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Effect of process parameters on the surface roughness of aluminum alloy AA 6061-T6 sheets in frictional stir incremental forming

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A B S T R A C T

Incremental Sheet Forming (ISF) is characterized by essential flexibility, great formability, and low forming forces and cost compared to the conventional sheet metal forming processes. ISF was born as an advance sheet metal forming process to perfectly fit previous requirements. Nevertheless, growing demand to apply the lightweight materials in several fields was placed this developed process in a critical challenge to manufacture the materials with unsatisfied formability especially at room temperature. Thus, utilizing the heat at warm and hot condition in some ISF processes has been introduced to solve this problem. Among all heat-assisted ISF processes, frictional stir-assisted Single Point Incremental Forming (SPIF) was presented to deal with these materials. In this work, this emerging process was utilized to manufacturing products from AA6061-T6 aluminum alloy. Experimental tests were performed to study the influence of main parameters like tool rotation speed, feed rate, step size and tool size on the surface roughness of the produced parts. A Taguchi method and varying wall angle conical frustum (VWACF) test were used in the present work. The results find that tool diameter has a significant impact on the internal surface roughness produced via the forming process with a percentage contribution of 93.86 %. The minimum value of the surface roughness was 0.3 µm.

A R T I C L E I N F O

Keywords:
Friction stir forming;
Incremental sheet forming (ISF);
Heat-assisted ISF;
Surface roughness;
Aluminum alloy (AA6061-T6)

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1. Introduction

Currently, there is a growing market in the manufacturing of customized, rapid prototyping and low-cost sheet parts with small to medium batches (particularly in transportation, artificial medical alternatives, and aerospace industries) [1, 2]. The main reason for employing tool rotational speed in SPIF is to improve the formability of lightweight and hard-to-form materials which characterized by low formability at room temperature [3-5]. In addition, it leads to decrease the forces via the forming process [6-8]. Indeed, there are some drawbacks and tradeoffs that influence as a result of employing the spindle speed in SPIF. Low surface quality, lubricant failure, and high tool wear rate are the disadvantages of frictional stir incremental forming process [9]. In addition, SPIF at high rotation speed promotes the probability for developing tool marks on the worked sheets [10].

The surface finish or surface roughness is a serious drawback in ISF, which limits the expansion of this process in different applications. To obtain a better surface texture, it is important to control several processes and material factors like forming angle, tool rotation, tool size and shape, step size, sheet thickness, and friction and lubricant. Thus, the researchers considered the influences of these main factors on the final surface topography of the produced parts in SPIF.

A study conducted by Durante *et al.* [6] aimed to investigate the influence of the tool rotational speeds and its directions on the surface texture of aluminum alloy AA7075-T0 formed by SPIF. The experimental results proved that no significant effect of these two parameters was present in the studied speed range between 0-600 rpm, and the obtained varied values of the surface roughness were mainly dependent on whether the tool was rotated or not.

During SPIF of the aluminum alloy AA3003-H14, a model was established by Hamilton and Jeswiet [11] which can be employed to improve the external surface of manufacturing SPIF parts by selecting adequate forming parameters via a process such as feed rate and tool rotation speed at high speeds. This presented model can predict the orange peel effect and provide a good guide to enhance the surface quality. In addition, the surface roughness for the parts with high rotation speed/feed rate is less than those of with a low ratio.

Good surface roughness results were obtained during the manufacturing of medical parts by SPIF from the known titanium alloy Ti-6Al-4V by Olesksik *et al.* [12]. The obtained surface finish of the formed parts were influenced by the forming tool roughness and friction case at the tool-sheet zone.

In fact, the final formed angle in SPIF is used as an index for both formability and surface roughness where the change in stretching value in the formed part leads to the change in both the forming angle and surface finish. In this way, Bhattacharya *et al.* [13] investigated the impact of tool size (4 mm, 6 mm , and 8 mm), step size (0.2 mm, 0.8 mm, and 1 mm), and wall angle (20^{o}, 40^{o}, and 60^{o}) on the surface roughness of aluminum alloy AA5052 via SPIF. The results of experiments showed that the surface quality of the formed parts decreases as to the increase in tool sizes for all step sizes. In addition, surface finish decreases due to the increasing of the forming angle.

Palumbo and Brandizzi [14] proved that both the surface roughness and the part's accuracy are influenced by the tool rotation speed when the forming of the titanium alloy Ti6Al4V was studied. The spindle rotation range of 800-1600 rpm was with two values of step sizes; 0.5 mm and 1 mm. The value of R_a became 011.9 μm compared to the initial sheet roughness of 0.5 μm.

