Experimental Investigations on Incremental Sheet Forming of Commercial Aluminum Alloys for Maximum Production Quality

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***Abstract*—Single point incremental sheet forming (SPIF) process got a great attraction among other existed sheet metal forming processes because of their flexibility to manufacture complex products. Mass manufacturing can be achieved in terms of small-batch production and prototype products. The work material is formed into the expected mechanical parts using design tools by causing the plastic deformations at the contact locations with the help of designed contour paths. The objective of this research work is to study the formability of commercial aluminum alloy material under various test conditions for investigating the production quality in terms of dimensional accuracy and surface roughness. During the experiments, the wooden cubes are used as a base plate configuration for controlling the free stretching during the forming process. The aluminum alloy material mechanical properties are adopted and integrated into the finite element (FE) code. The tool paths for truncated cone shape are modeled in Fusion 360 software, and the coordinates are converted into 3D punch tool coordinates by the tool path generation framework tool for modeling the numerical simulation. In numerical modeling, three kinds of mesh settings are used to construct the mesh for producing consistent results. Afterward, the obtained results are tested against the experimental observations and the desired parts dimensions to confirm the accuracy of the established FE model. Thickness variations in the formed parts are discussed in detail in terms of the thinning area, thinning location, and its size in percentage. A comparison of tested geometries displays that reduction in thickness tends to be uniform in the wall region and small fluctuation noticed near the tool retraction location. overall, the numerical results of the SPIF process are well agreement with the experimental measurements in terms of geometry dimensions and thickness reduction. In addition, the surface roughness was noticed to be increased when the step size is more extensive, and on the other hand, the machining time tends to be more if the contour step size is small in the SPIF process.**

***Index Terms*—incremental sheet forming, finite element model, aluminum alloy, thinning location, surface roughness**

I. Introduction

In industrial practices, aluminum alloys are extensively used due to their mechanical properties, and the applications can be noticed widely in automobile and aircraft manufacturing industries. Moreover, the desired components can be easily manufactured and cost-effective. A countable number of researchers are working to fulfill customer needs without adjusting the quality using various manufacturing methods. Evident to note down that the newly developed manufacturing methods should be able to produce desired parts for the selected material, and also any kind of changes have to be altered in an effortless manner for a new design or concept. Among the available forming processes such as roll forming, deep drawing, stamping, the incremental sheet forming (ISF) is the most widely adopted manufacturing processes in automobile and aerospace industries because of their flexibility of forming parts. But this process requires more understanding about the neck-fracture mechanism during the forming process as the material is formed in stepwise bending procedures using designed tool paths. On the contrary, to achieve the optimized design of the ISF process, the investigation on the process parameters such as tool radius, spindle speed, feed rate, and step size is mandatory. Besides possessing practical design knowledge will lead to a proper outcome in terms of product quality, mass manufacturing, and make the industries more balanced in production cost.

For reducing the production cost in an early stage of the design process, the finite element (FE) method can be used to model and simulate the ISF process. These procedures are helpful in obtaining a favorable design for the desired components, and it needs little computational time and effort. An extensive number of research articles have been published about the single point incremental forming (SPIF) to manufacture the hollow parts, as shown in Fig. 1(a). The notable benefit advantage of this process is it does not require any predesigned die, and the procedures can be carried out using a simple flat sheet by causing the local plastic deformations. The process can be modeled using the computer numerical control (CNC) milling machine [1], [2]. Malwad et al. [3], Manish Oraon [4] et al. and Suresh Kurra et al. [5] were modeled reasonable number of experiments to discuss the surface quality of formed products in terms of working parameters such as step size, forming angle, tool diameter, feed rate and lubricant type. They produced surface roughness prediction models using artificial neural networks, support vector regression and genetic

Manuscript received November 14, 2019; revised February 10, 2020.

doi: 10.18178/ijmerr.9.9.1264-1270

programming. The influence of the tool path on AA7075 material was inspected using both experiments and numerical models by Erika Salem et al. [6] and Neto et al. [7]. They developed and examined the SPIF process using the FE model in terms of strain, stress and thickness distribution in the formed parts. The residual stresses in both circumferential and meridional directions were found to be positive in the inner skin and negative in the outer skin. The stresses were developed predominantly in the circumferential direction because of the geometrical restrictions.

