Experimental Investigation of Incremental Forming Process of Bilayer Hybrid Brass/St13 Sheets

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Abstract: In this study, the incremental forming of two layers' brass/St13 sheets through the single-point process was experimentally examined. To investigate the formability of sheet in this process, the desired shape was designed through solid works software, and then surf cam application was used to observe tool motion and extraction of CNC program. G-codes were transferred to the CNC machine and the incremental bilayer sheets forming process was carried out in two different modes, that is, in one case, the brass sheet was placed on top and the steel sheet below, and in the other case they exchanged places. Afterwards, the effects of parameters such as forming tool diameter, vertical step size, and feed rate at three levels on fracture height, fracture angle, and strain were studied. In order to minimize the experiments, the experiment design based on response surface method (RSM) was employed. The results indicated that by increasing the tool diameter, vertical step, feed rate, the fracture angle, and fracture height decreased. The maximum fracture height and angle were estimated 46.5 mm and 71.44 degree, respectively, with tool diameter of 10 mm, speed of 1800 mm/min, and vertical step size of 0.25 mm. According to strain measurement results, steel sheets could bear higher strain rate than brass sheets, and in the case that the steel sheet was on top, the fracture height of bilayer sheet increased. The maximum strain of 0.72 was obtained in SB mode with tool diameter of 10 mm, feed rate of 1000 mm/min and vertical step of 0. 5.

Keywords: Brass/St13 bilayer sheet, Fracture angle, Fracture height, Incremental forming

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1 INTRODUCTION

Over the past decades, incremental forming has been a well-known process in sheet forming. For the first time, the idea of incremental forming in America was patented by Rous [3] in 1960 and then Leszak [4] in 1967. This method received a lot of attention in the early 1990s especially in Japan. In 1964, Matsubara [5] used this method to form and produce parts with metal sheets. The first period, 1986-1996, in Japan can be considered as the primary history of incremental forming. Inventions patented over this period can be recognized as ISF (incremental sheet forming). This method could not attract the attention of manufacturers due to limited numerical control machines at the time. Since 1978 with initial work of Mason [6], this method has been employed. Mason and Appleton (1984) patented their inventions in this field in Japan. These developments (incremental forming) were patented in Japan from 1989 to 1996 by Iseki et al. on stainless steel and titanium sheet with a thickness of 0.7 mm. Iseki et al. have been known as pioneers of this development in Japan during 1989 to 1996.

The second period [6] (1993-2000): this method was accompanied with so many achievements compared to the modern procedures including TPIF (two-point incremental forming) though exclusively patented as an invention in the East and Japan. The third period [6]: incremental forming method was patented in the Wets 2000 onwards which has continued till now. Evolving the numerical control machines, incremental forming started to grow and develop and was used at an accelerating speed and most recently has drawn researchers' attention in Europe and Canada. This process can be presented in three phases. Shim and Park [7] conducted the first studies in 2001 on the determination of forming limit diagram FLD (forming limit curve) in the incremental forming process for aluminium, suggesting that a greater formability rate of a sheet metal in incremental forming process is greater than other traditional methods. Filice et al., [8] designed empirical experiments to derive FLD and revealed that increased formability is the result of local plastic deformation around tool. In another study, Fratini et al., [9] examined the effect of some important mechanical properties of materials on their FLD in both incremental and traditional forming processes and found that strain work hardening of materials had the greatest impact on formability.

Jeswiet and Young [10] studied forming limit of various alloys of aluminium carbon steel sheet 1011. They carried out their study on five different shapes, cone, sphere, hyperbolic, pyramid, and a special flower shape with five similar parts. Considering the effect of previous studies indicating increase in the level of forming limit in this process, researchers also estimated strain of forming limit for the flower shaped sheet. It was reported that compressive strains are created during formation of this particular shape. Presenting a series of analytical relations between stress and strain in this process, Martinez et al., [11] explained the status before a sheet starts to tear. Luo et al., [12] introduced a new system of incremental punching forming. Modelling and simulation of punching forming were analysed. Lue et al., [13] offered the second part of their study developing an incremental punching forming new system based on hydraulic structure. One of the objectives of the study was to examine the effective parameters numerically and experimentally.

