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An Experimental Investigation on the Forming Force in Asymmetric Parts Formed Using Single Point Incremental Forming

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Abstract

Single point incremental forming (SPIF) is used to form small batch production of different shapes of parts. Present study is focused on investigation of part asymmetry on the forming behavior of the parts formed using SPIF process. Wall angle as an asymmetry is considered for forming of the pyramidal frustrum. The wall angle is varied from 50^o to 65^o and subsequent forming forces are recorded using force dynamometer. It is observed that the increase in the wall angle for symmetric part results in increased formability to a threshold wall angle of 55^o, beyond which the formability of material decreases. For the asymmetric parts, the difference in the forming forces of forming different wall angles (50^o and 55^o) is 28%. The difference in the forming force increases to 93.27% for part having wall angles of 50^o and 60^o. Furthermore, during forming of asymmetric part, it is observed that the maximum forces go on increasing till the wall angle reaches to 60^o followed by sudden decrease in the forming forces. When compared to forming of symmetric part under similar conditions, it is observed that the symmetric part reaches to its fracture limit earlier as compared to that of asymmetric part. The numerical simulation gives some clear insights in the forming behavior of the asymmetric parts. Furthermore, it is observed that equivalent plastic strain first increases, and then decreases considerably resulting fracture of part of wall angle 65^o.

Keywords: Forming forces, asymmetric parts, SPIF, Wall angle

INTRODUCTION

Incremental forming process has been studied since the past 25 years and is being used to form complex shapes in a short period of time. ISF process does not require any specific dies for the forming process. It requires minimal tooling and less amount of time as compared to traditional sheet forming processes. The blank is held in place by the backing plate and blank holder when employing the ISF method, and a tool is free to move on the blank in the negative z-axis with a little incremental step [1]. ISF requires shorter lead times and less expensive initial investments in the modern marketplace, where smaller-scale production and limited series are significantly more advantageous. ISF can be characterized from a number of perspectives including the forming procedure, part shape, tool path strategy, tools employed, etc. [2]. The most significant and favored ISF process variations are the hybrid incremental sheet forming (HISF), two-point incremental forming (TPIF) and single-point

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incremental forming (SPIF). The vast majority of parts for automobiles, ships, airplanes and also biomedical implants are produced using the sheet forming technique. Ability to form different part shapes without using a dedicated die makes the ISF process a stand out sheet metal forming operation. Major research in the area of ISF is related to SPIF or TPIF processes. Very complex and interesting shapes have been formed while the study in the field of incremental forming process, but large number of researchers have used conical frustum or pyramidal frustum as part geometry. It is evident from the literature that major research contribution in the field of ISF comprises of forming of axisymmetric parts.

Though incremental forming has the ability to form any part shape, majority of the research is carried out on very common parts such as conical frustum or pyramidal frustum. However, research is also carried out on other part geometries as well such as non – symmetric parts such as biomedical implants etc. Shim and Park [3] and Park and Kim [4] studied the formability of parts formed using ISF process. Authors used triangular, rectangular, pentagonal, hexagonal and conical frustums to study the formability. In addition, octagonal frustums having convex and concave surfaces, bucket shape and stepped shapes are also formed using SPIF and TPIF process. One of the major conclusions of the study is the initiation of fracture at the corners of the formed part. Positive forming i.e. TPIF process results in forming of sound parts with good geometric accuracy. Jackson at al. [5] attempted to form sandwich panels comprising three-layer blank Al/Al foam/Al. Authors found that sandwich panels having high ductility and incompressible cores can be formed using ISF process. Radu and Cristea [6] studied the geometric accuracy of the stepped features in the prismatic and conical frustrum made of three different materials. Authors found that there is contradictory effect of parameters on the geometric accuracy and suggested the parameters optimization in order to get the optimum result. Panjwani et al. [7] worked on forming of L and M shapes using flexible bolts as support during the forming operation. Authors reported backing plate cannot be used in geometries which different elevation at different location. To overcome this problem, authors used flexible bolt support near the forming area, which considerably improves the geometric accuracy of formed parts. Without the bolt support, the part shape is completely distorted. Ambrogio et al. [8] formed prosthesis made of titanium alloys using the SPIF process. The prosthesis is of asymmetric shape. Several tests such as drop test were performed to test the performance of the formed part. Authors reported that the prosthesis survived all the test. Ambrogio et al. [9] formed partial part shape using ISF process and remaining part using additive manufacturing process to obtain specific features of the part. Authors deposited material at the areas of high local thinning in the incremental forming process, thereby increasing the strength of the formed part. Ndip-Agbor et al. [10] used multi-pass SPIF process to form complex shapes. Authors associated the stepped feature generation to rigid body motion caused by intermediate steps. Furthermore, authors parameterized the correlation between the rigid body motion and stepped feature generation. A methodology was adopted which reduces the stepped feature generation and improved formability. Gandla et al. [11] studied the surface roughness of the asymmetric part shape by varying the wall angle of the part. D–shaped parts were formed with different wall angles using full factorial design of experiments method. Authors found that the methodology used by them resulted in higher accuracy of results of image processing when the images are used at any orientation for the image processing. Zhai et al. [12] investigated the forming force and surface roughness in ultrasonic – assisted incremental sheet forming process. They found that the ultrasonic vibration has significant effect on smaller tool size and small sheet thickness only. When the ultrasonic vibrations are added, there is considerable reduction in the forming forces. Furthermore, Li et al. [13] studied the effect of ultrasonic vibrations in incremental sheet forming of varying angle pyramidal frustum. Authors found that the ultrasonic vibration – assisted incremental forming results in reduced internal stresses and uniform thickness distribution of the formed parts. Su et al. [14] studied the influence of forming parameters on the forming limit of SPIF process using forming limit angle and maximum thinning rate. Authors concluded that the proposed methodology is only useful to predict the forming limit of simple shapes such as conical frustum, and will be ineffective for complex and asymmetric shapes. Wankhede et al. [15] formed D-shaped part, wherein three sides of the part have straight edge, whereas the fourth edge is semi-circular. Authors concluded that tool diameter and step depth has significant influence on forming force. Furthermore, authors optimized the significant process parameters to improve the manufacturing time, forming forces and surface quality of the formed parts. Apart from these, very few researchers have applied efforts to study the mechanics of forming and influence of parameters on various response characteristics. Furthermore, Wankhede et al. (2022) optimized the significant process parameters. Huang et al. [16] investigated the part size and thinning rate in SPIF process. Proposed method is useful to evaluate the dimensional changes of formed part of any shape. Rosa-Sainz et al. [17] investigated the formability, micro – mechanics of failure and temperature analysis of the polycarbonate sheets deformed by SPIF. Authors reported three modes of failure viz. fracture, twisting and crazing. It is found that higher values of step depth increases the intensity of twisting, whereas high values of spindle speed results in crazing. Behera et al. [18] discussed Single Point Incremental Forming (SPIF), a sheet metal manufacturing process using a CNC-controlled hemispherical tool. SPIF offers flexibility and cost advantages but has limitations. The paper reviews recent developments in SPIF over the past decade, covering hardware, forming mechanics, accuracy, modeling, sustainability, and application areas. It aims to provide a concise overview of SPIF's current state and potential for industrial use. Bansal et al. [19] outlined the emphasis on the process variables and how they affect accuracy, failure mechanics, deformation, formability a modified analytical model for incremental sheet forming (ISF) was presented that can estimate produced component thickness, forming forces and contact area with accuracy.

