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Effect of the Single-Point Incremental Forming Process Parameters on the Surface Roughness of Aluminum Alloy Al 2024-O Draw Pieces

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ABSTRACT

The incremental sheet metal forming process is a highly adaptable manufacturing process for producing three-dimensional products without the need for specialized tool typically required in traditional forming processes. This innovative process finds extensive applications in various industries, including aerospace, automobile, and other industrial applications. This study explores the application of the single-point incremental forming (SPIF) process to manufacture truncated pyramids while investigating the impact of specific process parameters on surface roughness. In this study, three parameters wall angle, sheet thickness, and step depth were examined, each at three different levels. A full factorial design (L27) was used to design the experimental work and statistical analysis utilizing Analysis of Variance (ANOVA) was utilized to analyze the collected data and predict the impact of single-point incremental forming process parameters on surface roughness. The tool geometry was a hemispherical end tool with a diameter of (8 mm) and the sheet material was aluminum alloy (Al 2024-O). The computer numerical control (CNC) milling machine was used to move the tool. The optimal average roughness (Ra) value was achieved with a wall angle of 60°, a sheet thickness of 2 mm, and a step depth of 0.2 mm.

Keywords: Al 2024-O sheet; truncated pyramid; forming die; SPIF process; surface roughness.

INTRODUCTION

In recent years, there has been a growing interest in incremental forming processes within both industrial applications and academic research. This surge in interest is attributed to the ability to use a single tool to create various geometric shapes, resulting in significant cost reduction [1, 2]. Incremental forming stands out as a highly adaptable method for shaping three-dimensional complex parts, offering superior flexibility and formability compared to traditional sheet metal forming processes [3, 4]. Incremental sheet metal forming (ISMF) is classified into three types based on the tool employed: single-point incremental forming (SPIF), double-point incremental forming (DPIF), and multi-point incremental forming (MPIF) [5]. The single-point incremental forming (SPIF) process is widely used in the incremental sheet metal forming process. Typically, this process involves fundamental components, including a forming tool, a backing plate, a blank holder, and a sheet metal blank [6]. The forming tool moves along a predetermined path to create the required geometric shape using a computer numerical control (CNC) machine. In this process, the tool is secured in the CNC milling machine and follows the tool path generated using computer-aided design (CAD) software. This enables the sheet to be formed layer by layer, as illustrated in Figure 1 [7, 8].

Slota et al. [10] conducted a study on the surface roughness and the residual stresses arising during the single-point incremental forming process of a truncated cone. The material employed was low-carbon steel cold rolled (DC04) with a thickness of 0.8 mm. The measurement of surface roughness was applied using the contour

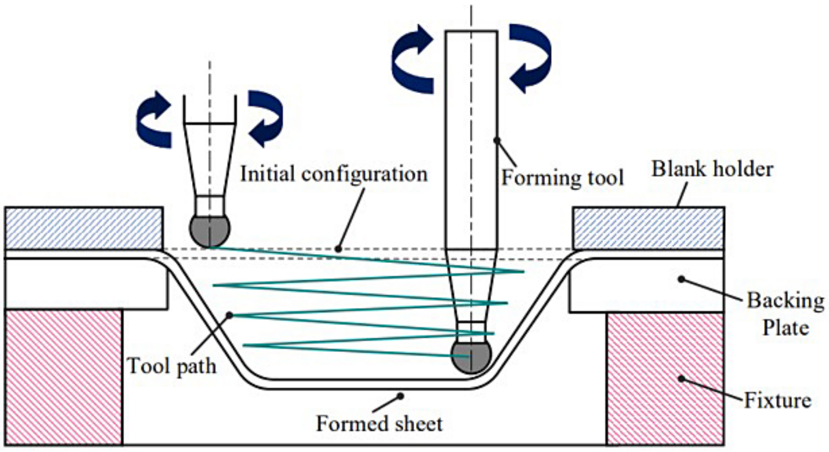


Fig. 1. The SPIF process [9]