Ambrogio *et al.* [15] performed an experimental study on three aluminum alloys, AA1050-0, AA5754, and AA6082-T6, with different sheet thicknesses. It was proven that the step size, forming angle, and sheet thickness have a significant impact on the surface roughness of the shaped parts, while it had an insignificant impact on the feed rate.

In this regard, Silva *et al.* [16] studied the influence of both the step size and feed rate on the surface roughness of SAE 1008 steel material. It was shown that an adequate roughness could be obtained with a feed rate and step size of 8400 mm/min and 0.2 mm, respectively. Lasunon *et al.* [17] examined the effect of some factors on the surface finish. Their results proved that the forming angle, step size, and its interaction affected the achieved surface texture, while there was little influence on the feed rate.

The good surface finish can be achieved depending on the tool trajectory. Usually, the tool trajectory with a constant step depth leaves marks at the end of each circle of the path and, therefore, produces a poor surface quality; especially with high step values compared to the spiral tool path [18]. Skjoedt *et al.* [19] proved that scarring can be removed by using a spiral trajectory during SPIF. Lu *et al.* [20] given a tool path algorithm based on specified critical edges. A superior surface roughness can be obtained by using this algorithm with respect to the traditional tool path employed in ISF.

An empirical research was conducted by Liu *et al.* [21] to investigate the influence of tool size, feed rate, step size, and sheet thickness on the surface texture of the final part made from aluminum alloy AA7075-T0. The response surface methodology and Box-Behnken design were applied to analyze the results. Better surface roughness was achieved with parameter values of 25 mm for tool size, 6000 mm/min for feed rate, 0.39 mm for step size, and 1.6 mm for sheet thickness.

Mugendiran *et al.* [22] built a quadratic model with second order based on three process parameters (tool rotation, feed rate, and tool diameter) to estimate the influence of the mentioned variables on both the surface finish and wall thickness distribution during the forming of aluminum alloy AA5052. Optimum values of surface roughness R_a and final sheet thickness (t) were 2.45 μm and 0.753 mm, respectively. These optimal values were obtained at rotation speed, feed rate, and step size of 1931 rpm, 654 mm/rev, and 0.65 mm, respectively.

Another study was conducted by Lu *et al.* [23] to determine the impact of the tool design on the surface quality of four aluminum alloys named AA6111, AA5052, AA2024, and AA1100. The obtained results concluded that better surface roughness could be achieved with new oblique roller-ball tool (ORB) rather than the conventional tool. The employment of ORB helped in reducing the friction at the tool-sheet zone and at the same time, reduced the forming loads and increased the formability of the studied materials.

A detailed experimental study by Azevedo *et al.* [24] aimed to estimate the effect of several types of lubricants on the surface roughness for steel DP780 and aluminum alloy AA1050-T4. It was concluded that the existence of lubricant is an important factor to obtain better surface texture. This finding supported the results of previous studies [25-27].

In this work, friction stir-assisted SPIF was utilized to manufacturing AA6061-T6 sheets that have been utilized in several applications in industrial sectors. Besides the mentioned benefits, friction stir-assisted SPIF shows superior profits, where, it does not need an exterior heating source and the surface finish is better than the other two heat-assisted ISF types: electric-assisted ISF and laser-assisted ISF.

2. Materials and methods

2.1 Material

Uniaxial tensile test was achieved to get the stress-strain curve of AA 6060-T6 sheet with a thickness of 2 mm. Fig. 1 presents the specimen dimensions which are according to ASTM E8M standard.

Fig. 2 and Table 1 describe the true stress-strain curve and the chemical composition of the material used, respectively. It is clear that the material has a suitable total strain at fracture, which is preferred in incremental sheet metal forming.

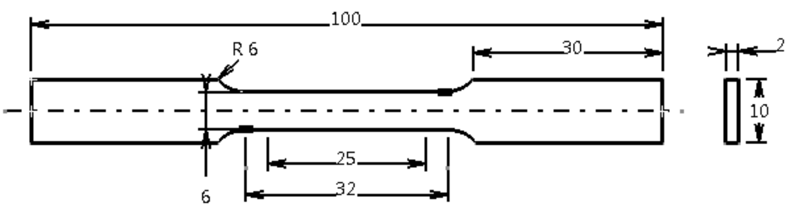


Fig. 1 Specimen dimensions of the uniaxial tensile test (dimensions in mm)

Table 1 Chemical composition (wt %) of the material

Material	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Al
AA6061-T6	0.52	0.19	0.27	0.07	0.91	0.1	-	0.02	0.01	97.91