Tisza et al., [14] studied incremental forming of aluminium 1050 with a thickness of 0.6 mm numerically and experimentally. The final depth and wall thickness were compared, using the results obtained from software and experimental method. Henrard et al., [15] performed their studies on cone shaped aluminium sheet and used simulation method to investigate single-point incremental forming. They tested the effect of force imposed on incremental forming. Then, they measured forces during incremental forming of two cone shaped aluminium sheets with wall angle of 20 and 60 degrees, using experimental method and finite element simulation. Leon et al., [16] investigated the effect of force and geometrical parameters such as tool radius, shape diameter, and the number of tool rotation on thickness, using software and finite element model. According to the results, the greater the force, the greater impact it had on the thickness. Less force will be needed if tool radius and the number of tool rotation increase. Senthil et al., [17] performed a numerical analysis of incremental forming magnesium alloy metal focusing on the stress and strain. Dongkai et al., [18] studied incremental forming process of magnesium titanium alloys with a thickness of 4.1 mm at room temperature to evaluate the effect of friction and heat generation on forming.

Mugendiran et al., [19] conducted a study on aluminium sheet AA5052 at room temperature. Then, they drew FLD chart. The research was done on three shapes: pyramid, cup, and cone. It was found that the cone-shaped sheet had more favourable thickness distribution. Shanmuganatan et al., [20] surveyed incremental forming aluminium 3003 and its use in automotive industry, aerospace, agriculture, and architecture with an emphasis on wall thickness and surface roughness. Giuseppina et al., [21] reviewed and analysed incremental forming of polymers. Suresh Kura [22] conducted an experimental and numerical study on the formability of steel with an emphasis on wall angle and thickness distribution. The results revealed that finite element model was more accurate than mathematical model in anticipation of thickness changes. Oscar et al., [23] examined tool dynamics during the forming process. The sheet metal spring back and friction and force were examined using simulation method. Nagarajan et al., [24] investigated incremental forming of aluminium alloy 2024, 5083, and 7075 and analysed the results through software and experimental method focusing on wall angle.

All research studies on the formality of sheet metal have focused single-layer sheets. However, this method can be used for manufacturing multilayer sheets considering the properties of bilayer sheets and the capability of the process. In general, multilayer sheets consist of two or more layers of metal, which are widely used in various industries due to their diverse features such as mechanical properties, electrical conductivity, corrosion resistance, and offering combined properties. Zahedi et al., [25] studied single-point incremental forming process of AL1050 bilayer sheets and low carbon steel st12, experimentally and numerically. They evaluated the effect of parameters' tool radius, vertical step size, and feed rate on wall angle.

To determine the fracture height, they used force component derived by ABAQUS software. The present study aimed to investigate fracture height, fracture angle, and strain resulting from brass/st13 bilayer sheets' incremental forming. Fracture height and angle were obtained in a specific shape by changing the input parameters such as tool diameter, vertical step size, and feed rate at three levels. To minimize the experiments, the experiments were carried out based on RSM. There has been also an emphasis on the experimental measurement of strains on the fracture height and angle along direction and perpendicular to the edge of the shape.

2 EXPERIMENTAL

2.1. Materials and equipment

St13 and brass sheets with 0.5 mm in thickness in dimensions of 160×160 mm^2 and glued using polyurethane glue were used. Fixture, forming tool, and CNC machine were used. The equipment used were as follows: CNC machine, model MCV-1020BA (Fig. 1); fixture or mold to hold the sheet tight during incremental forming operation.

Fixture is fixed on the CNC machine table and plays an important role in the experiments. A highly accurate experiment is relied on proper design and manufacturing of fixture. Then, the fixture was manufactured considering size and application; fixture production stages are shown in Figs. 2 and 3.