The formability is generally affected by the process parameters such as spindle speed, feed rate, and tool diameter, lubricant and tool path [8], [9]. Markanday et al. [10] investigated the formability issues more in detail to achieve better formability. They tested the formed parts for spring back, thinning percentage and maximum forming depth. Denis Daniel et al. [11] researched the geometrical accuracy via a preliminary survey to examine the influence of the support force and the support angle. Naranjo et al. [12] explored the positive side of FE tools by studying different shapes of titanium ASTM B-265. They stated that the ANSYS tool could simulate the SPIF process more effectively when the finer elements are considered. Though, it can be useful to understand the deformation mechanism and the influence variables in terms of stress and strain distributions at each forming step. Similarly, Memicoglu et al. [13] exploited the numerical model for suggesting the best approach to reduce the computational time by adopting the proper meshing procedure and symmetric boundary conditions.

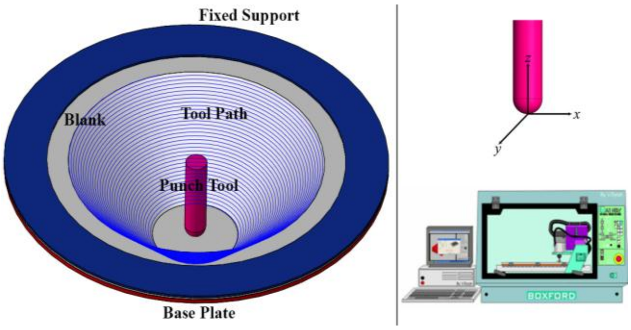


Figure 1. Schematic diagram of SPIF process.

The present work is aimed to investigate the formability of commercial aluminum alloy material using both experimental and numerical procedures. The truncated cone with a wall angle 30 and 60 degrees are employed, and the contour tool paths are designed using Autocad fusion 360 software. For controlling the extra stretching, the wooden cubes are used in the die free spaces. Then, the CNC input files are converted into 3D coordinates using the newly written tool path conversion framework for modeling the numerical simulation. The material properties of aluminum alloy are included in the material cards to describe the material elastic-plastic behavior. In addition, different step sizes are utilized to examine the surface quality and the total machining time. Eventually, the predicted results of the SPIF process are compared against the experimental observations and the desired geometry coordinates to discuss the model's usefulness.

II. Experimental Procedures

The chemical composition of commercial aluminum alloy is summarized in Table I. Incremental sheet forming experiments were conducted using the flat sheets with dimensions of 240 mm × 280 mm and thickness of 0.5 mm [14]. The punch tool was manufactured using high-speed steel (HSS) as it has to be rigid and undeformable. Truncated cone with various tool angles (30^{o} and 60^{o}) and different step sizes was designed by Solidworks and imported into Fusion 360 to develop the tool paths for modeling the real-time experiments. The experimental conditions are listed in Table II, and the test set-up are illustrated in Fig. 2.

TABLE I. Chemical Composition of Aluminum Alloy

Al	Si	Fe	Cu	Mn	Zn
96.8-99.0	0.6	0.7	0.05-0.20	1.0-1.5	0.10

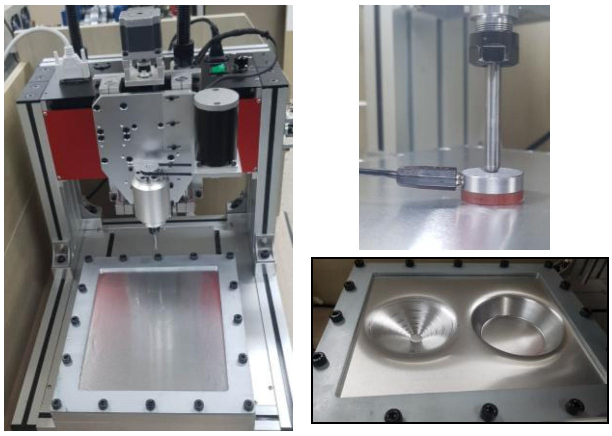


Figure 2. Experimental set-up.