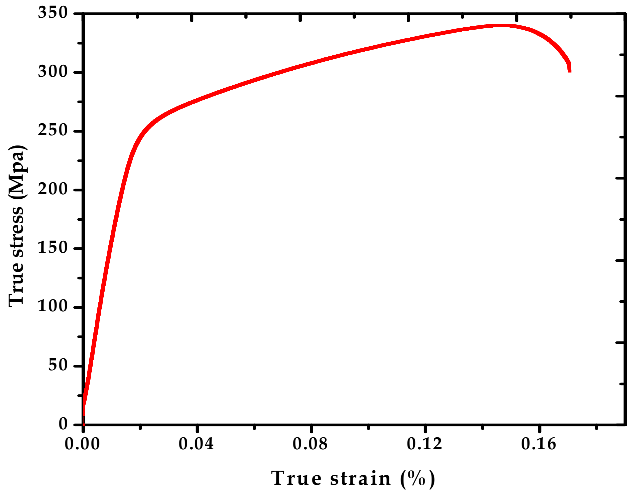


Fig. 2 The stress-strain curve of AA6061-T6

2.2 Experimental setup

The necessary task of the jig, which use in the forming process, is tightly hold the sheet specimen with both clamping and backing plates. Forming jig included of four clamping plates, backing plate, four columns and base plate. The dimensions of the backing plate are 170 × 170 × 20 mm with a central hole of 70 mm in diameter, which represent the outer diameter of final product. In order to get a smooth material forming, the inner diameter of the backing plate was filleted with 60 mm radius. On the other side, the aluminum sheet is with dimensions of 150 × 150 × 2 mm. The whole jig assemble was mounted to the bed of CNC milling machine (OKUMA MX 45VA). Fig. 3 displays the experimental setup of the forming jig.

Two forming tools with hemispherical ends were employed in the experimental tasks. The tools are with two different diameters, 10 mm and 15 mm and with a same of length of 110 mm. Moreover, these tools were hardened and tempered with 60 HRC and made from high-speed steel (HSS) material. In order to decrease friction effect at the contact zone thereby increase the tools life and surface quality of the final product, tool tips were polished. Fig. 4 explains the dimensions of the tools used in the experiments.

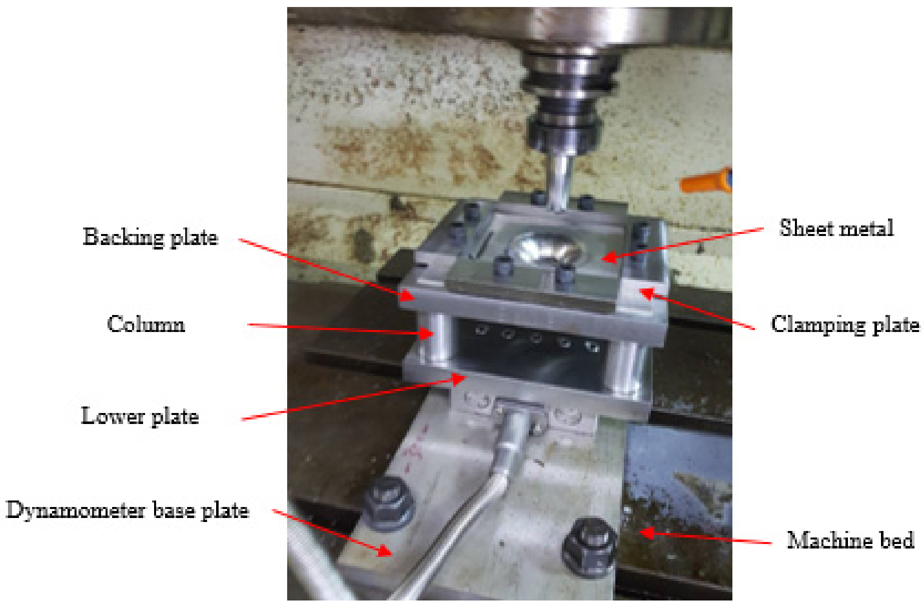


Fig. 3 The forming jig

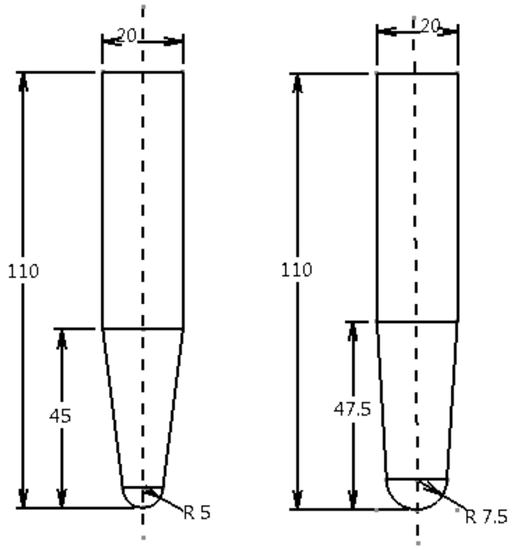


Fig. 4 The forming tools (all dimensions in mm)

