experimentally on the explosively welded Al/Cu bimetal sheets [17]. The results showed that the forming force increased with increasing the tool diameter and using aluminum as a top layer (contact with tool). Also, using a spiral tool path increased the average forming force and decreased the maximum thickness changing. The formability increased with increasing the tool diameter and using the copper as a top layer with the spiral tool path. Honarpisheh et al. had an experimental and numerical investigation on single point incremental forming of explosive bonded clad sheets [18].

Gheysarian et al. experimentally and mathematically investigated effects of incremental forming process parameters on incremental forming of the explosive-welded Al/Cu bimetals [19]. The results showed that the presented mathematical method could provide a suitable description of the operation and corresponded with the experimental results. Honarpisheh et al. investigated single point incremental forming process on explosive-welded Al/Cu bimetal [20]. The findings indicated that by increasing the tool radius and vertical pitch size, the forming force increased and the wall thickness decreased. Sakhtemanian et al. investigated mechanical and geometrical properties of St/CP-Titanium bimetal sheet during the SPIF Process [21]. The results showed that by increasing the vertical step down, hardness and tensile properties of the specimens increased but the thickness reduction in the wall of the pyramidal specimens increased and also the surface quality decreased. In addition, micro structural studies showed that by increasing the vertical step down from 0.1 to 0.3, the grain structure transformed from an equiaxed state to a fibrous state and led to the formation of texture in the microstructure, to which mechanical properties improvements can be attributed. In the year 2012, Honarpisheh et al. investigated annealing treatment on the interfacial properties of explosive-welded Al/Cu/Al multilayer [22]. The obtained results indicated that, after an increase of the annealing temperature, the thickness of inters metallic compounds increased and the amount of hardness along the thickness of the joining interface diminished. Their SEM and micro-hardness tests verified the existence of microcracks at the top and bottom interface of the annealed sample sat 400 ˚C. This confirmed the formation of brittle inter metallic compounds at the joining interface and also indicated the low ductility of these compounds [23]. In 2012, an investigation of cold rolling influence on mechanical properties of explosive-welded Al/Cu bimetal showed that thickness reduction increased the ultimate strength and hardness significantly while the elongation percentage diminished and examination of fracture on the surfaces revealed that, due to the brittle nature of the intermetallic compounds at the joining interface, the nucleation and propagation of microcracks have been accelerated under stress and plastic deformation [24]. Sedighi et al. investigated the influence of cold rolling on near-surface residual stress distribution in an explosive welded multilayer [24]. The results of their experiment indicated that high tensile residual stresses are placed at the surface of explosive-welded multi layers and also found that the cold rolling process reduced the surface residual stresses of the multilayer and performing this process with higher thickness reduction creates a higher level of surface residual stresses. In 2018, Kotobi et al. investigated through-depth residual stress measurement of St/Ti bimetal after sheet laser bending process and reported that this process can create significant residual stress at the heat affected zone (HAZ) and saw a discontinuity at the interface of the material in their residual stress profile [25]. The maximum compressive and tensile residual stresses are raised by the increase of laser power and number of scanning passes and both of them are reduced by magnifying scanning velocity. They also reported that laser bending process can increase the surface microhardness at the HAZ which can be attributed to the reduction of grain size. By the year 2015, Honarpisheh et al. investigated mechanical and metallurgical properties of explosive-welded Al/St/Al multilayer sheet after annealing treatment [26]. The obtained results indicated that, with the increase of the annealing temperature, the thickness of inter metallic compounds increased and the amount of hardness along the thickness of the joining interface diminished. These layers were consisted of inter metallic compounds of Al_2Fe which at some points its thickness reaches to about 35μm.

According to the reported experiments, Fei et al. in 2013 compared simulative and experimental results of springback phenomenon after the ISF process and showed that using the FEM-PSONN model is an accurate prediction method of springback [27]. In another research, Khan et al. had a prediction on springback in the SPIF and concluded that very promising results can be obtained with regard to reducing the shape deviations due to springback [28]. In a study by Wang et al., they tried to reduce the springback for double-sided incremental forming (DSIF)and found that reverse bending and squeezing can decrease the springback of DSIF part, and reverse bending looks more effective to reduce the amount of the springback [29]. Zhang et al. annealed the ISMF samples after the process to reduce the residual stress caused by the process and found that annealing can significantly reduce the amount of springback [30]. After all researches, no perusal has been doneto investigate theeffect of process parameters on springback phenomenon in the ISF process, therefore in the current study, this factor has been considered to be reported.