TABLE II. Test Conditions of SPIF Process

Thickness (mm)	Spindle speed (rpm)	Feed rate (mm/min)	Step size (mm)
0.5	5000	1000	0.2
			0.5
			0.8

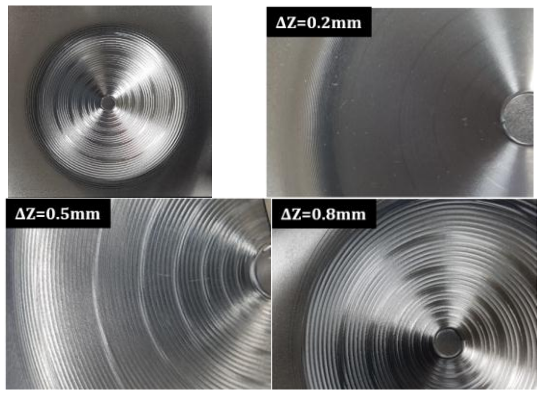


Figure 3. Surface roughness (formed cone shape).

Fig. 3 shows the effects of step size on the formability of truncated cone geometry. The surface roughness was found to increase with the step size changes and the significant formabilty was observed at small step size. Because of the usage of a low quantity of lubricants, the wear fracture is observed in the formed products as shown in Fig. 4. On the other hand, due to the improper definition of the contour path inputs, the test samples have experienced the fracture during the experiments. So careful investigation is required on the CNC input file before running the actual experiments to rectify the manual errors.

Figure 4. Fracture specimens from tested samples.

III. Finite Element Modeling of SPIF Process

For defining the material properties of commercial aluminum alloy in the numerical tool (Table III), The stress-strain curves are approximated by the Hollomon power law, Eq.(1), to describe the material strain hardening behavior.

TABLE III. Mechanical Properties of AA3003 Material

ρ (Kg/m^3)	E (GPa)	σ_Y (MPa)	ν	K (MPa)	n
2700	70.1	152.2	0.33	192.7	0.039

$$\sigma = K\varepsilon^n \tag{1}$$

In Eq.(1), σ, K, ε, and n are true stress, strength coefficient, true strain, and strain hardening coefficient, respectively. A cone geometry with 30^o and 60^o wall angles with a depth of 30 mm were modeled in Autocad Fusion 360. In addition, the material properties and the tool path are considered as essential inputs for modeling the SPIF process. Consequently, the deigned tool paths were converted into 3D tool coordinates of moving rigid tool considering different step increments to examine the formability of selected material. A contour path was modeled from 0.2 to 0.8 mm, considering a tool radius of 3 mm, a feed rate of 1000 mm/min, and a spindle speed of 5000 rpm. Besides, the material properties are included in a material card having details of material elastic-plastic behavior (MAT18).

For achieving reasonable numerical results, the material blank has meshed with finer elements using three kinds of mesh settings by dividing the blank into deforming section (radial mesh) and non-deforming section (non-radial mesh) as depicted in Fig. 5. On the other hand, the rigid punch tool has meshed with a significant number of coarse elements for controlling tool penetration against the blank during the forming process. A forming one-way surface to surface contact method with soft option 4 was defined to model the interaction between the blank and the punch tool. Because of the use of excessive lubricant during the SPIF experiments, the friction coefficient was considered to be 0.1, and due to material thickness, the shell element formulation type 16 with 5 integration points through the thickness direction was adopted for the numerical modeling. For optimizing the computational time, the mass scaling option was used, and it was identified to be more useful.

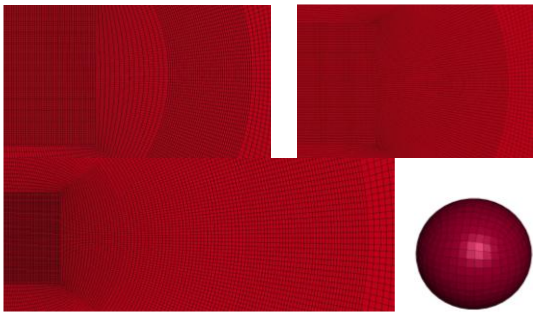


Figure 5. Finite element model for SPIF process.

IV. Results and Discussion

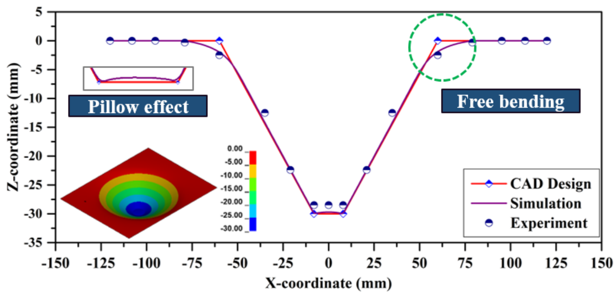


Figure 6. Shape comparison against the experiments (30^o angle).