From the review of the available literature, it is found that many researchers have applied the research efforts to understand the mechanics of the SPIF process. The major focus of many of the researchers is forming of symmetric parts such as conical frustums or pyramidal shapes. The sheet metal parts used in many industrial and biomedical such as implants, applications are not symmetric in shape. Few researchers such as Panjwani et al. [7], Wankhede et al. have considered the forming of the asymmetric parts and evaluating the influence of the process parameters. Asymmetry in the part is generated by using some specific shapes such as M and L shapes [7] or forming of the D – shaped frustum [15]. Su et al. [14] have reported that the formability evaluation methods used are applicable for simple and symmetric parts only, and the forming mechanics of the complex and asymmetric shapes if completely different from the symmetric and simple shapes. Hence, there is a stern need to apply research efforts to investigate the forming mechanics and effect of parameters on the forming mechanics of the asymmetric parts formed using SPIF process.

The major objective of the present work is to investigate the forming forces in asymmetric part formed using SPIF process. Efforts are applied to form asymmetric part using SPIF process. pyramidal frustums of different wall angle are formed, considering the wall angle as the asymmetry of formed part. Numerical simulations are performed using ABAQUS Explicit software tool to study the influence of asymmetric wall angle on the forming forces and surface roughness. Furthermore, experiments are performed to validate the results obtained using numerical simulations.

MATERIAL AND METHODOLOGY

Incremental forming of pyramidal frustrum in the present experimental work is carried out on a vertical machining center (VMC). As shown in Figure 1, a simple fixture is used to hold the blank sheet in place. A backing plate and a clamping plate that securely holds the sheet metal blank along with nuts and bolts are used to fasten the sheet with the fixture. The blank sheet is used is of Aluminum alloy Al-6061 sheet metal. Aluminum alloy Al-6061 is frequently used in the automotive industry, building materials, equipment for chemical processing plants, and the aerospace industry. A milling tool force dynamometer was mounted on the work table of VMC machine to record all the forces acting on the sheet during the forming operation. The force exerted on the sheet at every second is recorded in the data acquisition system. The forming tools are made of stainless-steel SS-305. These tools are manufactured on a lathe and then hardening process is performed to ensure that the tools do not wear off during forming operation. The tools are hardened to 32 HRC before the operations are performed. Further they are polished to create a smooth and shinning surface. The tool

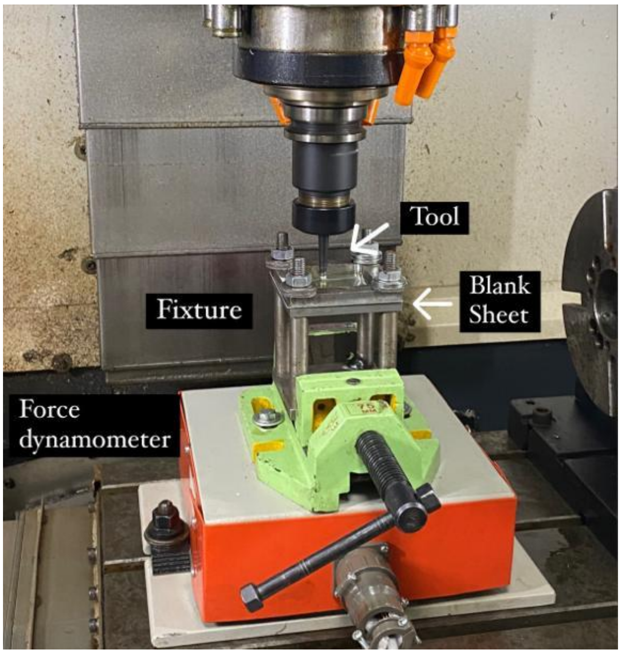

Figure 1. Experimental setup along with fixture and forming tool.

considered for the experimentation work has a radius of 5 mm. The experimental setup consists of a fixture of 80 mm × 80 mm plates with support rods on each corner. The aluminum sheets of 0.8 mm thickness were cut and holes were drilled at every corner with the help of a drilling machine. Two support plates as shown in Figure 1 are manufactured in order to support the aluminum plates from both sides as there is no specific die used in this procedure.

To commence the ISF process, the initial step involves preparing the sheet metal workpiece. This preparation entails securing the sheet to a fixture or the bed of a CNC machine [1]. This is typically achieved by utilizing vacuum or mechanical clamps, ensuring a stable and secure positioning of the sheet during the subsequent stages of the process. To perform forming operations on VMC machines, it is necessary to input tool path of the desired part in the form of G-codes and M-codes. These codes are generated using CAM module of Autodesk fusion 360 software tool. It allows users to specify parameters such as tool diameter, feed rate, step depth, spindle speed, and generate toolpaths based on aforementioned information. By providing these necessary inputs, the software generates the required codes for the operation on VMC machine. The numerical simulations of incremental forming process are done using ABAQUS Explicit software. Mesh type used for the simulations is quad dominated mesh with the mesh size of 2 mm, whereas the dynamic explicit material model is used.

Both symmetric and asymmetric part shape are formed in the present experimental work to study the influence of wall angle on the forming force. The symmetric parts have same wall angle on all sides of the pyramidal frustum, whereas asymmetry is generated using variation of wall angle for different sides of the pyramid. To generate the asymmetry, two opposite wall angles are same, whereas remaining two walls are inclined at a different wall angle. Figure 2 depicts the symmetric and asymmetric pyramidal frustum formed. The pyramidal frustrum having 40 mm base and 16 mm height are formed for different wall angles.

Experiments in present work are conducted based on the process parameters listed in Table 1.

The wall angle is varied by five degrees starting from 50° up to 65° as shown in Table 1. At first, a pyramidal frustrum of 50° wall angles on each side is considered and then the wall angles on opposite sides are increased by 5° to 55°. Similarly, for the next part, two opposite sides of wall angle 50^{o} are

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kept constant and remaining two sides of the pyramid are formed with a wall angle of 60°. In this way, the asymmetry of the part is varied to a final wall angle of 65° as shown in Table 2.