Fig. 1 Image of CNC machine used in incremental forming process tests

Fig. 2 Construction of the top plate and fixture clamp or mold

Fig. 3 The grinding clamp plates and the bottom plate during the process of making fixture – mold

Fig. 4 The Fixture used in the experiments

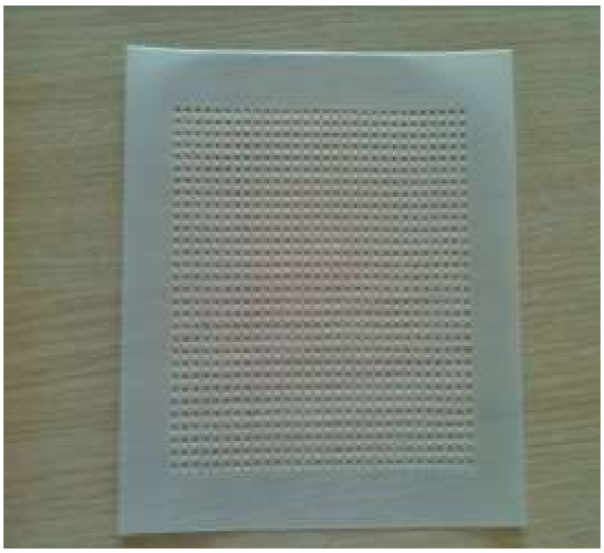

Fig. 5 The stencil designed to make circles with a diameter of 3 mm on the sheet

The fixture dimension was 25×25×25 cm^3, containing two bottom and top plates which hold the sheets. The bottom and top plates and the clamp were fixed on the bases (Fig. 4). The clamp was a 200×200×10 mm^3 plate fully finished by flat grinding machine with an average roughness of 0.8 µm. Some holes were embedded on it to pass 8-mm screws in order to connect the clamp to the bottom plate so it can tightly hold the sheet.
Two sheets with different materials and different properties were used. One was brass and the other St13 which were glued. These two sheets were placed close to each other in sandwich form. Sheet harness was 8.7 HRC (87 HB) for St13 and 6 HRC (60 HB) for the brass. These sheets were cut in dimensions of 160×160 mm^2 and then perfectly cleaned. After preparing the sheets, some regular circles with equal sizes were made on the sheets. This was done using a stencil cutting device designed by laser and CNC machine (Fig. 5). To measure the strains after forming, some circles were sprayed on the upper sheet (Fig. 6).
Forming tools were designed and constructed in accordance to the shape during the test. Thus, the tools needed were initially designed and constructed. Fig. 7 represents the tools before heat treatment.

2.2. Equipment for measuring the samples in incremental forming process

The equipment used to measure the pieces exact size included 1) digital calliper and 2) design software to estimate the angles on the fracture height used in special cases. Using these tools, the parameters could be measured. In order to calculate fracture angle over incremental forming process, SOLIDWORKS software was employed.
As the incremental forming process advanced, the shape's gradual height growth could be read from the controller board of CNC machine. The fracture height depth could also be read by the calliper. It is shown that sheet thickness distribution over the incremental forming process follows the law of Cosines where t_i is the initial sheet thickness, t_f is the final thickness, and θ is the final slope of the piece formed. Thickness at any point was predicted through equation (1), known as the law of Cosines.