2.3 Experiments

A varying wall angle conical frustum test (VWACF) was used to achieve the tests because of its homogenous geometry with the symmetrical parts [38]. The intended model of the product was designed to get maximum diameters (outer and inner of 70 mm and 12 mm, respectively), a height of 41 mm and a radius with 60 mm of the varying slops. Fig. 5 explains the designed dimensions of the targeted cone.

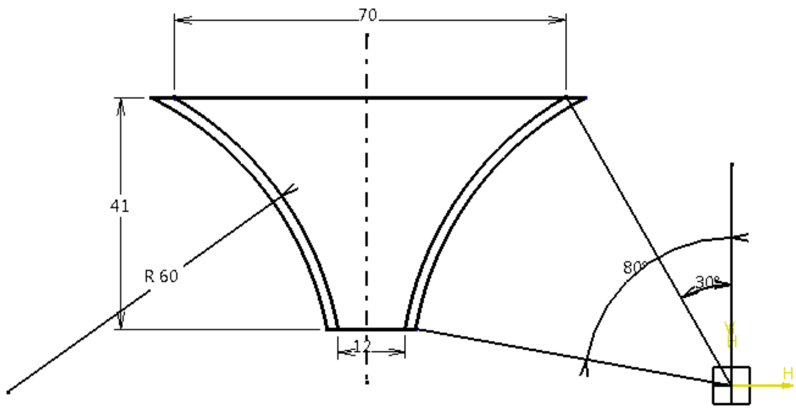


Fig. 5 The conical profile (dimension in mm)

A spiral trajectory of the forming tool with a certain step size was designed to generate the tool path. This path can be characterized by a pure stretch deformation during the forming process, which helps to create a sheet thickness that uniformly distributed [39]. Moreover, it assists to remove the peaks of the forming forces and at the same time, no stretch marks can leave on the working sheet surface. On the other hand, these sockets regularly happen with counter type. The CAD/CAM was used to create the product profile and generate the spiral tool path by NC code, as displayed in Fig. 6.

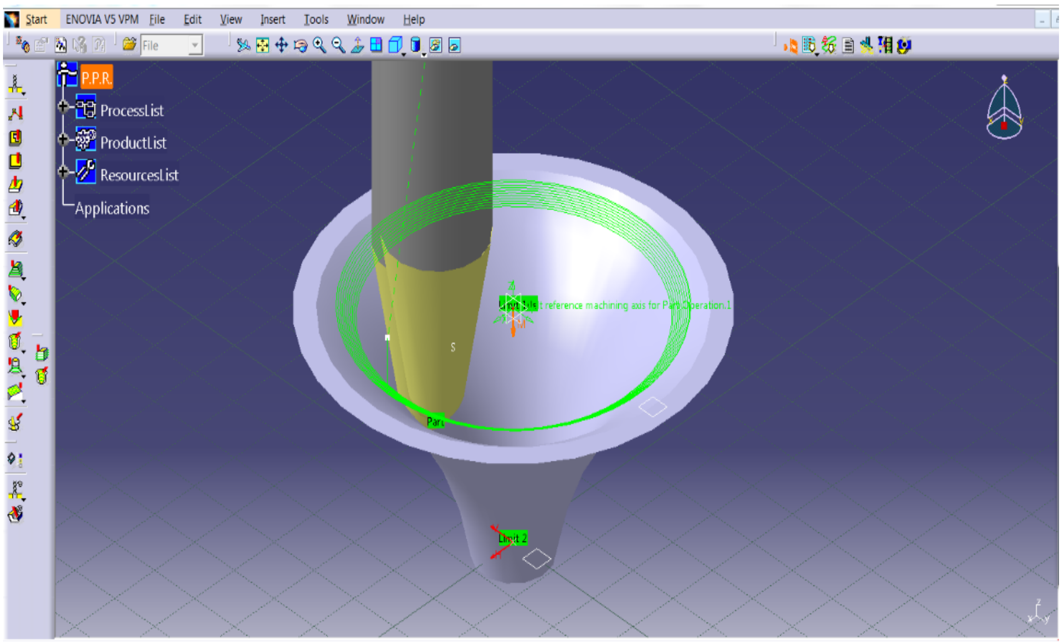
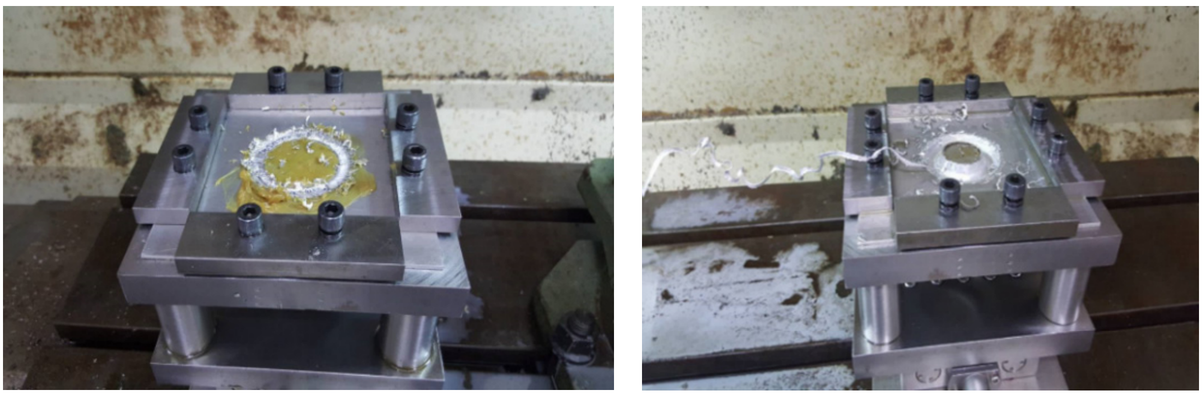