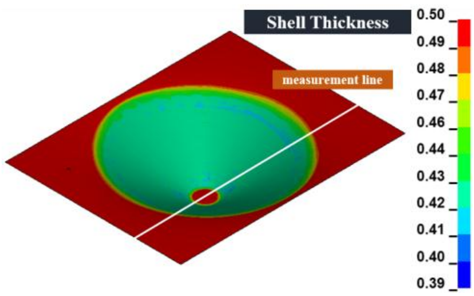
The experimental results are investigated in detail about the forming depth and its dimensional accuracy, surface quality, and machining time. From produced parts, the part cross-section coordinates are measured manually by drawing the cut section in a white paper. In addition, the forming depth and thickness variation are determined using the measuring tools such as the height measurement gauge and the micrometer wall thickness caliper gauge. The predicted result SPIF process for cone geometry is illustrated in Fig. 6. For the model validation process, the cross-section coordinates are extracted from a solved numerical model by creating a path along the longitudinal direction and plotted with the experimental measurements and the coordinates of expected geometry, as shown in Fig. 6. It is identified that the experimental observations and the numerical results are significantly agreement with the real section. Also, the comparison graph is evident that the free bending is noticed to occur at the initial stage of the forming process, and its due to there is no extra support in that region. On the other hand, there are a little deviation identified, and it was because there was a considerable gap between the punch tool and the blank during the start of the experiment. At a low radius region, the pillow effect was noticed to happen, and the height was estimated to be minimum.

After SPIF process, the material thinning behavior can be estimated from the sine law in terms of final wall thickness (t_1) using a relationship between the wall angle (α) and the initial wall thickness (t_0) as expressed below [15], [16]:

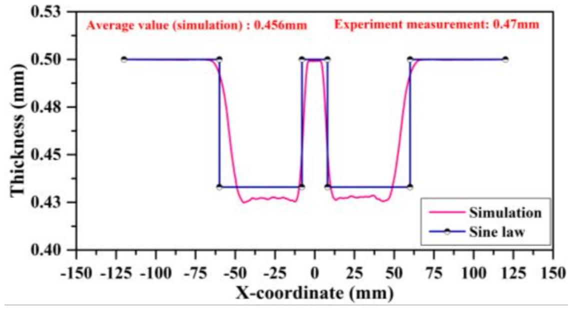
$$t_1 = t_0\left(\sin\left(\frac{\pi}{2} - \alpha\right)\right) \qquad (2)$$

However, Young et al. [15] and Ambrogio et al. [16] showed that the sine law prediction accuracy was found to show some deviation, to put it in another way, the thickness was varying in the formed part along the wall angle. The thickness estimation was less than the sine law prediction in Young et al. [15] research work, and they concluded that it might be due to an over spinning condition in shear forming. Similarly, in Ambrogio et al. [16] work, close to the sheet perimeter, the thickness was determined to be higher than the prediction as well as lower in the remaining profile location.

The thickness distribution is plotted using the measurement line coordinates, as shown in Fig.7(a). The thinning variations from both sum and visual reveal that thinning behavior is found to be uniform and showed symmetric distributions. The numerical model could be partitioned into two sections: a section that intent to deform and the remaining section. Additionally, the sine law is employed to establish a thickness variation and illustrated against the predicted result in Fig. 7(b). From numerical results, it can be seen that at the start, the blank experiences bending deformation in which the plastic deformation is not expected to happen, and it is because of the tool compression and the support distance. After that, the thinning phenomenon noticed to be stable and showed steady progress, but at the tool retraction region, the thickness variation displayed little oscillations. Compared to the theoretical predictions, the thickness reduction happens to be almost inside and only 0.008 mm is larger than the sine law prediction. Further, the thickness measurement from the experiment is much more evident to prove the accurate development of the numerical model.



(a)



(b)

Figure 7. Thinning behavior against experiments and theoretical.