$$t_f = t_i \cos\theta \tag{1}$$

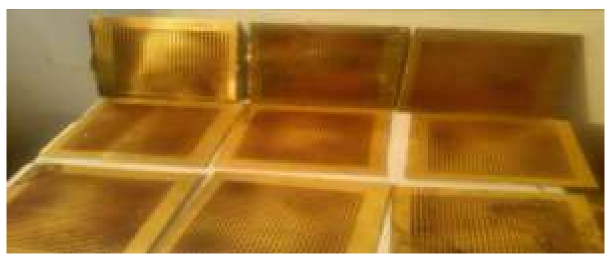

Fig. 6 Sprayed circles on sheet for measuring strains

Fig. 7 The tools before heat treatment

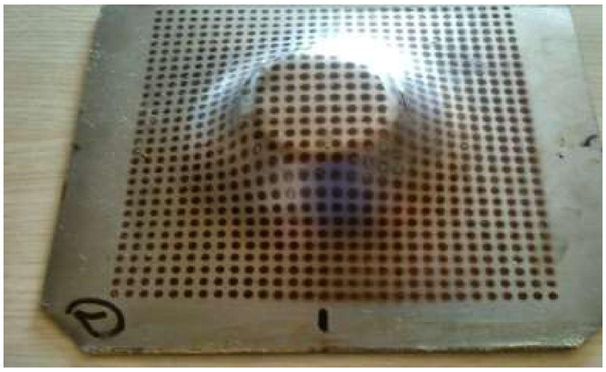

Fig. 8 An example of carved and formed circles on the sheet after incremental forming

2.2.4. Measurement of strains

To estimate the strains, one row of circles deformed on the pieces was considered. Then, two diameters of deformed circles were measured in the direction and perpendicular to the edge of the shape using the digital calliper. Fig. 8 shows the circles after deformation.

3 RESULTS AND DISCUSSION

3.1. The effect of input parameters on the fracture angle and fracture height

Totally, 26 tests were carried out based on RSM design of experiment. Three parameters of vertical step size (P), feed rate (f), and tool diameter (d) were considered as input parameters. Fracture angle (θ) and fracture height (h) were considered as output parameters. All the tests were arranged as follows: once the brass sheet was located up with st13 under it (BS mode), the next time they exchanged places (st13 sheet was up and brass sheet was under it) (SB mode). The results of fracture angle over BS and SB modes are represented in Tables 1 and 2, respectively.

Table 1 The effect of input parameters fracture angle and height in BS mode

P (mm)	f (mm/min)	d (mm)	θ (deg.)	h (mm)
0.75	1800	20	61.17	32
0.5	1000	20	58.42	28.5
0.25	1800	20	61.56	32.5
0.5	2400	20	58.11	28
0.5	1800	15	64.22	36
0.25	1000	15	64.59	36.5
0.75	1000	15	60.59	31.25
0.25	2400	15	60.78	31.5
0.75	2400	15	59.22	29.5
0.25	1800	10	61.94	33
0.75	1800	10	61.36	32.5
0.5	1000	10	69.02	42.5
0.5	2400	10	60.39	31

Table 2 The effect of input parameters fracture angle and height in SB mode

P (mm)	f (mm/min)	d (mm)	θ (deg.)	h (mm)
0.75	1800	20	58.81	29
0.5	1000	20	60.39	31
0.25	1800	20	66.24	38.5
0.5	2400	20	59.22	29.5
0.5	1800	15	63.83	34.5
0.25	1000	15	66.83	39.5
0.75	1000	15	61.70	32
0.25	2400	15	61.17	32
0.75	2400	15	60.78	31.5
0.25	1800	10	71.44	46.5
0.75	1800	10	59.61	30
0.5	1000	10	66.44	39
0.5	2400	10	61.56	32.5

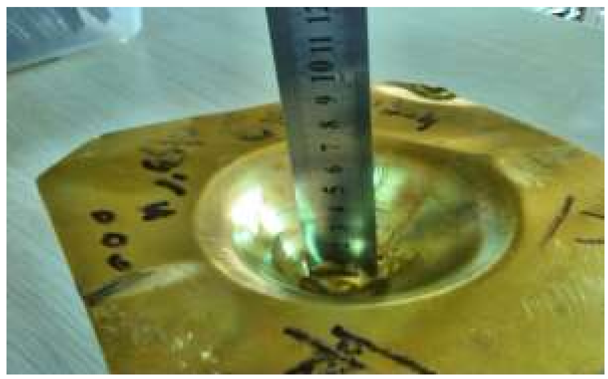

Fig. 9 Maximum fracture height with tool diameter of 10 mm, step size of 0.5 mm and feed rate of 1000 mm/min in BS mode