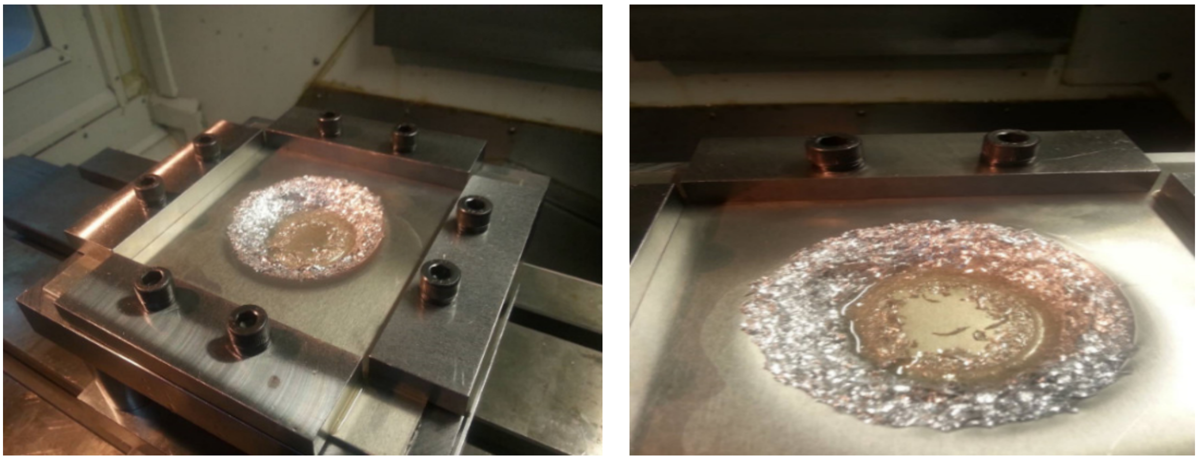
Fig. 6 Generating the tool path by CATIA

The continual motion of the forming tool via forming process leads to a local heating at the contact zone due to the local friction. In addition, this heating increases the rate of the tools wear. This will affect both surface roughness and geometric accuracy of the produced parts. These harmful effects can be prevented by using different types of lubricants. In this study, lubricant SAE 0W-40 was employed to diminish the friction effects. Taguchi technique was employed to help in the design of the tests with a minimum number of runs to save the time and overall cost [40, 41]. Design of experiment (DoE) which comprises of selection process parameters and their influential levels that depended on the previous studies. From these studies, it was concluded these factors and their levels are extremely affected by the material properties. In order to find the correct and suitable process parameter levels that can be used to obtain successful sets of experiments, many primary trials were conducted. Fig. 7 (a) and (b), and Fig. 8 (a) and (b) show the first failed trails due to the use of high rotation speed and feed rate, and small tool size, respectively.