2. Research Method

In this study, the SPIF process was executed on explosive welded Cu/St/Cu multilayer sheet and after the process, a frustum was made on the multilayer sheet (Like a vertical cone cup). The vertical step down and sample depth were designed to be 25 mm with the circular crater of 90mm. Three layered sheets with steel core and side layers of copper with a total thickness of 2.6 mm have been considered. The thickness of the steel layer and the copper layer was 1mm and 0.8mm respectively. Steel has favorable mechanical properties and copper is light weighted and contains suitable corrosion resistance. The sheets were cut in the dimension of 140*140 mm and each was installed on the fixture tightly, hence, during the process, the sheet won't move. The hemispherical tip ISF tool with 10 mm diameter is made of cold work steel. The tip was covered by Nitride to increase the erosion resistance and also Ti-N lubricant was used continuously to decrease the friction in the forming zone.

The design of experiment according to Table 1 was made by three parameters of the vertical pitch with three levels of 0.5, 0.75 and 1mm, the rotational speed with three levels of 100, 150 and 200 rpm and the feeding rate with three levels of 500, 1000 and 1500 mm/min.

Table1. View of testing parameters and their levels

	Vertical pitch	Rotational speed	Feeding rate
Level 1	0.5	100	500
Level 2	0.75	150	1000
Level 3	1	200	1500

After settings the experiment in the Mini-Tab software and entering the required information to simplify the results of the test layout, Table 2 was achieved and according to these results, the experiments will be dealt with.

After modeling and designing the mold, the bottom part of the mold was fixed on the CNC table surface with three clamps and was completely connected to the table to avoid any movement during the tests. First, the tool touched the top of the bottom part of the mold to calculate the location along the Z axis and the remaining steps were performed according to the CNC program instruction, then three-layered sheets were made in square shaped with six holes embedded on the bottom mold for testing and fastening. According to the design of experiments, nine samples are needed. Figure 2 shows the sheet closure in the fixture and deformation of the sheet.

Table2. The layout of experiments in real numbers of parameters by the Taguchi method

No.	Vertical step down	Rotational speed	Feeding rate
1	0.5	100	500
2	0.5	150	1000
3	0.5	200	1500
4	0.75	100	1000
5	0.75	150	1500
6	0.75	200	500
7	1	100	1500
8	1	150	500
9	1	200	1000

Figure2. A view of the sheet closure in the fixture and deformation of the sheet

In the next step nine experiments were investigated with variable parameters ofthe vertical step, rotational speed, and feeding rate,then, the appearance of the sheet was assessed after the ISF process. Amount of springback angle is one of the most important parameters in this experiment which is obtained using a digital goniometer. The main angle in the geometric model of the CNC program assumed to be 120 degrees.Afterward, the opening angle of the outer wall of the tapered cup with the horizontal line (θ1) (Figure 3a) and the upper angle of the inner wall of the tapered cup with the horizontal line (θ2) (Figure 3b) were discussed. A digital goniometer with an accuracy of 0.1mmwas used to measure obtained angles of the samples which the results are shown in Table 3.

Table3. The results for the angles of θ1 and θ2 after the incremental forming process

Experiment Number	Vertical Step Down	Rotational Speed	Feeding rate	Angle $\theta 1$	Angle $\theta 2$
1	0.5	100	500	121.5	120.7
2	0.5	150	1000	121.6	120.3
3	0.5	200	1500	121.3	120.5
4	0.75	100	1000	120.5	121.3
5	0.75	150	1500	122.3	120.5
6	0.75	200	500	121.5	121.3
7	1	100	1500	121.3	121.5
8	1	150	1000	121	121.6
9	1	200	500	121.5	120.9