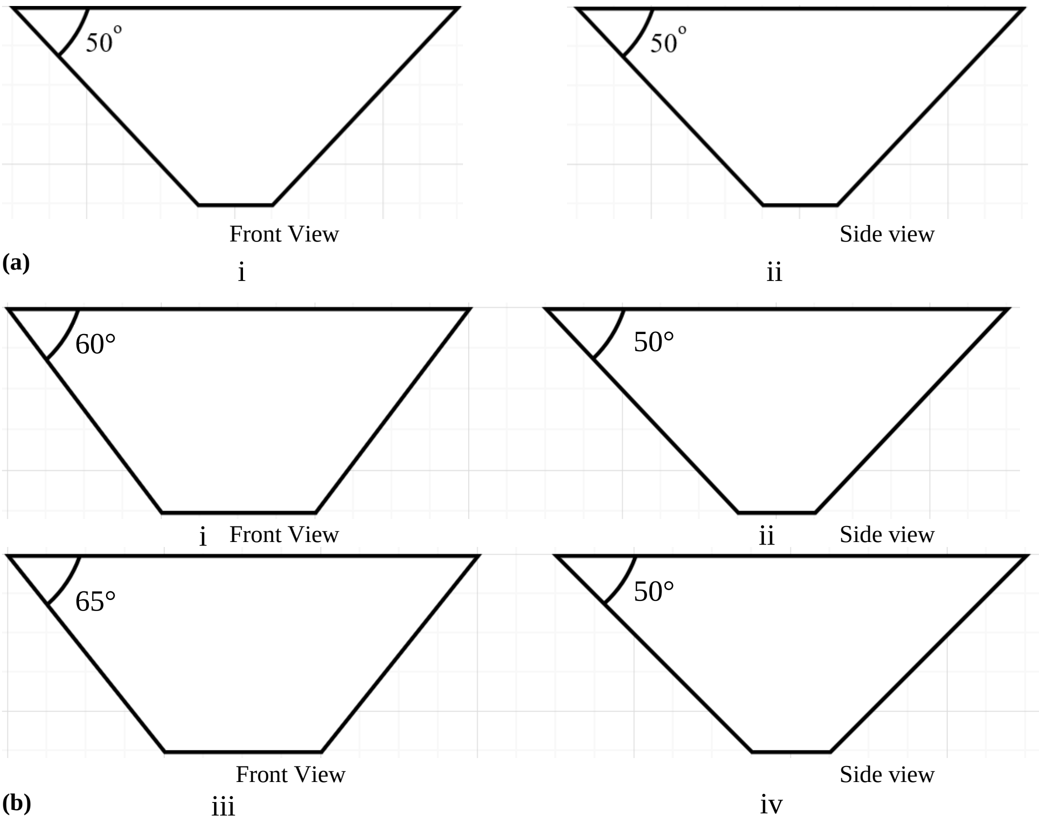


Figure 2. Variation in wall angle. (a) Symmetric pyramidal frustum, (b) Asymmetric pyramidal frustum.

Table 1. Parameters for forming asymmetric pyramidal frustrum.

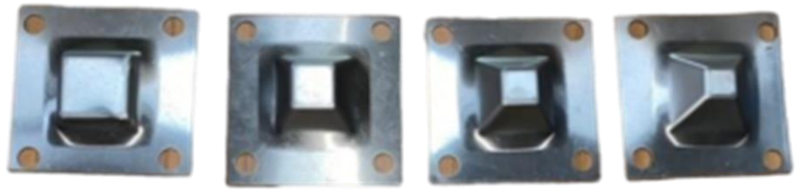
Parameter	Units	A1	A2	A3	A4
Tool radius	mm	5	5	5	5
Wall angle	Degrees	50	55	60	65
Step Depth	mm	0.5	0.5	0.5	0.5
Feed Rate	mm/min	200	200	200	200

Table 2 Wall angles used to form symmetric and asymmetric parts.

Set 1-Symmetric	Set 2-Asymmetric
1. Wall angle 50°	a. Wall angle 50°
2. Wall angle 55°	b. Wall angle 55°
3. Wall angle 60°	c. Wall angle 60°
4. Wall angle 65°	d. Wall angle 65°

As shown in Figure 3, the first set of experiments are performed to form symmetrical parts with 50°, 55°, 60° and 65° wall angles on all sides. While performing experiments, all parts are successfully formed except for the part with wall angle of 65°, which fractured while forming. Furthermore, the second set of experiments comprises of asymmetric parts, wherein part asymmetry is introduced as discussed in section 2 and depicted in Figure 2. During forming of the asymmetric parts, the pyramidal frustrum having wall angle of 65° could not be formed successfully. Table 2 shows the variation of wall angles in each set.

Set 1



Set 2

Figure 3. Pyramidal parts formed using SPIF process.

RESULTS AND DISCUSSION

In this section, the results of asymmetric part formed using SPIF process are discussed. The simulation results and experimental results are compared for validation of the force required for forming of pyramidal frustrum.

While forming the parts, various forces like feed force, cross feed force, thrust force and torque have been taken into consideration. The feed force experienced by the forming tool varies over time due to several factors like wall angle, feed rate etc. These fluctuations occur as the tool interacts with various sections of the workpiece. For instance, the feed force rises when the wall angle of formed part is increased or when the feed rate is elevated. The cross-feed force in CNC machining is also the force exerted on the forming tool during the movement perpendicular to the workpiece being machined. Similarly, the thrust force fluctuates as the tool interacts with various regions of the workpiece. The torque needed to maintain a consistent forming speed varies during the forming process. As the forming tool engages with the blank sheet, the torque increases. Furthermore, the torque starts decreasing the tool exits the blank sheet. Figure 4 to Figure 9 depicts the feed force varying with respect to time and cross-feed force varying with respect to time.

Figure 4, 6 and 8 depicts the feed force variation during the incremental forming of the pyramidal frustum with respect to time. It is observed that the force varies between maximum and minimum value, representing the positive and negative values of feed force being applied on the pyraidal frustum during the forming process. Figure 4 depicts the feed force for wall angle of 50^o (symmetrical part), Figure 6 depicts the feed force for wall angle of 55^o (asymmetrical part) and Figure 8 depicts the feed force for the part of wall angle 60^o (asymmetric part). It can be observed from the figure 4, 6 and 8 that with increase in the part asymmetry due to increasing wall angle, there is slight increase in the feed force.