Geometry and Topology (GT) 3D optical microscope, while the x-ray diffraction method was utilized to measure the residual stresses. The findings revealed that the surface roughness of the outer surface was smaller compared to that of the inner surface. Additionally, the results demonstrated that there was no discernible relationship between the residual stresses and the surface roughness. Krasowski et al. [11] utilized the X-ray diffraction technique to measure the distribution of residual stresses generated in the parts formed. The single-point incremental forming process was employed to shape the DC04 steel with a thickness of 0.8 mm, creating the geometry of the truncated cone. The outcomes indicated the presence of tensile residual stresses at the outer part of the truncated cone. Furthermore, the interaction between surface roughness and these tensile residual stresses intensified the corrosion process. Trzepiecinski et al. [12] investigated the impact of the single-point incremental forming process parameters on the surface roughness of stiffened ribs crafted from aluminum alloy panels. The materials utilized were Al 7075-T6 with a thickness of 0.8 mm and Al 2024-T3 with thicknesses of 0.4 mm and 1mm. An artificial neural network was applied to investigate the effect of step depth and tool rotational speed on the surface roughness. The findings indicated that the surface roughness (measured in terms of arithmetic mean height (Sa) and maximum height (Sz)) escalated with larger step sizes. However, a decrease in spindle speed correlated with an increase in Sz while leading to a decrease in Sa. Szpunar et al. [13] studied the influence of the step depth, the feed rate, and the spindle speed on the forming force and the surface roughness during the single-point incremental forming process of a truncated cone made from pure titanium grade 2 with a thickness of 0.4 mm. The rotational direction of the tool was in two directions; clockwise and counterclockwise movements. The experimental tests were designed using the central composite design in conjunction with the response surface method. Additionally, ANOVA was employed to analyze the effect of the process parameters on the forming force and the surface roughness. The findings revealed that an increase in spindle speed resulted in a reduction of the forming force. The primary factor influencing the forming force was identified as the step depth. Additionally, higher spindle speeds correlated with increased surface roughness. Krasowski et al. [14] investigated the impact of forming parameters and tool strategy on the surface roughness in the single-point incremental forming process, specifically focusing on shaping thin-walled panels with longitudinal stiffening. The study utilized aluminum-clad material (Al 2024-T3) with a thickness of 0.4 mm, and under investigation parameters included spindle speed, feed rate, and tool path strategy. Two tool path strategies were applied, multi-step z-level contouring and spiral with continuous sinking. The simulation of the single-point incremental forming process was conducted using the 3D-finite element analysis (Abaqus) program. The results confirmed that the major parameter influencing formability is the tool path strategy. Specifically, the multi-step z-level tool path strategy demonstrated the ability to shape the rib with a depth of 3.53 mm without risk of cracking. The tool path was the main parameter affecting the surface quality of the product during the single-point incremental forming process. Trzepiecinski et al. [15] studied the effect of feed rate, step depth, and spindle speed on the surface roughness of both sides of the truncated cone produced through the single-point incremental forming process. Pure titanium grade 2 sheet metal with a thickness of 0.4 mm was employed in the study. The experimental work was designed using the central composite design with 20 tests. The ANOVA and artificial neural networks were employed to explore the impact of process parameters on the surface roughness. The results indicated that the feed rate and the step depth had the most significant impact, providing the highest information capacity concerning kurtosis and skewness of the inner surface of the product. Zaba et al. [16] conducted a study on the influence of the step size on the maximum forming angle, formability, surface roughness, hardness, mechanical properties, microstructure, and texture of bimetallic Al/Cu sheets with a thickness of 1 mm. The non-contact optical 3D scanner was employed to acquire the geometry and dimensions of the product formed. Two strategies of sheet forming were investigated: forming from the Cu side and forming from the Al side. The results showed that increasing the step size by more than 1.1 mm led to develop the rupture in the product increasing the deviation between the product geometry and the desired geometry with increasing the step size. Moreover, the results showed that the maximum wall angle can be achieved when forming the Al/Cu bimetallic sheet from the Al side. ULLAH et al. [17] presented a novel method to obtain the optimal location of the support tool to improve the geometrical accuracy. The grey relation analysis was used to study the effect of double-sided incremental forming (DSIF) on the forming time, sheet thickness, surface roughness, and accuracy. The results showed that the best geometrical accuracy was achieved with the 10° of the support tools to its local normal.

The present study aims to determine how the SPIF process variables (wall angle, step depth, and sheet thickness) affect the surface roughness of the truncated pyramid produced. Through reviewing related works, they usually study the effect of incremental forming process parameters on the annealed aluminum alloys, while in this work, unannealed aluminum alloys Al 2024-O will be studied.