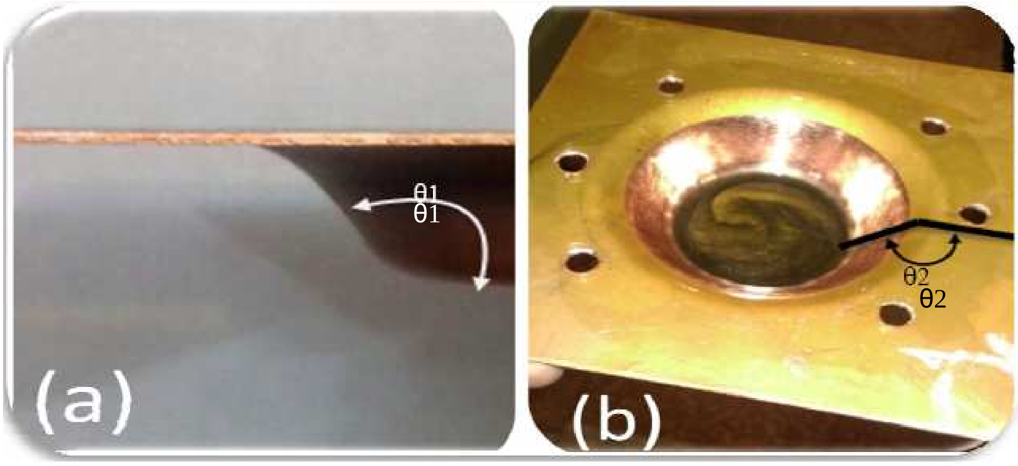

Figure3. (a) A view of the angle of θ1, (b) A view of the angle of θ2

As it can be observed in Figure 4, rupture has been occurred, caused by drawing, in the experiment no. 3.

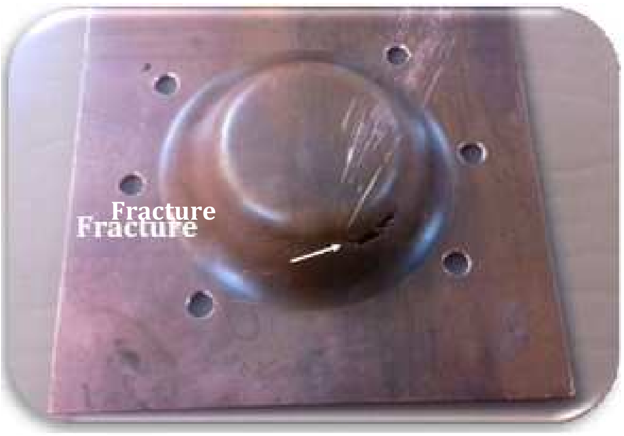

Figure4. A view of rupture after drawing

After measuring angles of θ1 and θ2,springback amount of these angles can be calculated from equation 1, which the results are shown in Table 4.

$$\beta 1 = \theta 1 - \theta 1^{o} \qquad \beta 2 = \theta 2^{o} - \theta 2 \tag{1}$$

β1 is spring back amount of θ1 angle and β2 is springback amount of θ2 angle and $\theta 1^{o}$ and $\theta 2^{o}$are the nominal angles which are 120□.

Table4. The springback angles of β1 and β2

Experiment Number	Angle $\theta1$	Angle $\theta2$	Angle β1	Angle β2
1	121.5	120.7	1.5	-0.7
2	121.6	120.3	1.6	-0.3
3	121.3	120.5	1.3	-0.5
4	120.5	121.3	0.5	-1.3
5	122.3	120.5	2.3	-0.5
6	121.5	121.3	1.5	-1.3
7	121.3	121.5	1.3	-1.5
8	121	121.6	1	-1.6
9	121.5	120.9	1.5	-0.9

3. Result and Discussion

In this study, the ISF method was used to produce three-layered Cu/St/Cu with exact geometrical dimensions. Before the ISF process, all conditions of forming, like sheet selection, rotational speed, feeding rate, vertical pitch size and etc., should be considered and examined carefully. The CATIA software was used to design the mold and important results obtained from experiments. After completion of the designing process for the molds, subsequent stages of experimental testing were done. According to the table 2,different springback angles have been obtained with changes in the parameters of the test while comparing of various experiments angle of θ1 with a hypothetical angle (ideal angle of 120□)in incremental sheet formingprocess.In this experiment, the Taguchi method had been employed in the Mini-Tab software to optimize the results and find the lowest values of the springback angle. As can be seen in Figure 5, the Taguchi method analysis was used to reach the optimal value of the tested parameters for the mean value of the springback angle (β1).