The force versus true distance along the formed part is depicted in Figures 5, 7 and 9. Figure 5 depicts the force versus true distance of pyramidal frustum of wall angle 50^o (symmetric part). It can be seen that, as all four sides of the pyramidal frustum are having equal wall angle, the forming force is equal over the true distance. The values of forming force required is about 150 KN and is nearly same for the part. It indicates uniform force requirement for forming the symmetric part. Furthermore, as the wall angle of two sides of next part (Figure 7) increases from 50^o to 55^o, it can be observed that the forming force during forming of wall angles 50^o and 55^o is different. For the wall angle 50^o, approximately 125 KN of forming force as depicted on the right-hand side of the graph, is required. Whereas, higher forming force, about 160 KN is required to form large wall angle. The difference between the required forming force of different wall angle is about 28% (35 KN).

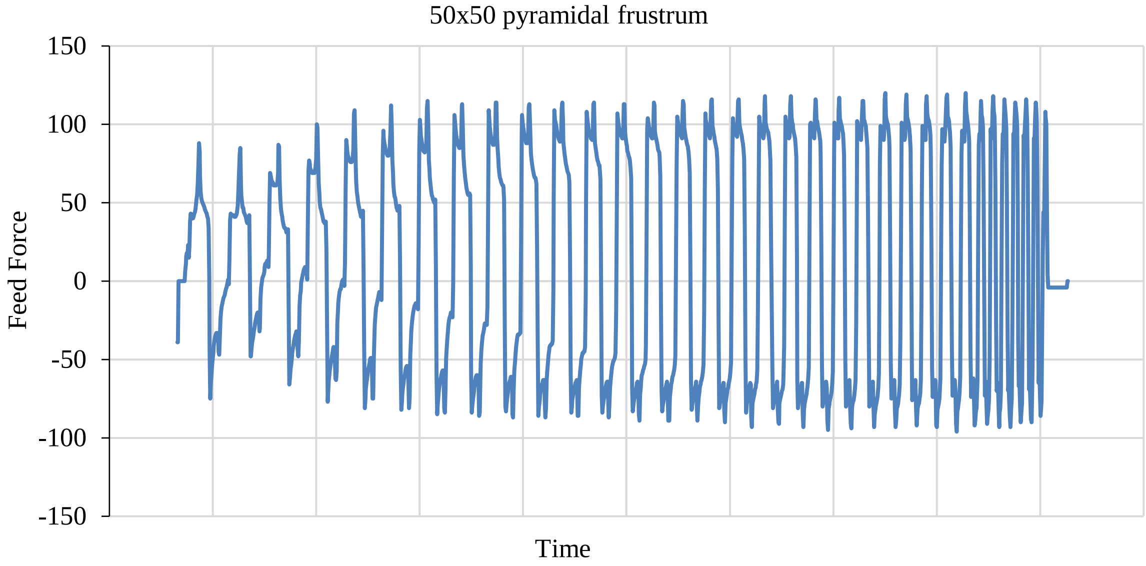


Figure 4 Force vs Time graph for set 2 (a).

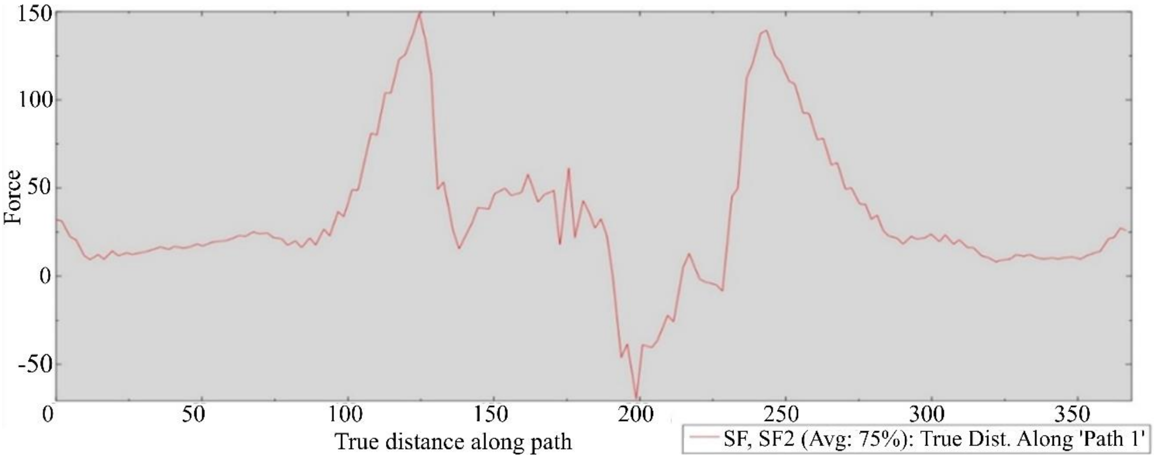


Figure 5. Simulation results for set 2 (a).

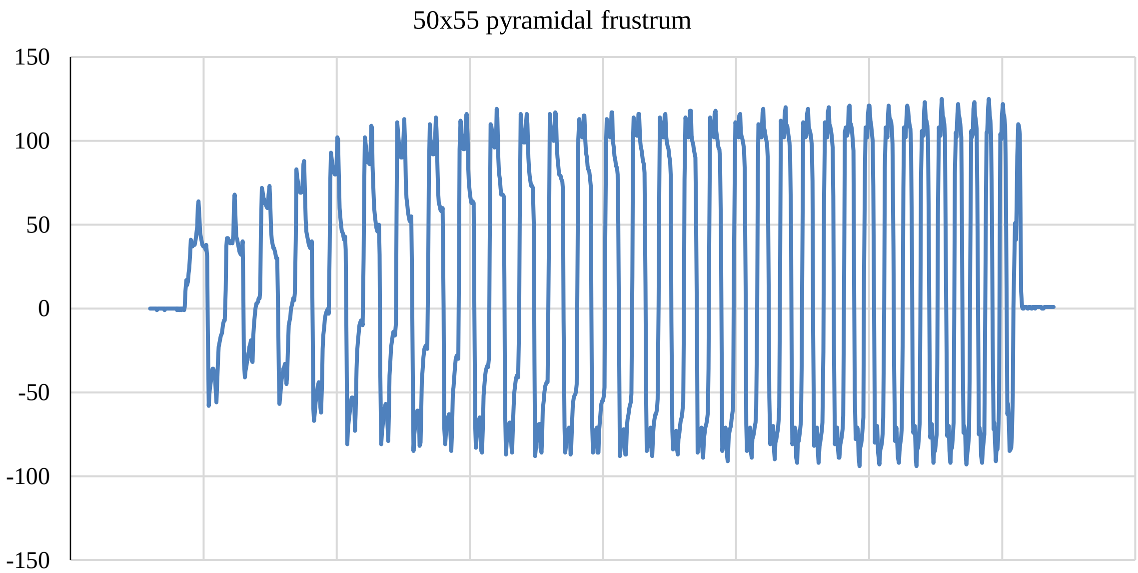


Figure 6 Force Vs Time graph for set 2 (b)