(a) (b)

Fig. 7 Samples failed due to use high levels of rotation speeds and feed rates



(a) (b)

Fig. 8 Samples failed due to use a small tool size

Table 2 Process factors and their levels

Description	Factor	Level 1	Level 2	Level 3	Level 4
Tool rotation speed (rpm)	ω	50	400	800	1200
Feed rate (mm/min)	f	250	500	-	-
Step size (mm)	z	0.2	0.5	-	-
Tool size (mm)	D	10	15	-	-

Table 3 Orthogonal array L8 (4^1. 2^3) of the experiments tests

Test	ω (rpm)	f (mm/min)	z (mm)	D (mm)
1	1	1	1	1
2	1	2	2	2
3	2	1	1	2
4	2	2	2	1
5	3	1	2	1
6	3	2	1	2
7	4	1	2	2
8	4	2	1	1

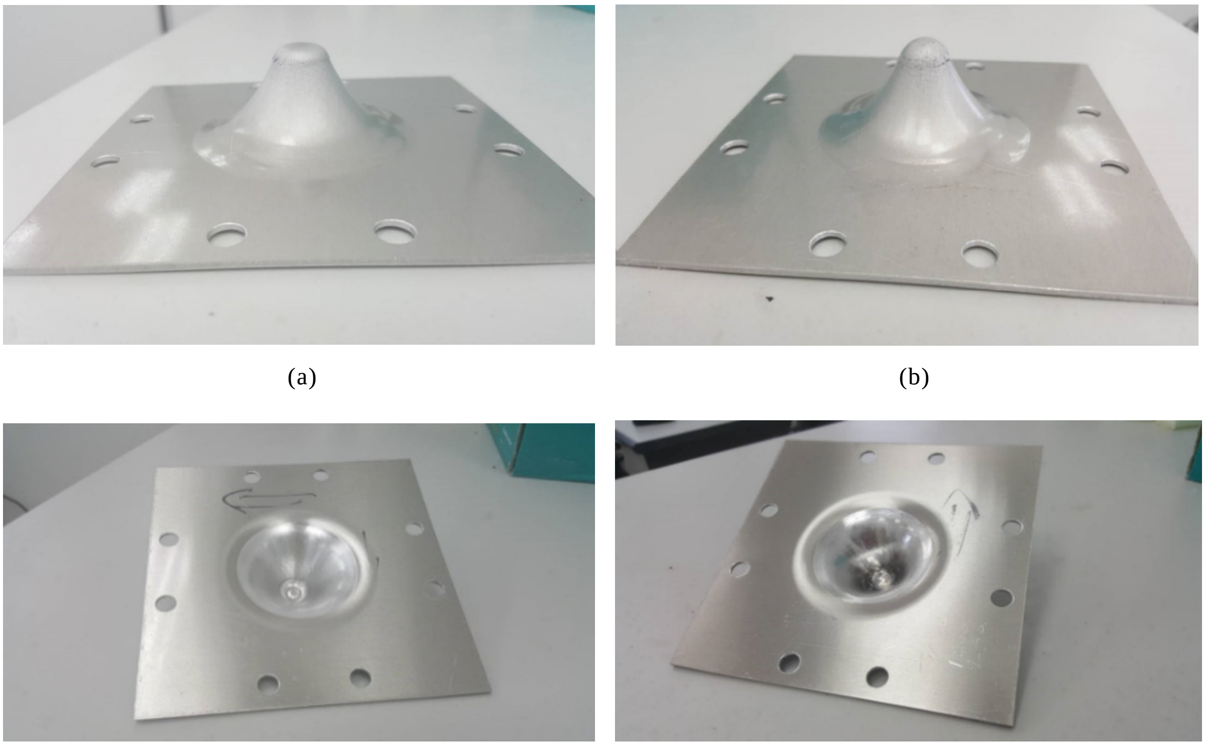
Tables 2 and 3 represent the process parameters, their levels, and the orthogonal array, respectively.

3. Results and discussion

A number of experimental tests were carry out to assess the effect of the tool rotation speed (ω), feed rate (f), step size (z) and tool size (D) on the final surface texture created through the SPIF. The experiments were stopped when the parts fracture. Where Fig. 9 (a), (b), (c) and (d) is demonstrated the samples that succeeded with the correct selection of parameter levels according to the mentioned designed array.

One of the main draw backs that accompany incremental sheet forming is the poor surface quality of the produced components [23]. Thus, appropriate combination and optimization of forming parameters is a challenge and an imperative issue to manufacture parts with excellent surface finish and other desirable process aspects; such as formability and forming forces. To achieve this goal, the Taguchi technique together with analysis of variance ANOVA, were employed to examine the influence of the tool rotation, feed rate, step size, and tool size on the obtained surface roughness. These four forming parameters have significant effects on SPIF, as mentioned in the literature.