MATERIALS AND METHODS

Sheet material

The work being done uses aluminum alloy (Al 2024-O) sheet material because it has good corrosion resistance with cladding, formability, high fracture toughness, and lower structural weight. Therefore, the Al 2024-O alloy was used in many applications, such as aerospace, structural aircraft parts, pistons, and gears. Table 1 lists the chemical compositions of this alloy.

Products geometry

The truncated pyramid geometry was formed with a total depth in the z-axis (30 mm) and at three angles of the product wall (40°, 50°, and 60°) respectively as shown in Figure 2. The SolidWorks program is used to design a virtual model of the truncated cone draw piece. There are several reasons for choosing the truncated pyramid geometry, including its utilization in many industrial applications such as material handling and conveyor systems, aerospace and defense (sensor housings, antennae, and aerodynamic structures), and storage containers.

Tool path generation

Iso-planar tool paths were used to form the truncated pyramid geometry. As shown in Figure 3, the UGS-NX9 software was used to generate the G-codes and then sent to the computer numerical control (CNC) milling machine to carry out the single-point incremental forming process.

Design of experiments

In this work, a full factorial method was used to design the single-point incremental forming process. The step depth, thickness, and wall angle were the process parameters, and each parameter has three levels, as illustrated in Table 2. A full factorial design is selected to research how each parameter affects the surface roughness as well as how different parameters interact with one another. The other parameters were constant, including the feed rate (800 mm/min) [18], no rotation

Table 1. The chemical compositions of Al 2024 alloy

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	V	Zr	Other	Al
Weight %	0.07	0.18	4.6	0.6	1.3	0.01	0.09	0.02	0.01	0	0.03	Remainder

in spindle speed, and a hemispherical tool with a diameter of 8 mm [19], and the lubricant used is (SAE 5W-30) to decrease the tool wear and enhance the surface quality. During the forming process, the lubricant was utilized to fill the cavity of the blank. A one-way ANOVA was used to analyze the collected data from the SPIF process and the significance level was 0.05.

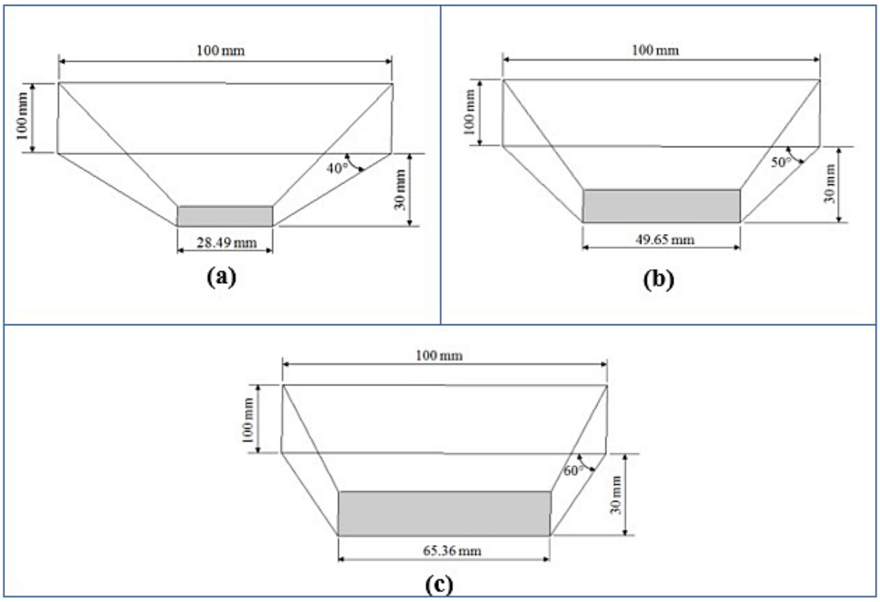


Fig. 2. The geometry of the truncated pyramid (a) a wall angle of 40º, (b) a wall angle of 50º, and (c) a wall angle of 60º