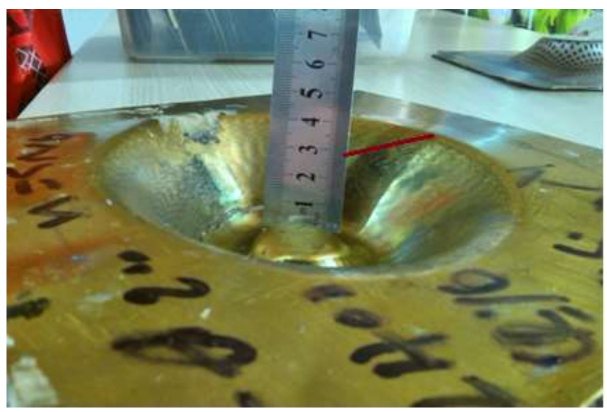

Fig. 10 Minimum fracture height with tool diameter of 20 mm, step size of 0.5 mm and feed rate of 2400 mm/min in BS mode. Looking at these tables, parameters associated with the maximum and minimum of fracture angles and fracture height during SB and BS modes could be found.

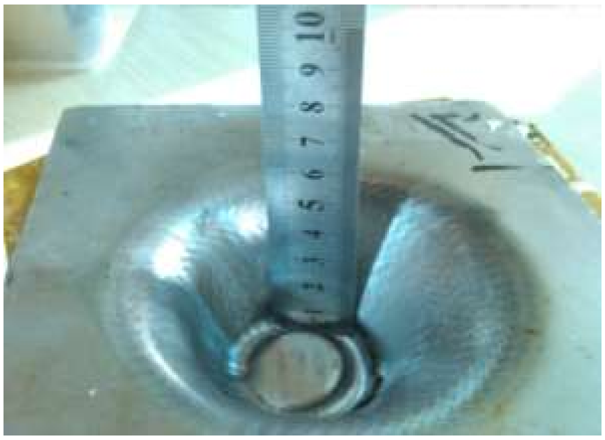

Fig. 11 Maximum fracture height with tool diameter of 10 mm, step size of 0.25 mm and feed rate of 1800 mm/min in SB mode

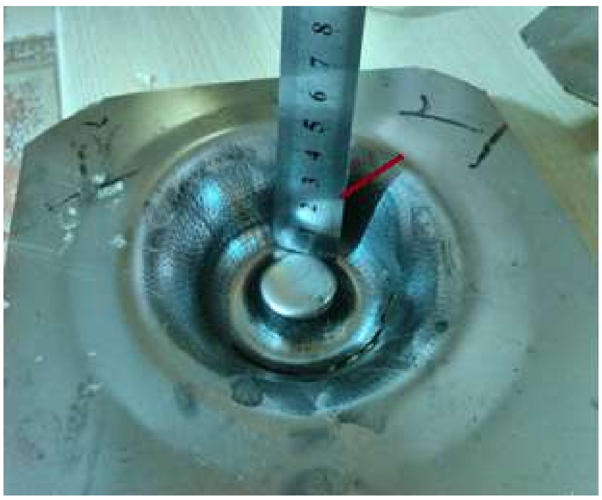

Fig. 12 Minimum fracture height with tool diameter of 20 mm, step size of 0.75 mm and feed rate of 1800 mm/min in SB mode

The results of fracture angle and fracture height measurement over BS mode are provided in Table 2; Parameters related to the maximum and minimum fracture angle and height can be figured out. The maximum fracture angle (69.02) and fracture height (42.5 mm) were achieved with tool diameter of 10 mm, feed rate of 1000 mm/min, and step size of 0.5 mm (Fig. 9).

Fig. 10 shows the minimum fracture angle (58.11) and height (28 mm) related to the parameters with tool diameter of 20 mm, feed rate of 2400 mm/min, and vertical step size 0.5 mm. The results of fracture angle and fracture height measurement over SB mode are provided in Table 3; parameters related to the maximum and minimum fracture angle and height can be figured out. The maximum fracture angle (71.44) and fracture height (46.5 mm) were achieved with tool diameter of 10 mm, feed rate of 1800 mm/min, and step size of 0.25 mm (Fig. 11). Fig. 12 shows the minimum fracture angle (58.81) and height (29 mm) related to the parameters with tool diameter of 20 mm, feed rate of 1800 mm/min, and vertical step size 0.75 mm. As displayed in Tables 1 and 2, when the feed rate increased from 1000 mm/min to 2400 mm/min, fracture angle and height decreased from 42.5 mm and 69.02 degree to the 29.5 mm and 59.22 degree in BS mode. The same behaviour happened in SB.