The experimental results for the surface roughness R_a and the congruous S/N ratios are recorded in Table 4. Moreover, the surface roughness values for the AA6061-T6 sheets as received are 0.175 μm and 0.411 μm, with and across the rolling direction, respectively.



(a) (b) (c) (d)

Fig. 9 Samples that succeeded with the correct selection of parameter levels

Table 4 The DoE matrix and the results for surface roughness and S/N ratios

Run	ω (rpm)	f (mm/min)	z (mm)	D (mm)	Across the forming tool path	
					Ra(μm)	S/N ratio
1	50	250	0.2	10	1.62	-4.1903
2	50	500	0.5	15	0.719	2.8654
3	400	250	0.2	15	0.581	4.7165
4	400	500	0.5	10	1.536	-3.7278
5	800	250	0.5	10	1.44	-3.1672
6	800	500	0.2	15	0.3	10.4576
7	1200	250	0.5	15	0.469	6.5765
8	1200	500	0.2	10	1.391	-2.8665

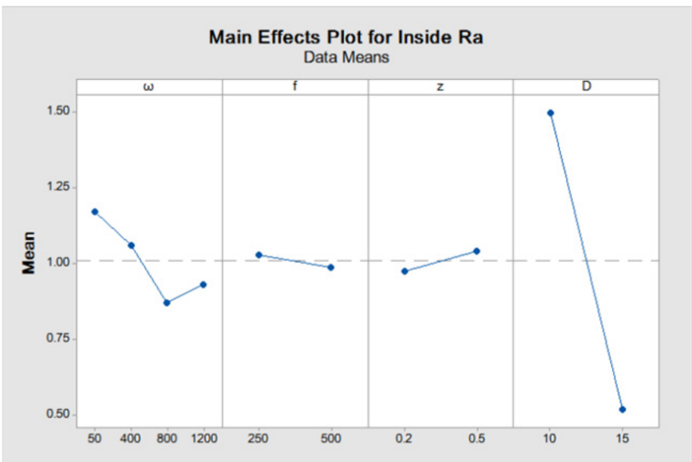


Fig. 10 The main effects of the various parameters on the surface finish

The main effect of the considered factors on the surface finish is presented Fig. 10. More or fewer impacts of the levels of these parameters on the output response can be noted. This graph shows the effect of tool size is a significant on the surface roughness. The other parameters such as rotation speed, feed rate, and step size have a less or negligible effect on the output.