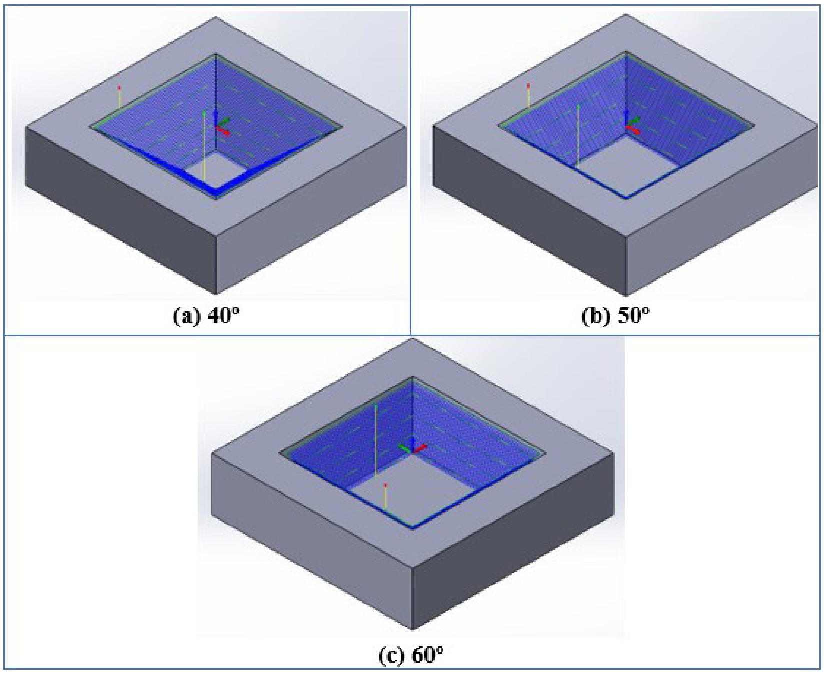


Fig. 3. The G-code of geometry (a) a wall angle of 40º, (b) a wall angle of 50º, and (c) a wall angle of 60º

Table 2. The levels of the SPIF process parameters

Parameter	Units	Level 1	Level 2	Level 3
Wall angle	deg	40	50	60
Thickness	mm	1	1.5	2
Step depth	mm	0.2	0.4	0.6

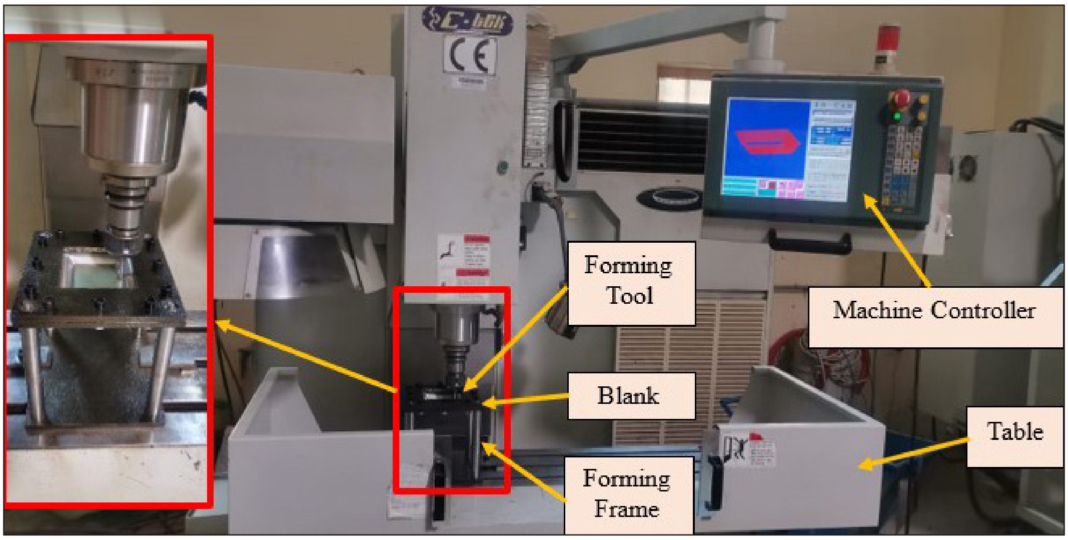


Fig. 4. The CNC milling machine used in the SPIF process

Experimental tools

In comparison to the conventional various sheet metal forming techniques, incremental sheet metal forming (ISMF) is carried out with less complex tools. On a CNC milling machine, an ISMF process is carried out. The experimental work was done using the "C-Tek" vertical milling machine, as shown in Figure 4. The tool in this machine provides the move in the z-direction, while the table in this machine provides the moves in the *x* and *y* directions.