Although, the process was done with higher velocity, increased feed rate had a negative impact on fracture angle and height. When the forming tool was rotating and was in contact with the sheet, it resulted in more friction and heat. The heat generated made the sheet softer and increased the formability of sheet. Increasing the feed rate in certain domain can improve the formability of sheet metal because of heat generation and softening the sheet. But by more increase in feed rate, the friction between tool and sheet increases (Due to the high heat and sticky friction), and the formability decreases.

As tool diameter increased from 10 to 20 mm, the fracture height and angle fracture decreased from 42.5 mm and 69.02 degree to 28.5 mm and 58.42 mm in BS mode. The same behaviour happened in SB. This is due to the more contact area between the tool and sheet. By increasing the tool diameter, tensile strain increases (in the incremental forming, the forming should be done by material flow) and therefore the sheet metal breaks in lower height.

By decreasing the tool diameter, forming force is applied in the small zone of sheet and causes increasing the formability (tensile strain decreases). According to Tables 1 and 2, it is observed that by increase in vertical step from 0.25 mm to 0.75 mm, fracture height decreased from 46.5 to 29 mm in SB mode and from 42.5 to 28 mm in BS mode. Thus, the fracture angle decreased from 69.02 to 58.11 in BS and from 71.44 to 58.81 in SB mode.

The reason for the reduction of fracture angle and height was the increase of vertical distance of a circular path from the next circle over the forming tool movement. As when the vertical step size increased, the forming tool strike on the sheet got harder and harder from one path to another. Besides, in this stage, the materials were displaced more than when vertical step size was lower. Consequently, the sheet started to vibrate, and therefore more likely to fracture.

3.2. Comparison of strains created by incremental forming in BS and SB modes

The strains were determined through the measurement of small and large diameters of circles turned into an oval shape during incremental forming process on brass and st13 sheets.

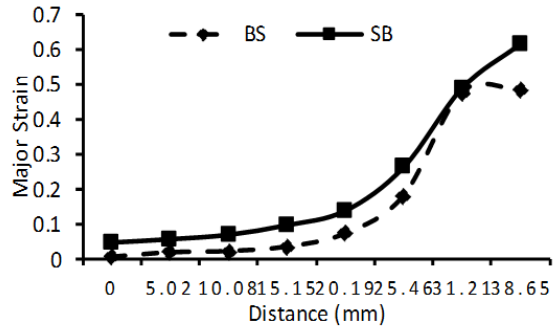

Fig. 13 Major strain, with d=15 mm, f= 1000 mm/min and P= 0.25 mm in SB and BS modes

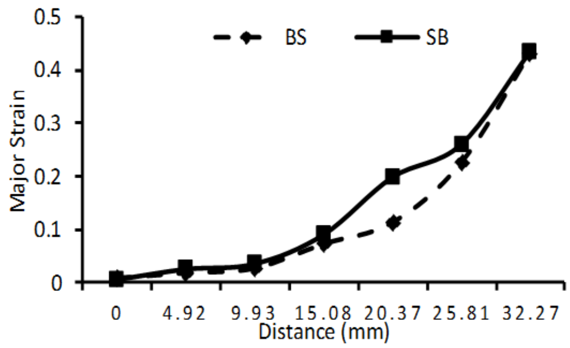

Fig. 14 Major strain, with d=15 mm, f= 1000 mm/min and P= 0.75 mm in SB and BS modes