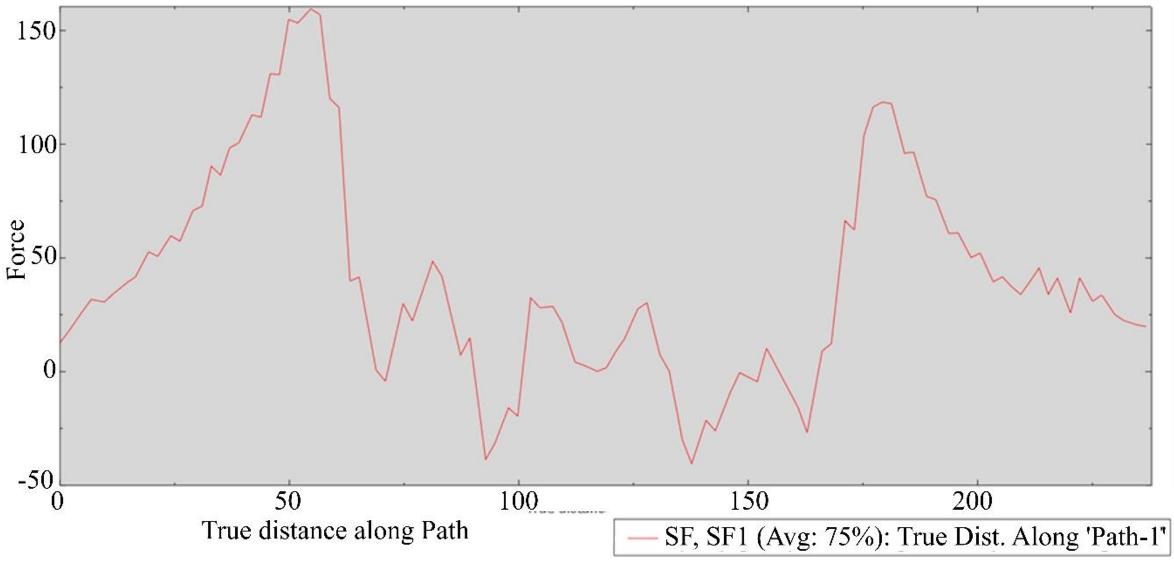


Figure 7. Simulation results for set 2 (b).

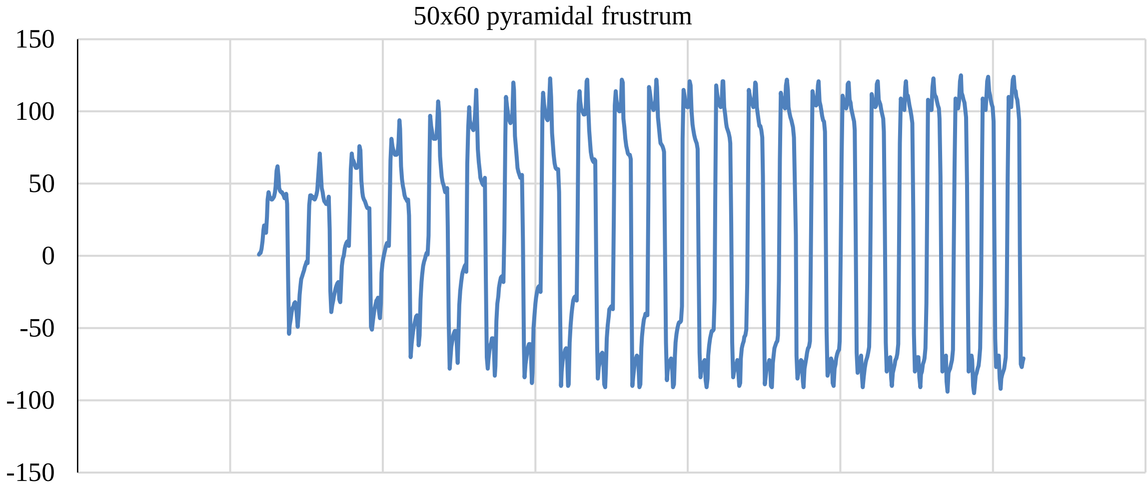


Figure 8. Force vs Time graph for set 2 (c).

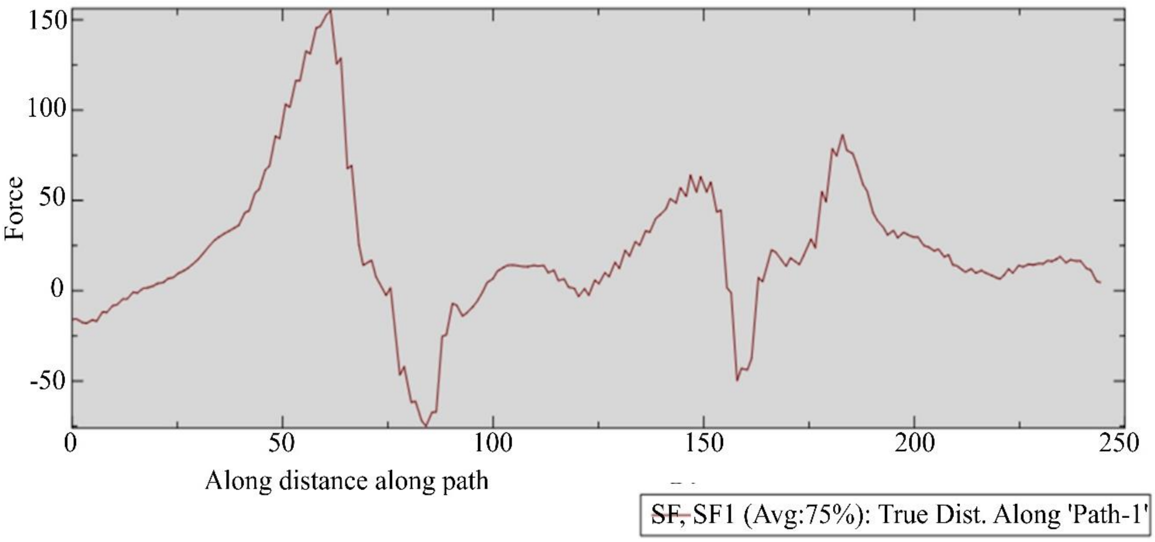


Figure 9. Force vs Time graph for set 2 (c)

Next, as the wall angle of two sides of pyramid increases to 60^o, the difference in forming force required also increases considerably as depicted in Figure 9. The maximum forming force for forming wall angle of 60^o is about 155 KN, whereas, other two sides of wall angle 50^o requires a forming force of approximately 80 KN. The difference in the forming force required increases to about 93.75% in the third case, which is very high as compared to any of the other parts. It is evident from the force versus true distance graph that as the asymmetry in the form of wall angle increases, there is considerable variation in the forming force required.