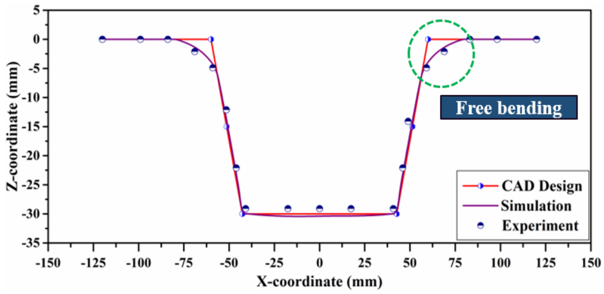
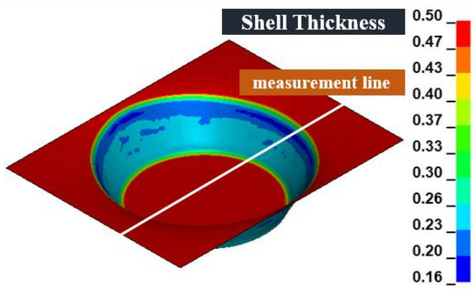
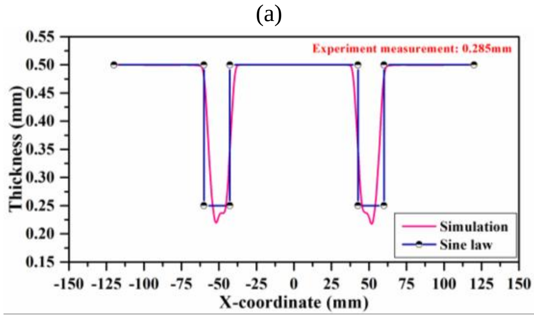


Figure 8. Shape comparison against the experiments (60^o angle).



(a)



(b)

Figure 9. Thinning behavior against experiments and theoretical.

Likewise, a truncated cone shape with 60^o wall angle was modeled using the same experimental conditions. For this model, the blank has meshed with quad finer elements. Same as before, the shape coordinates are drawn out from the cross-section, as depicted in Fig. 8. Fig. 9 shows that the blank experienced bending at the start of the forming process due to tool compression as same as in Fig. 6. Similarly, free bending can be removed by placing extra support in the region where the deformation was not supposed to happen. The simulated results exhibited a considerable difference from the expected shape and the experimental observations. However, the numerical results are well agreement with the actual measurements, and the deviation might be due to tool location and spring back effect during the SPIF process.

In comparison with the thinning behavior from the simulated results and the sine law, as shown in Figs. 9(a) and 9(b) prove that the thickness reduction in rolling and transverse directions are happened to fall along with the theoretical prediction and showed a small fluctuated variations at the tool extraction location. Further, the real thickness measurement noticed to be significant in the selected locations and the determined number is close to the theoretical estimation.

The plastic strain distributions in terms of contour plots for both simulated cone angles are shown in Figs.10(a) and 10(b). From these figures, it is realized to be uniform strain distribution, and the maximum strain was identified to occur close to support and observed to be smaller when the support is far away.

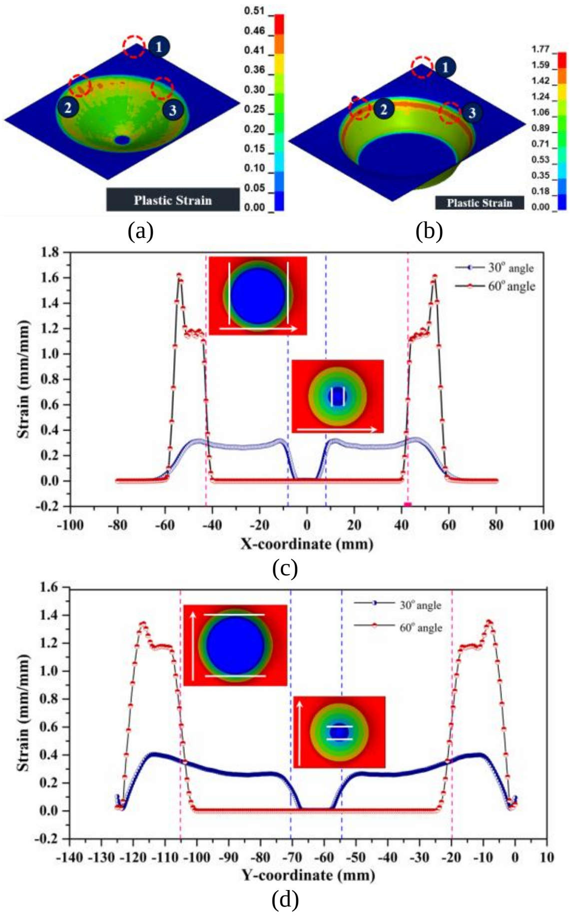


Figure 10. Strain variations in simulated part.