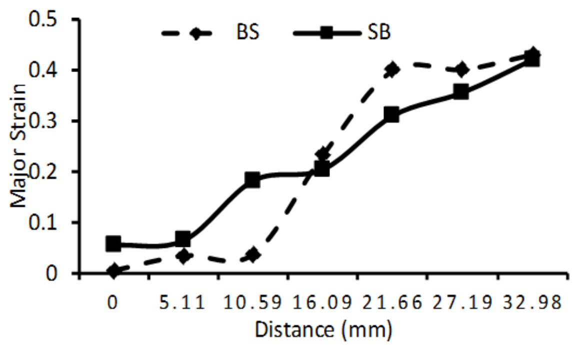

Fig. 15 Major strain, with d=20 mm, f= 1800 mm/min and P= 0.75 mm in SB and BS modes

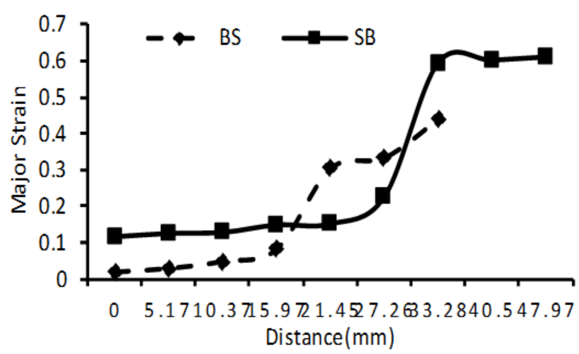

Fig. 16 Major strain, with d=20 mm, f= 1800 mm/min and P= 0.25 mm in SB and BS modes

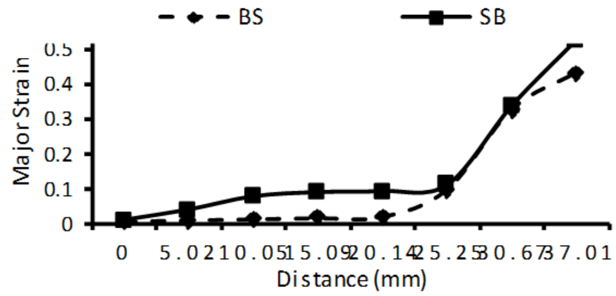

Fig. 17 Major strain, with d=15 mm, f= 2400 mm/min and P= 0.75 mm in SB and BS modes

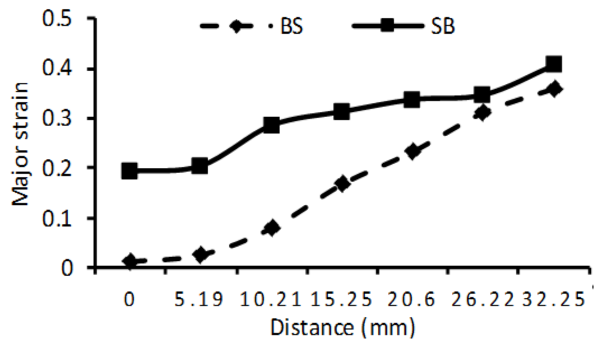

Fig. 18 Major strain, with d=20, mm, f= 1000 mm/min and P= 0. 5 mm in SB and BS modes

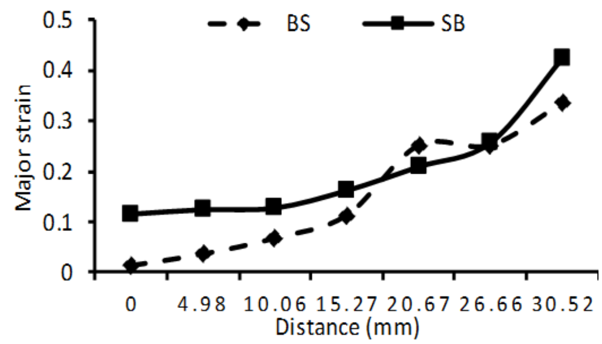

Fig. 19 Major strain, with d=20, mm, f= 2400 mm/min and P= 0. 5 mm in SB and BS modes