The option of "Nominal is Best" for mean values of all three parameters were selected according to Figure 6 to obtain the optimal angle of β1. The experiment with level 2 of thevertical step down, level 3 of the rotational speed and level 1 of the feeding rate was selected as the best test for the optimum value of β1 angle by the Mini-Tab Software Analysis System. This experiment was achieved with values of 0.75 mm for the vertical step down, 200 rpm for the rotational speed and 500 mm/min for the feeding rate. As it can be seen, increasing the vertical step size decreased the springback angle but increasing the rotational speed and feeding rate increased the springback angle, comparing the first and the last levels.

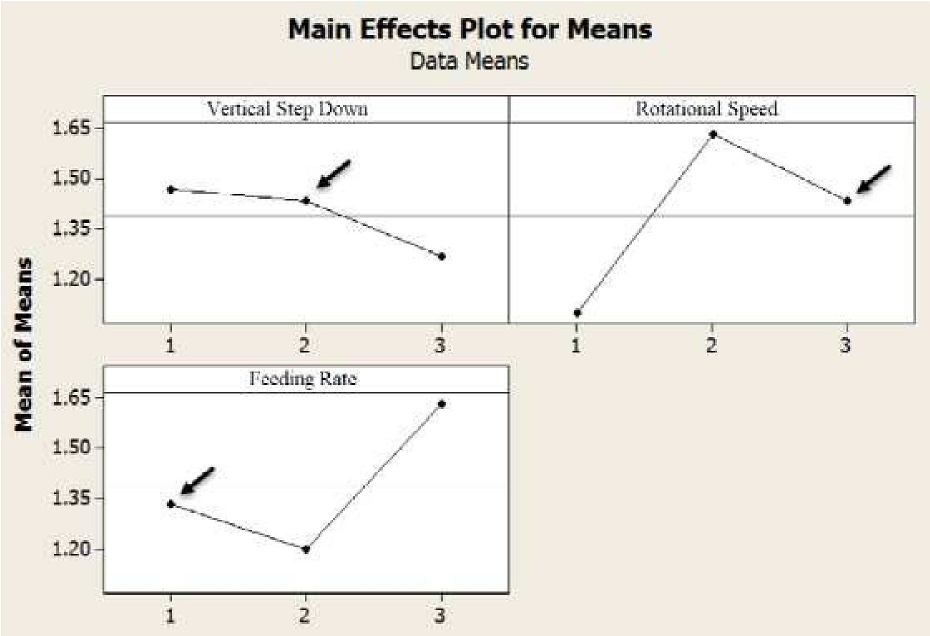

Figure5. Optimized amount of spring back angle of β1 with the "Nominal is Best" signal

Also, the optimal testing parameters for the mean value of the spring back angle of β2 is shown in Figure 6. The experiment with level 2 of the vertical step down, level 3 of the rotational speed and level 2 of the feeding rate, was selected as the best test for the optimum value of β2 angle by the Mini-Tab Software Analysis System. This experiment was achieved with values of 0.75 mm for the vertical step down, 200 rpm for the rotational speed and 1000 mm/min for the feeding rate. In this state, increasing the vertical step size increased the springback angle but increasing the rotational speed and feeding rate decreased the springback angle.