Figure 10 and Figure 11 depicts the variation of the maximum forming force with respect to the wall angle of formed parts for symmetric and asymmetric parts respectively. As shown in figure 10, it is observed that the forming force increases as the wall angle increases from 50^o to 55^o. The increase in forming force is attributed to the increased amount of material deformation done by the punch during the forming operation. This happens because the punch tip's higher lateral area makes contact with the blank, therefore the tool-sheet interface experiences a larger contact area for local deformation. Furthermore, as the wall angle increases to 60^o from 55^o, a slight decrease in the forming force is observed. The reduction in the forming force is because the material reaches to its forming limit and eventually fractures for the parts of wall angle of 65^o. Similar trends are also reported by [20] and [21] as well.

As depicted in Figure 11, the forming force during forming of asymmetric having wall angle 50^o to 55^o increases, similar to that of symmetric parts. But the forming forces goes on increasing as the wall angle increases from 55^o to 60^o. As discussed earlier, the increasing trend of the forming forces can be associated with the increased formability of the material for asymmetric parts. Both symmetric as well as asymmetric parts of wall angle of 65^o (Symmetric part having all walls inclined at 65^o and asymmetric part having two opposite sides of wall angle 50^o and remaining two sides having wall angle of 65^o) are fractured and could not be formed successfully [20, 21]. Figure 12 shows the fractured parts.

Figure 13, 14 and 15 shows the simulation results of A1, A2 and A3 parameters respectively. It can be observed that, as the wall angle goes on increasing, the equivalent plastic strain values first increase till wall angle of 55^o and then decreases.

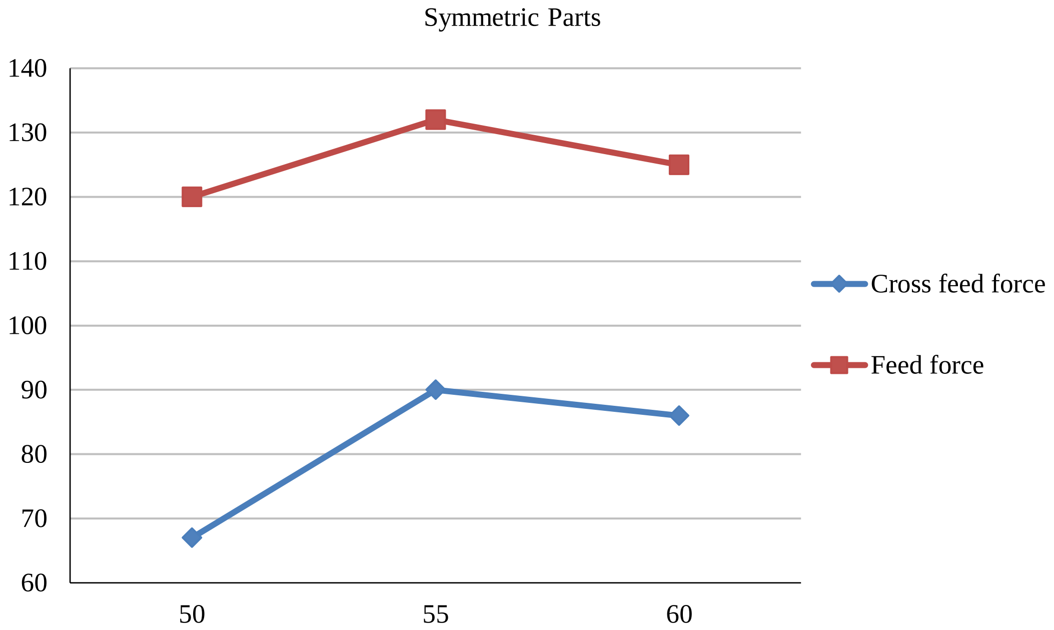


Figure 10. Forming force variation with increase in wall angle of symmetric parts (Set 1).

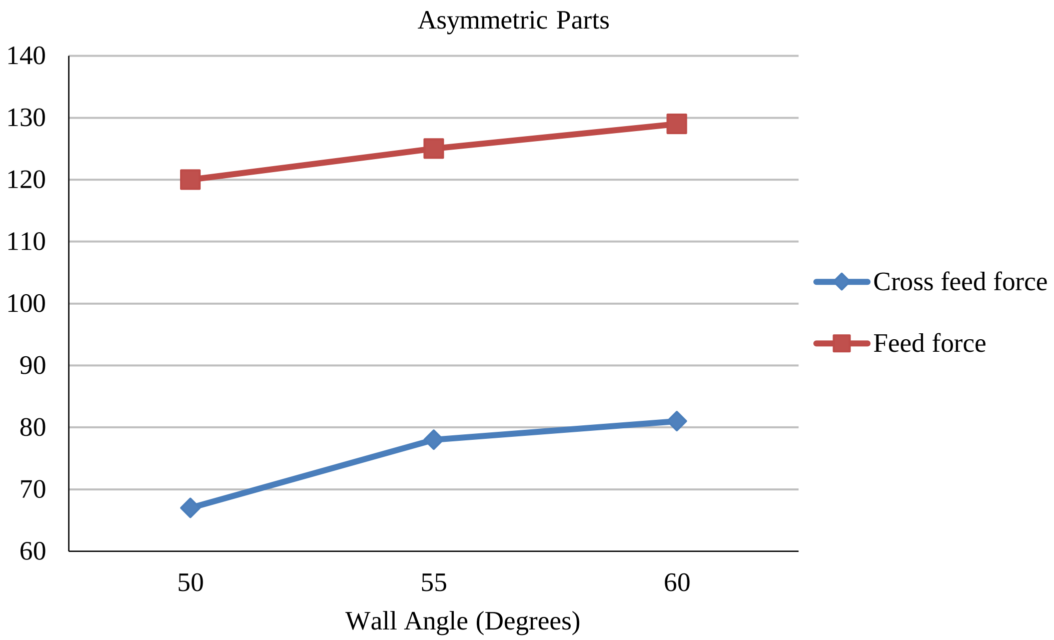


Figure 11. Forming force variation with increase in wall angle of asymmetric parts (set 2).