Moreover, due to the wall angle, the strain value is found to be larger when the cone wall angle is higher and vice-versa. Fig. 10(c) displays that there is no increment in strain when the support is located a little away from the forming location for both cases, whereas if the support is close to the forming location, the strain value is found to be increasing from the start of the support location. In addition, both contour plots and quantification graphs show that the strain distribution is perceived to homogeneous and more significant in the forming region for both cases. Due to the interaction between the blank and punch tools, the stress fluctuation has occurred in the formed profile as shown in Figs.11(a) and 11(b). This is because, during forming, the blank involves both bending and stretching deformations, and in other words, due to the punch tool motions, the blank expose to bending deformation because of tool compression and stretching deformation, as a result of tool radial motion. Mainly, Fig. 11(c) indicates that the stress fluctuations occur more in the non-forming region and on the other hand, the stress value is found to be increasing at each location inside the forming region.

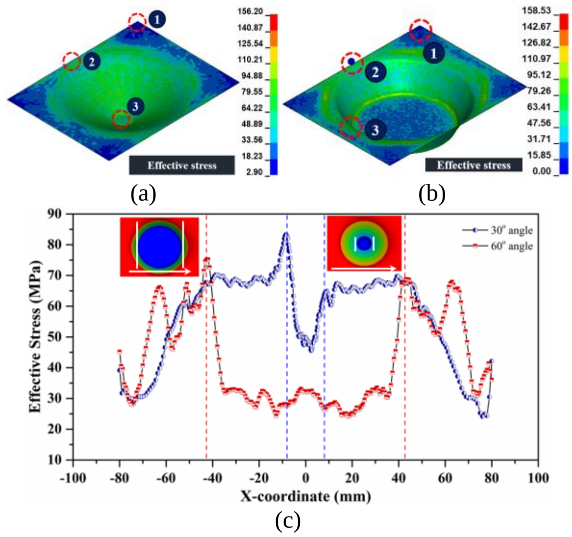


Figure 11. Stress variations in simulated part.

TABLE IV. COMPARISON OF CNC MACHINING TIME

Feed rate (mm/min)	Step size (mm)	Milling time (software)	CNC machine
1000	0.2	1hr 20min	1hr 28min
	0.5	33min	35min
	0.8	21min	23min

Table IV benefits us to understand the fact that if the tool path step size is getting higher, the milling time is reducing gradually, and the surface roughness tends to be increased. These discussions state that even though the CNC milling time is much larger, the SPIF process can be successfully developed by adopting proper mesh counts, boundary conditions, and mass scaling time settings. Besides, the numerical model approach established in this research work can be devised for complex shapes at the initial stage of the manufacturing process.

V. CONCLUSIONS

Investigation on the SPIF process was modeled for a truncated cone with a wall angle of 30° and 60° using commercial aluminum alloy material properties. The tool paths were designed from Fusion 360 for conducting the real experiments, and the developed tool path generation framework was used for 3D coordinates conversion for running the numerical simulations. The obtained results were found to be significant, and the conclusions are written from the outcomes. Loss in the shape accuracy was observed, notably when a base plate configuration is not adopted in the free bending locations and improper punch tool located at the start of the experiments. Besides, the thickness reduction happens relatively more extensive when the cone wall angle was higher. The pillow effect was recorded in the low radius location from the produced part. The machining time was significantly higher due to the small step size, but however, the computation time can be reduced with the help of mass scaling settings without compromising the results. In general, proper 3D modeling, tool path design, and base-plate configuration can lead us to the better production of regular/irregular products. If the tool step is smaller than the machining time tends to be higher and the surface quality-labeled to be good. It has required more trial and error studies considering various tool path designs for obtaining optimum design. Spindle speed, feed rate and punch tool radius can be altered and robust design can be achieved eventually. The modeling approach established in this research work can be used for several shapes at the start of the design stage and model improvement.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

In this research work, conceptualization, experiments, finite element modeling, tool path generation framework, investigation, validation, and original draft preparation were done by the authors Mohanraj Murugesan and Muhammad Sajjad, and the supervision was carried out by Dong Won Jung.

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