Forming frame

The blank was clamped on the CNC milling machine's table using the forming frame. It has multiple components, as shown in Figure 5. The sheet blank's initial measurements were (150×150 mm). The tool steel metal is used to manufacture the parts of the forming frame, and a CNC Oxy-Plasma cutting machine is used to manufacture the base plate, the top plate, the backing plate, the clamping plate, and the finishing dimensions for these parts are achieved using the CNC milling

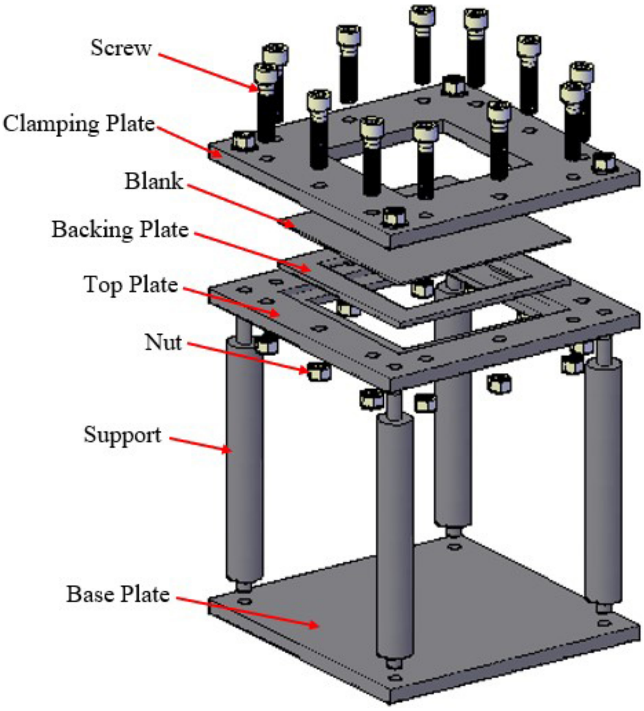


Fig. 5. The forming frame parts used in the SPIF process

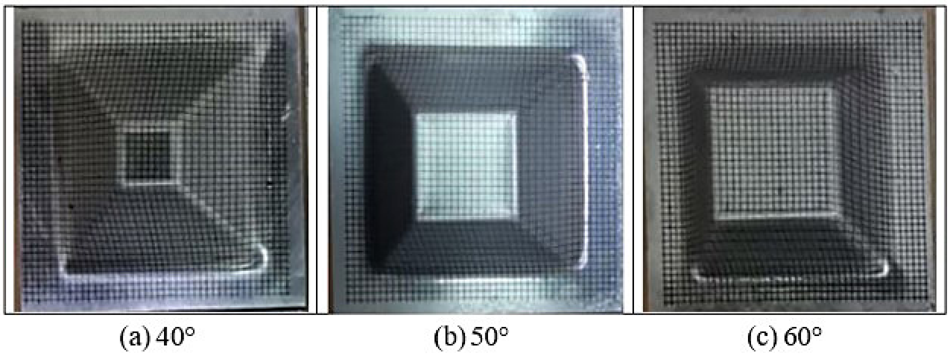

(a) 40° (b) 50° (c) 60°

Fig. 6. The products produced using the SPIF process for the wall angles: (a) 40°, (b) 50° and (c) 60°

machine. While the CNC turning machine is used to manufacture the supports.

Experimental work

The single-point incremental forming processes were performed using the CNC milling machine with three axes, as illustrated in Figure 4. The experimental works were done at the "University of Technology-Training and Workshop Center". Twenty-seven tests were performed according to the full factorial design, and the products are shown in Figure 6.

Surface roughness

The surface roughness is considered one of the most important outputs in the SPIF process, due to the friction between the tool and the sheet material formed. In this work, the "Mahr-pocket Surf III" portable device, as shown in Figure 7 was used to measure the arithmetical average roughness (Ra), and the device accuracy is 0.01 µm. The arithmetical average roughness value for the original sheet was 0.35 µm. The measurement was specifically conducted on the inner side of the truncated pyramid-shaped product. This choice was made because this inner surface comes into direct contact with the tool during the manufacturing process. To calculate the arithmetical average roughness, three readings were taken for each wall.