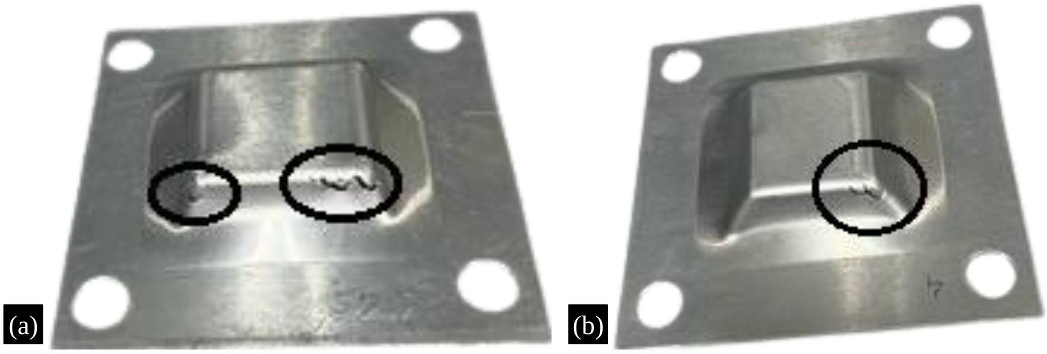
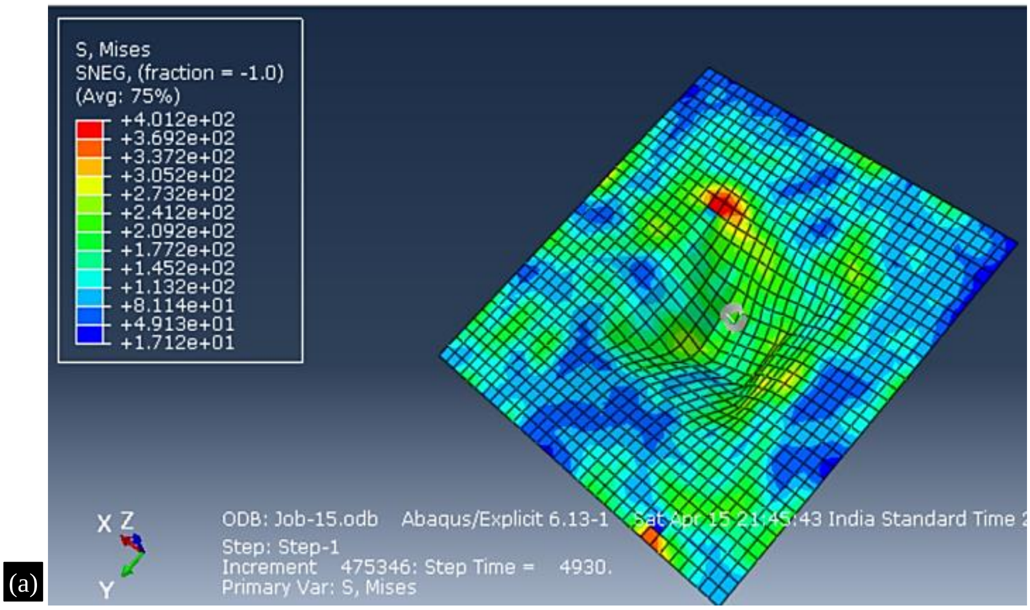


Figure 12. Fractured pyramidal frustum of wall angle 65°.



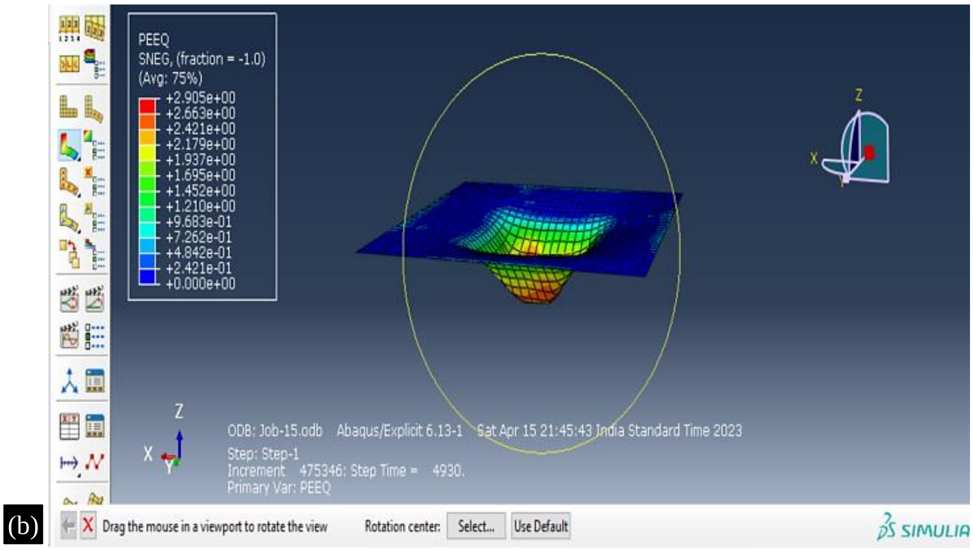


Figure 13. Simulation results for A1 parameter.