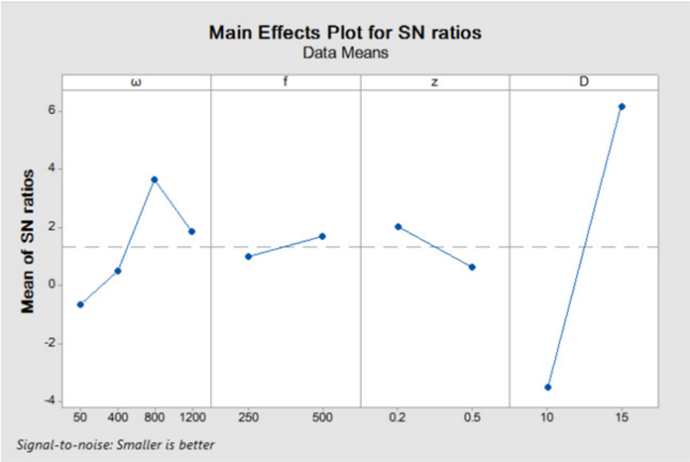


Fig. 11 Main effect for SN ratios for the surface roughness

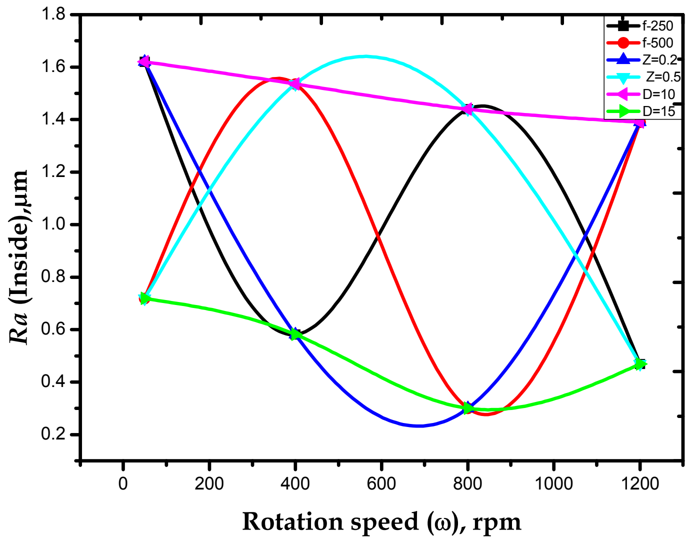


Fig. 12 The interaction effect of various factors on the surface roughness

Table 5 Analysis of variance for the surface roughness

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Significant	Contribution (%)
Regression	4	2.01239	0.50310	47.35	0.005	Yes	
ω	1	0.08094	0.08094	7.62	0.070	-	3.96
f	1	0.00336	0.00336	0.32	0.613	-	0.16
z	1	0.00925	0.00925	0.87	0.420	-	0.45
D	1	1.91884	1.91884	180.59	0.001	Yes	93.86
Error	3	0.03188	0.01063				1.56
Total	7	2.04427					100

Table 6 Statistical results of the developed regression equation of the surfaces roughness

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	3.581	0.237	15.08	0.001	-
ω	-0.000234	0.000085	-2.76	0.070	1.00
f	-0.000164	0.000292	-0.56	0.613	1.00
z	0.227	0.243	0.93	0.420	1.00
D	-0.1959	0.0146	-13.44	0.001	1.00

The optimal condition of the surface roughness R_a of the AA6061-T6 sheet formed by frictional-stir assisted SPIF was determined by the Taguchi analysis. Consistent with this method, the greater the value of the S/N ratio is the superior the aggregate performance is. The case indicates that the parameter levels with the highest S/N ratio should be designated as the best levels. In this study, the optimal condition for the process parameters, which provided a minimum *Ra*, was within the run number 6, as shown in Table 4, and Figs. 11 and 12.

The analysis of variance ANOVA helped to create these relative impacts of parameters and their percentages contribution to the surface roughness, shown in Table 5 while Table 6 presents the coefficients of the regression equation.

This regression equation was established based on the experimental results of the surface roughness *Ra*; the (Eq.1) can describe it.

$$\text{Inside } Ra\ (\mu m) \quad 3.581 \quad 0.000234\omega \quad 0.000164 f \quad 0.227 z \quad 0.1959 D \tag{1}$$

The fitting of the regression model is given by the determination coefficient R^2. The value of this coefficient refers to the close fitting of the regression equation. The values of the R^2, adjusted R^2, and predicted R^2 are 98.44 %, 96.36 %, and 87.86 %, respectively. Therefore, regarding the values of these coefficients, the established regression equation fits well and describes the surface roughness response. Lastly, normal distribution plot, Fig. 13, clarified that the residuals track the normal distribution. It can be noted that the regression equation has a good fit to their experimental data and are reliable to use.

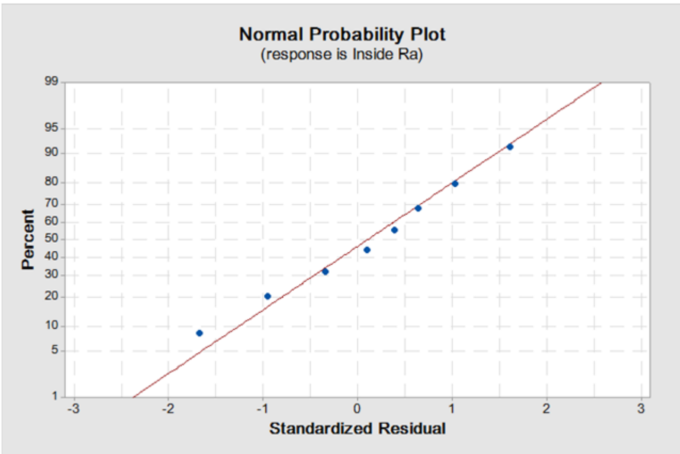


Fig. 13 Normal distribution of the surface roughness

4. Conclusion

In the present study, friction stir-assisted SPIF was performed to deform AA606-T6sheets. The purpose is to study the impact of certain process factors on the surface roughness of the produced parts. The results can be concluded in the following worthy points:

- The diameter of the forming tool have a significant impact on the internal surface roughness produced via the forming process of AA6061-T6. To attain an acceptable surface roughness, the percentage contribution of this parameter was 93.86 %.
- An optimal process parameters was achieved for the surface roughness during the forming process. The minimum value of the surface roughness was 0.3 µm at ω = 800 rpm, f = 500 mm/min, z = 0.2, and D = 15 mm.
- The value of the determination coefficient R^2 of the established regression equation of the surface roughness was 98.44 %. This high value refer to the close fitting of the suggested equation to describe the expected experimental data; it also means the response values highly adhere to the normal distribution.