RESULTS

The average roughness results were measured, as listed in Table 3. Figure 8 shows the relationship between the parameters of the SPIF process and the arithmetical average roughness.

Figure 9 shows the Pareto chart, which is used to identify how the process parameters affect (wall angle, thickness, and step depth) the outputs (Ra). The step depth parameter has a large effect on Ra, and follows the wall angle of the truncated pyramid, while the Ra is not clearly affected by the change in sheet thickness. The relationship between

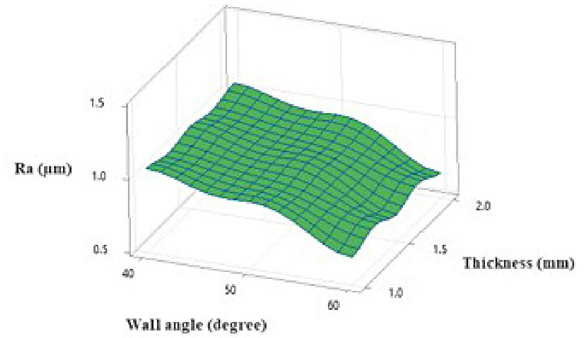
Fig. 7. The measurement process of the surface roughness

the process parameters and the mean response Ra is demonstrated using analysis of variance (ANOVA), as shown in Figure 10.

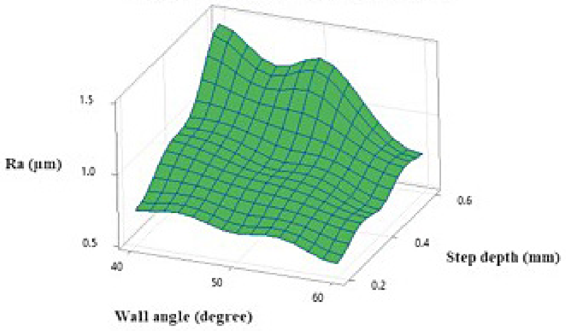
In this work, the surface roughness Ra is calculated by modeling the SPIF process parameters using a linear regression:

Table 3. The average surface roughness

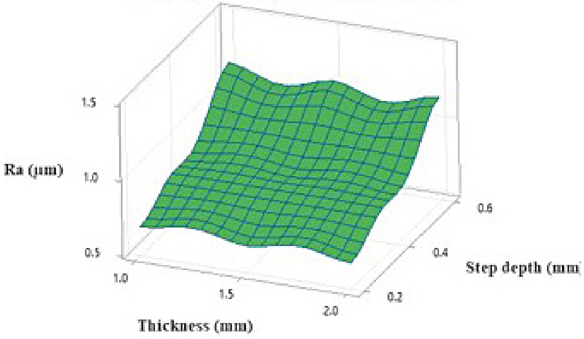
Experiment No.	Process Parameters			Average surface roughness (µm)
	Wall angle (degree)	Thickness (mm)	Step depth (mm)	
	60	2	0.6	0.76
	40	1	0.4	0.98
	40	2	0.2	0.74
	40	1.5	0.4	0.96
	60	1.5	0.2	0.58
	60	2	0.4	0.65
	40	1	0.2	0.73
	60	1	0.6	0.75
	60	1.5	0.4	0.67
	50	1.5	0.4	0.83
	40	1	0.6	1.46
	40	1.5	0.6	1.44
	60	1	0.2	0.61
	60	1	0.4	0.66
	50	1.5	0.6	1.3
	50	1	0.4	0.82
	60	2	0.2	0.55
	60	1.5	0.6	0.75
	50	2	0.4	0.82
	40	2	0.4	0.97
	50	2	0.6	1.32
	50	1	0.6	1.31
	50	1	0.2	0.69
	50	2	0.2	0.68
	40	2	0.6	1.42
	40	1.5	0.2	0.73
	50	1.5	0.2	0.67