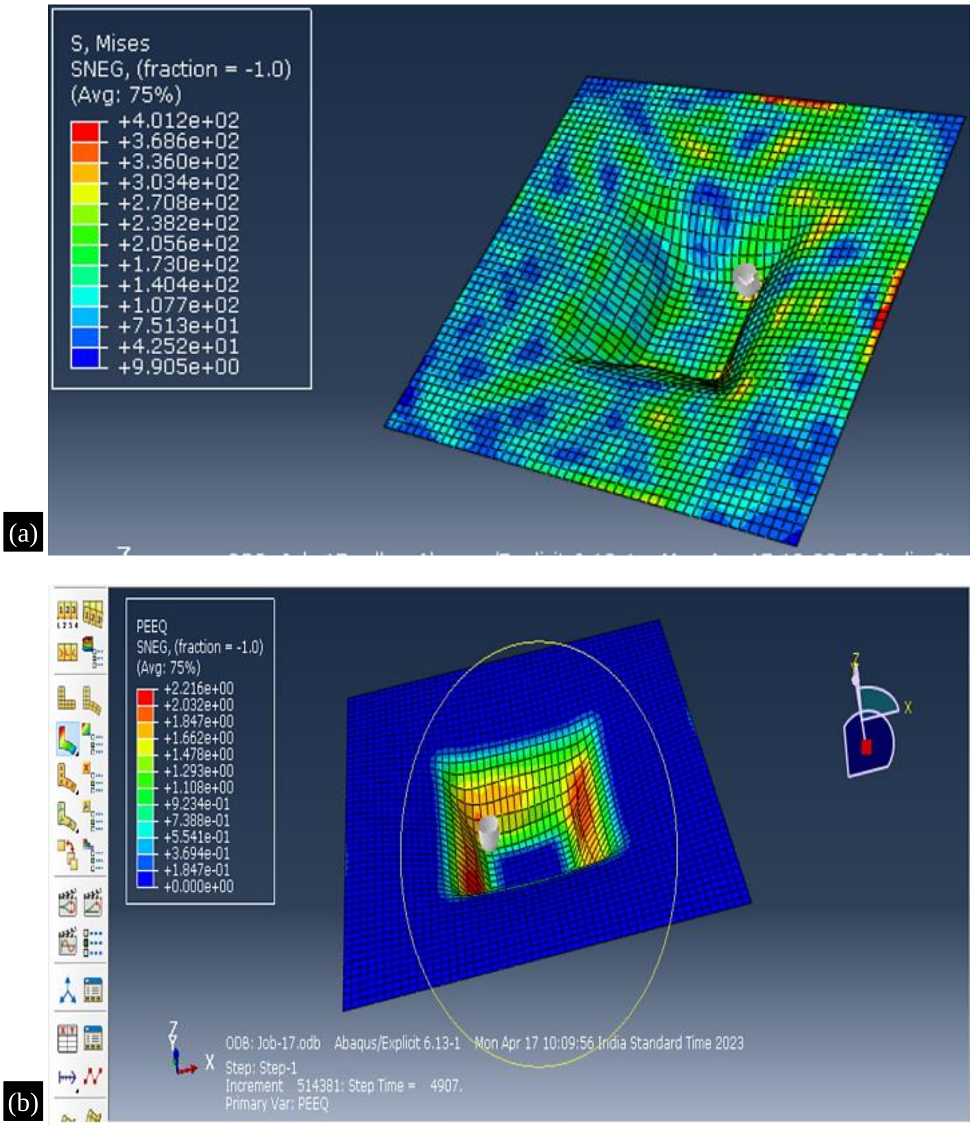


Figure 14. Simulation results for A2 parameter.

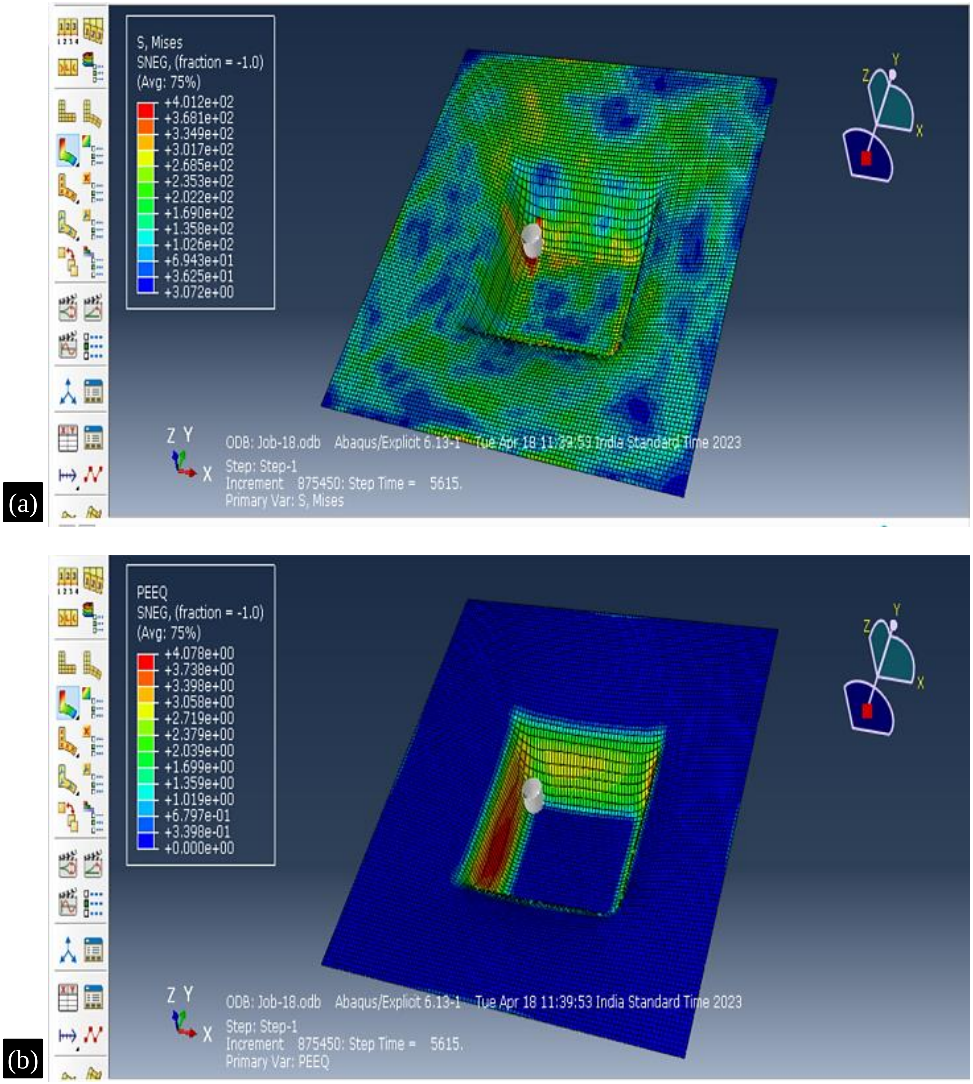


Figure 15. Simulation results for A3 parameters.

CONCLUSION

In this study, the processing of Al-6061 aluminum alloy material is experimented with the use of the single point incremental forming process. Effects of input factors on forming forces to form pyramidal parts have been experimentally studied. Wall angles are varied to study the forming forces acting on the component during forming operations and the surface roughness is measured. The following conclusions are drawn from this study:

1. As the wall angle increases, the feed force also rises. This phenomenon occurs because the punch tip's broader lateral surface comes into contact with the blank, leading to a larger contact area at the tool-sheet interface. As a result, there is an increased local deformation, contributing to the higher feed force.
2. In the similar way, cross feed force shows a significant increase as the wall angle increases. As the wall angle becomes steep, the force that is required to form the part also increases which leads to the increase in the cross-feed force.
3. The forming force increased with an increase in wall angle up parts achieve wall angle of 60°, beyond which the peak force decreased. This point also serves as the limiting factor and a sign of material failure because of excessive sheet metal thinning [20].
4. The forming force required to form symmetric part is about 150 KN. As the part asymmetry increases (two sides of 50° wall angle and remaining two sides of 55° wall angle), the forming

force for wall angle of 55° is higher as compared to wall angle of 50°. There is approximately 28% difference in the forming force required.

5. As the asymmetric wall angle of two sides further increases to 60°, the difference in forming force requirement increases considerably. About 93.27% higher forces are required to form the large wall angle of 60° as compared to small wall of angle 50°.
6. The forming force required for different areas of a part will ensure the sound forming of part.

The present study tried to understand the basic mechanics of forming of symmetric and asymmetric part. It gives some glimpses of the variation of forming force with respect to change in wall angle for both symmetric as well as asymmetric part. It is observed from present work, that there is sufficient evidence available to consider the mechanics of forming of asymmetric part. Present study is a preliminary examination on the influence of asymmetry on the forming mechanics in SPIF process. There is scope of further investigation on asymmetry of the parts formed using SPIF process.

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