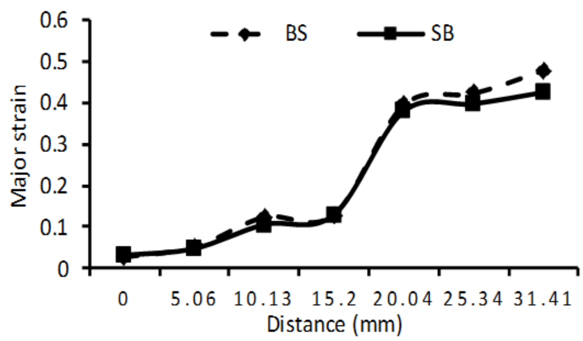

Fig. 20 Major strain, with d=10, mm, f= 1800 mm/min and P= 0. 75 mm in SB and BS modes

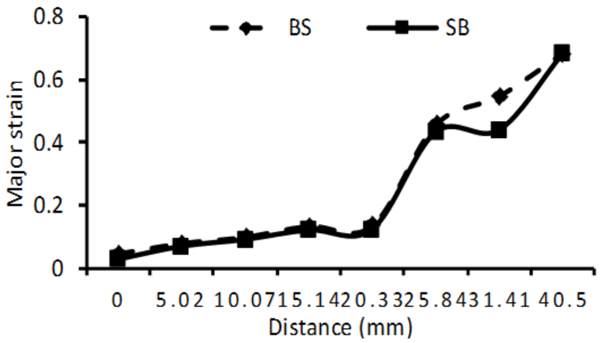

Fig. 21 Major strain, with d=10, mm, f= 1000 mm/min and P= 0. 5 mm in SB and BS modes

According to Figs. 13, 14, 15, and 16, with decreasing the vertical step size, the major strains increased. This shows that the fracture height increased. For example, when the fracture height was equal to 39.5 mm and fracture angle was 66.83, the maximum strain was 0.6186, and when fracture height and angle were 31.5 and 60.78 degree, respectively, the strain value was 0.431. The feed rate had the same effect on strain in SB and BS modes. Figs. 14, 17, 18, and 19 indicate that with increasing the feed rate, fracture height decreased.
According to Figs. 15, 18, 20, and 21, by increasing the tool diameter, the strains decreased. For example, the maximum of major strain in Fig. 22 (d=20 mm, f= 1000 mm/min and P= 0. 5 mm) is 0.42 and in Fig. 25 (d=10 mm, f= 1000 mm/min and P= 0. 5 mm) is 0.76.
According to the results of strain measurement in Figs. 17 to 25, the steel sheet could bear more strain than brass sheet. So, in the case that the steel sheet was located on the top, the fracture height of bilayer sheet increased. This depends on the mechanical properties of steel sheet; as work hardening power of steel sheet (in power law formula) was 0.2387 and of brass sheet was 0.21. As a result, the strain in necking of steel sheet was greater than in brass sheet, indicating that the formability of steel sheet was higher than brass sheet.

4 CONCLUSION

In this study, forming of bilayer brass/st13 sheet was experimentally examined during incremental forming process. To do this, the effect of tool radius, vertical step size, and feed rate on the fracture height, fracture angle, and major strains were investigated. According to the results, when tool diameter increased from 10 mm to 20 mm, fracture height dropped from 42.5 mm to 28.5 mm, and the same thing happened with the angle. Furthermore, along with increase in feed rate, materials' deformation and displacement opportunities decreased along with incremental forming, thus the sheet was more likely to break sooner.
With increase in the step size, strike on the sheet, during incremental forming, got harder and harder from one path to the next; moreover, the amount of materials' displacement at this time was greater, with lower step size. This made higher vibration of the sheet, leading to the fracture of the sheet. The highest amount of fracture height and angle were, respectively, 46.5 mm and 71.44, obtained with feed rate of 1800 mm/min, diameter of 10 mm, and vertical step size of 0.25 during SB.
Since formability of st13 was more than the brass sheet, fracture height and angle were greater in SB than in BS mode. This was confirmed through the results of strain measurement. Greater fracture height and angle of bilayer sheet in SB was a result of mechanical features of steel sheet.

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