(a) Ra vs wall angle and thickness



(b) Ra vs wall angle and step depth



(c) Ra vs thickness and step depth

Fig. 8. The relationship between Ra and the process parameters

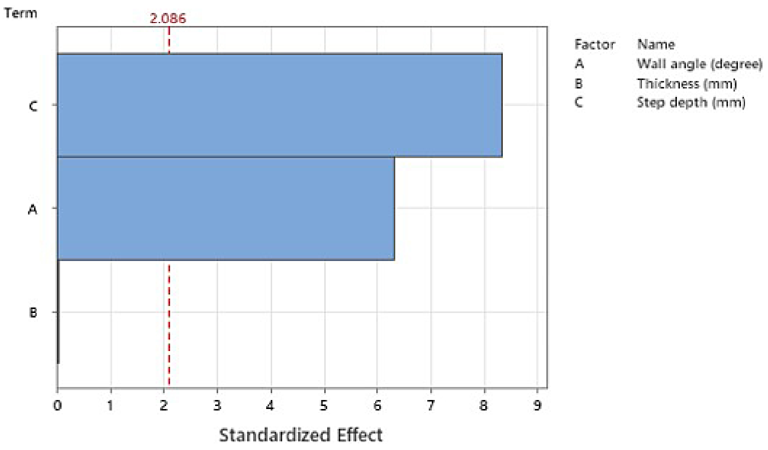


Fig. 9. The Pareto chart of the Ra's response to the SPIF process parameters

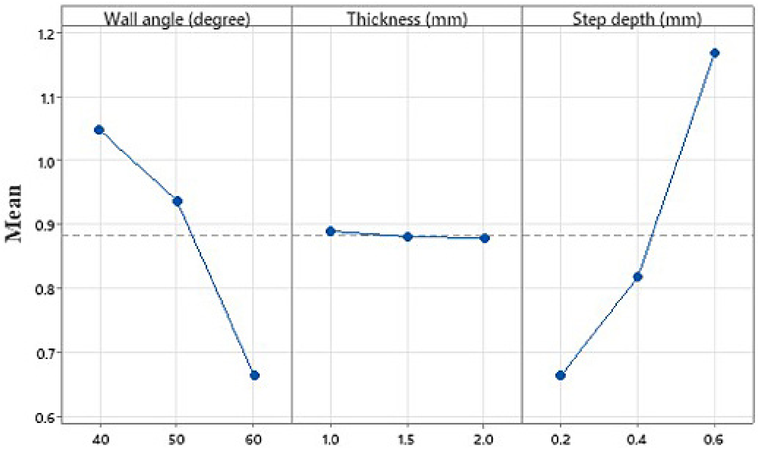


Fig. 10. The relationship between the process parameters and the mean Ra

$$\text{Ra}\ (\mu\text{m}) = 1.355 - 0.01917 \cdot \text{WA} - \\ - 0.0111 \cdot \text{T} + 1.258 \cdot \text{SD} \quad (1)$$

where: WA – the wall angle (degree);
T – the sheet thickness (mm);
SD – the step depth (mm).

From the surface roughness results, we conclude that the truncated pyramid's Ra and the wall angle are inversely related and it is directly proportional to the tool's step depth. While the change in the sheet material thickness has a very slight effect on the Ra. Due to a reduction in the tool's non-contact area between the two vertical steps, the arithmetical average roughness of the truncated pyramid decreases as the wall angle increases because more plastic deformation occurs in the material when the wall angle increases leading to homogeneous strain distribution. Also, the large angle of the wall led to more gradual changes in the tool path that reduced the localized deformation and Ra. Consequently, the Ra will decrease. The increase in the step depth led to an increase in the arithmetical average roughness because the lowest value of the step depth led to an increase in the contact area between the tool and the sheet material.

The wall angle of 60°, the sheet thickness of 2 mm, and the step depth of 0.2 mm produced the lowest value of the arithmetical average roughness, and the wall angle of 40°, the sheet thickness of 1 mm, and the step depth of 0.6 mm produced the highest value of the arithmetical average roughness.

CONCLUSIONS

The main conclusions of this work can be summarized as follows based on the results that were extracted and the analysis of these results using ANOVA. The optimum level for the parameter of minimum average roughness was obtained at the third level of the wall angle and sheet thickness and the first level of the step depth. The average roughness decreased as the wall angle increased. The influence of the sheet thickness parameter on the average roughness is that increasing the thickness led to a slight decrease in the average roughness (Ra). The average roughness increased as the step depth increased. The maximum Ra value was 1.46 μm at a wall angle of 40°, thickness of 1 mm, and step depth of 0.6 mm and the minimum Ra value was 0.55 μm at a wall angle of 60°, thickness of 2 mm, and step depth of 0.2 mm.

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