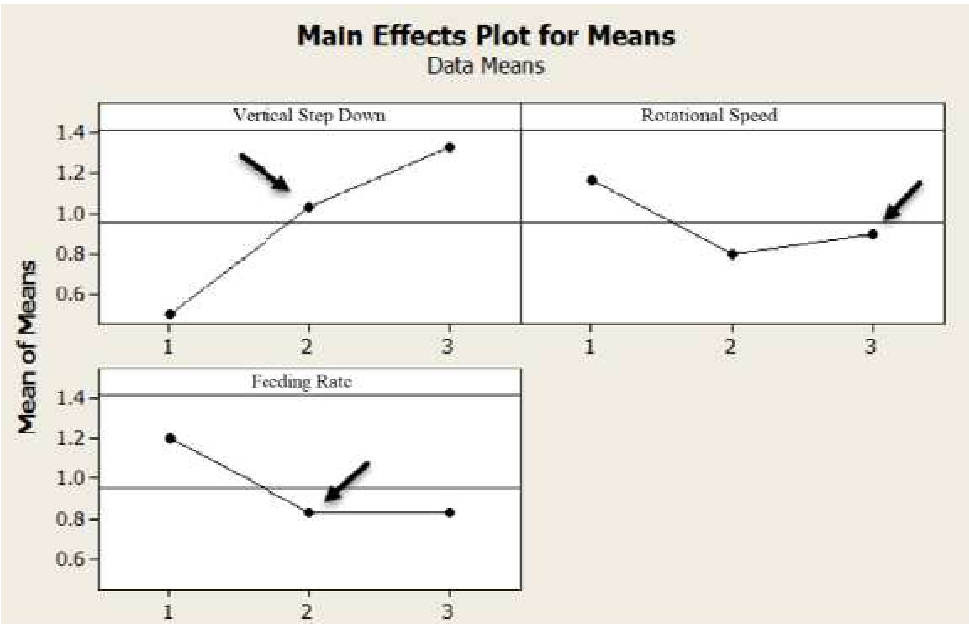

Figure6. Optimized amount of spring back angle of β2 with the "Nominal is Best" signal

In another analysis, parameter values have been calculated in which the lowest angles of the springback observed. In order to find the lowest parameter values for the test to find the lowest springback angle(β1), an experiment with level 1 of the vertical step down, level 2 of the rotational speed and level 3 of the feeding rate, was selected.The test results for the least amount of spring back angle was selected. This experiment was achieved with values of 0.5 mm for the vertical step down, 150 rpm for the rotational speed and 1500 mm/min for the feeding rate. Figure 7 shows a view of the optimal testing in order to find the least amount of spring back angle of β1. For this condition also, increasing the vertical step size increased the springback angle, though increasing the rotational speed and feeding rate reduced amount of the springback angle, comparing the first and the last levels.

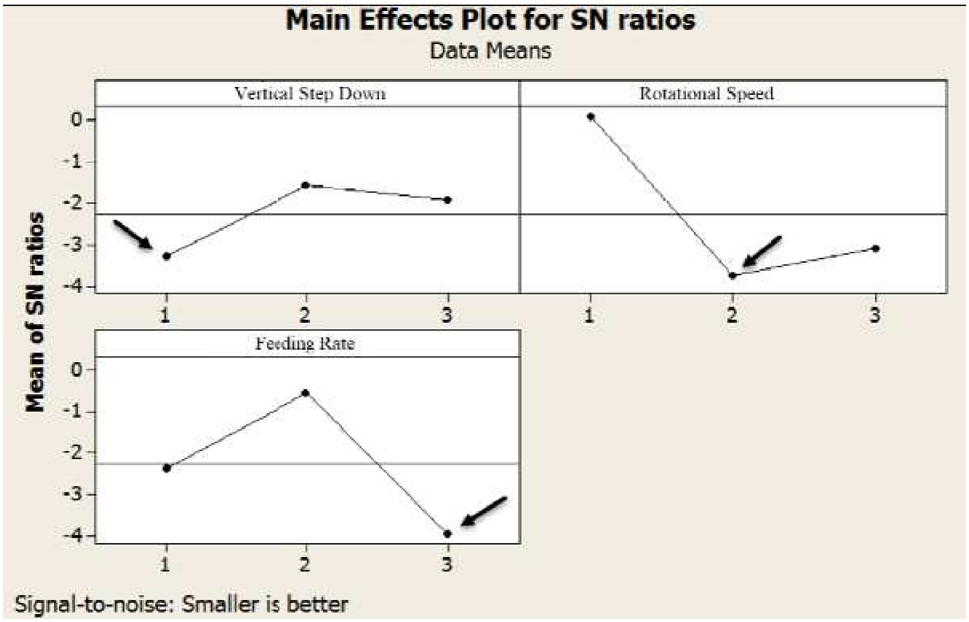

Figure7. Optimized amount of spring back angle of β1 with the "Smaller is better" signal

Also, the optimal testing parameters for the least value of the springback angle of β2 are shown in Figure 8. The experiment with level 3 of the vertical step down, level 1 of the rotational speed and level 1 of the feeding rate, was selected as the best test for the optimum value of β2 angle by the Mini-Tab Software Analysis System. This experiment was achieved with values of 1 mm for the vertical step down, 100 rpm for the rotational speed and 500 mm/min for the feeding rate. In the last condition, increasing the vertical step size decreased the springback angle and increasing the rotational speed and feeding rate increased the springback angle.

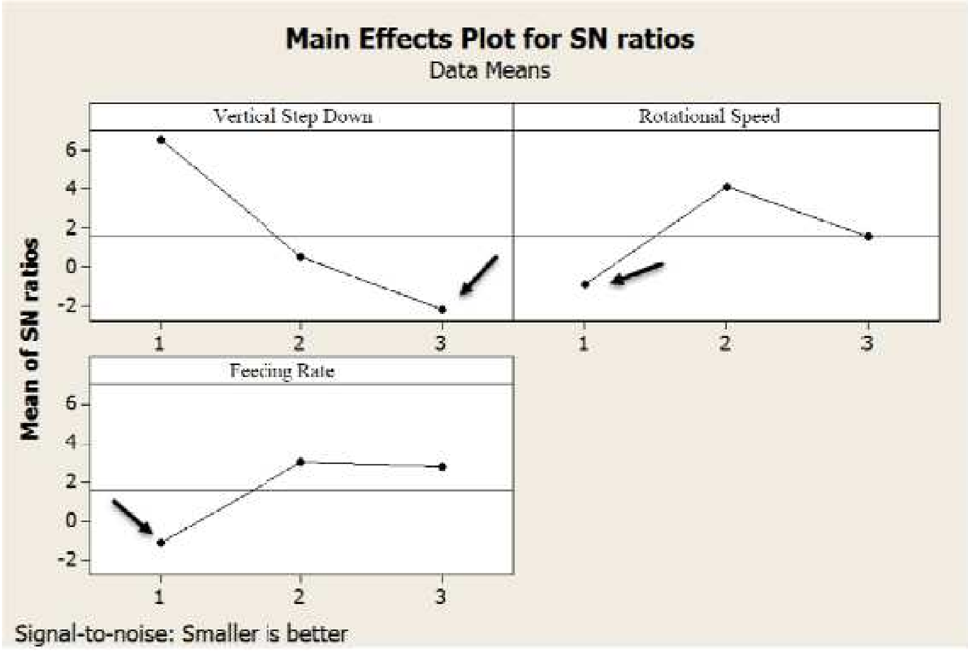

Figure8. Optimized amount of spring back angle of β2 with the "Smaller is better" signal

Explosively welded three-layered Cu/St/Cu sheet was usedin this study. In order to reduce the layer thickness from 2.6 mm to 1.6 mm, the sheet was rolled by 4 passes. In the 3rd test, with parameters value of 0.5 mm for the vertical step down, 200 rpm for the rotational speed and 1500 mm/min for the feeding rate, the sheet ruptured. To examine the rupture reason, at first, the test was repeated to determine if there were any problem with the test parameters in the selected variations or not, but by re-testing, no rupture in the sheet was observed in accordance with the performed test parameters in the third experiment. In considering other possibilities, the type of sheet metal welding, as well as sheet rolling, is considered. If the welding is not properly done in an area of the sheet, it can be problematic, but according to the other tests, it is known that explosive welding can be used with a high percentage of certainty to bond sheet layers properly. Also, sheet rolling has the potential to lead to the rupture,but rolling was done in such a way to properly attach the sheets to each other in order to reduce defects of the experiments.

4. Conclusion

After the execution of experiments, optimizing the results was made on the Mini-Tab software using the “nominal is best” and “smaller is better” signals, and the following results obtained:

1. In the signal of “nominal is best”, the optimal results of β1were obtained with values of 0.75 mm for the vertical step down, 200 rpm for the rotational speed and 500 mm/min for the feeding rate and of β2 angle were obtained with values of 0.75 mm for the vertical step down, 200 rpm for the rotational speed and 1000 mm/min for the feeding rate.
2. In the signal of “smaller is better”, the optimal results of β1 were obtained with values of 0. 5 mm for the vertical step down, 150 rpm for the rotational speed and 1500 mm/min for the feeding rate and of β2 angle were obtained with values of 1 mm for the vertical step down, 100 rpm for the rotational speed and 500 mm/min for the feeding rate.

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