Investigation of Surface Roughness in Single Point Incremental Sheet Forming Considering Process Parameters

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***Abstract*—Single point incremental forming (SPIF) is a die-less forming method in which the sheet is incrementally formed using the forming tool with predefined contour paths of the desired shape. Moreover, any complex parts can be manufactured using this method by modifying the tool paths and the forming tool dimensions because of its flexibility. This paper aims to investigate the surface quality of the incrementally formed parts using the statistical approach. The incremental forming process experiments were planned using the design of experiments approach considering central composite design with face-centered option. The surface roughness was then estimated using the Mitutoyo Surftest SJ-400 surface roughness tester in the tested samples; the response surface methodology was employed to construct the prediction model of surface roughness. Subsequently, the proposed empirical models were examined using numerical and graphical verifications. The predicted results showed a good agreement with the experimental results displaying a higher correlation estimation with moderate prediction error. The forming parameters, tool radius, and step size showed a significant impact on the surface finish than that of the feed rate parameter. The results displayed from the entire surface roughness measurements that the best surface finish was recognized for both cone angles in the test conditions of a 2.5 mm tool radius, a 0.2 mm step size, and a 2000 mm/min feed rate, respectively. On the other hand, the low surface finish was observed in the forming conditions of a 2.0 mm tool radius, a 0.8 mm step size, and a 1000 mm/min feed rate. The systematic approach to investigate the surface roughness in terms of the empirical model approach is reported here; it can be used for any chosen material to examine and to manufacture products in real-time industrial applications.**

***Index Terms*—Single point incremental forming, forming tool, aluminum alloy, surface roughness, design of experiments, central composite design, response surface methodology, empirical model**

I. Introduction

Despite new materials entering the market, aluminum alloys remain the best choice of material, although other materials such as copper and titanium are presented in the market, because of their high strength, corrosion resistance, ease of forming, and cost-effectiveness. The single Point Incremental Forming (SPIF) process is widely used in automobile and aerospace industries to form various complex geometries, as shown in Fig. 1 [1]. In the SPIF process, a working sheet is deformed through a high-speed rotational tool, which follows a specific tool path based on our desired geometry. Sometimes due to the application of an inappropriate tool path causes over thinning of material, and it can be overcome by using multi-step tool path strategies [2]; this also results in higher forming height in our desired parts. Other tool paths, such as unidirectional and bidirectional tool path strategies, can be implemented to analyze the residual stresses in the developed parts [3]. The research study further shows that the tool path can also result in spring back and low surface quality in the formed parts, which can be overcome by using radial travels of the working tool through the center of the workpiece [4]. Apart from the tool path, other input parameters such as tool radius, step size, forming angle, forming height, and lubrication can also affect the process and the formed parts' quality. Manish Oraon *et al.* studied these parameters in the SPIF process; they found that the minimum deformation force can be achieved in a 0.2 mm thick sheet using a forming speed of 20 mm/min and a step size of 0.1 mm, keeping a 45^{o} wall angle [5]. Also, they pointed out that higher forming force is required in case of larger step size and tool radius to form any part while lowering the tool diameter in such case can cause a fracture in the desired part [6]. The effect of some factors, stress triaxiality, normalized load angle, and forming stage, on ductile fracture can be analyzed in detail using a high-precision finite element model [7]. The process productivity can be increased significantly by studying the sheet fail under shear and brittle failure mode [8].

SPIF process has the advantage of manufacturing complex shapes and due to which few defects could be found while forming some complex geometries, like spring back, which affects the accuracy of the formed parts, parameters such as thickness reduction and forming force can study to minimize this defect [9]. For investigating the effect of these two factors, Finite Element (FE) analysis can be implemented to minimize the manufacturing cost [10]. Moreover, in an inappropriate tool path, the forming force can also result in the twist defect, which can be reduced by choosing a

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proper tool path for each type of geometry configuration [11]. Selection of input parameter is also crucial in terms of surface quality in the formed parts; larger step size or feed rate can cause surface roughness in the parts while minimizing the matching time [12]. Similarly, other parameters such as spindle speed, sheet thickness, tool diameter can also affect the surface quality by altering its values. For evaluating each parameter behavior in the formed parts, the design of experiment (DOE) has been used to identify the effects of these parameters [13]. Grey Relational Analysis (GRA) can also identify the most influencing parameters; tool diameter and spindle speed are considered the main factors responsible for surface roughness in the SPIF process [14].

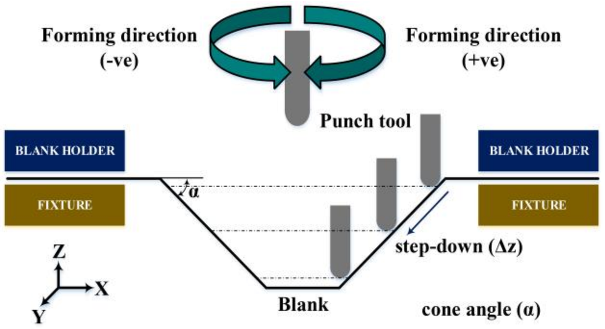

Figure 1. Schematic diagram of single point incremental forming process.

This research's main objective is to study the forming parameter's influence on surface roughness for the commercial aluminum alloy (AA3003-H18) sheets as the better surface quality with higher formability is the primary concern in the incremental forming process producing the industrial application components. The product was formed considering the cone shape with two forming angles to investigate the forming parameters in terms of the surface quality. For modeling the real-time experiments, the systematic approach using the design of experiments (DOE) was adopted, and the tests were performed according to the design table. Lubricant, a combination of oil and grease, was utilized to smooth the blank and forming tool transition. The response surface methodology was employed to develop mathematical equations for the response variable, material surface roughness, and verified using numerical and graphical validations.

II. Experimental Procedures of SPIF Process

Single point incremental forming experiments were carried out using the modified CNC vertical milling machine [15-18]. For modeling the tests, the punch tools and the aluminum alloy AA3003-H18 Al sheets were prepared using pre-cut dimensions and various radius based on machine working area and designed experiments, respectively. In detail, the sheet dimensions were selected considering the customized CNC machine working area, and the sheet area was 240×280 mm^2 with a thickness of 0.5 mm. Due to the impressive mechanical material properties of the high-speed steel (HSS) material, it was chosen to manufacture the punch tool for performing the SPIF process to produce the conical geometries as shown in Fig. 2 and Fig. 3. Besides, the forming tool trajectories were constructed using the spiral-type tool path for an entire experiment. For estimating the surface roughness on the incrementally formed parts, the Mitutoyo Surftest SJ-400 surface roughness, as illustrated in Fig. 4, was adopted. For investigating the surface finish, the experimental parameters, such as tool radius, step-size, and feed rate, were taken into consideration in this research work, as tabulated in Table 1. For maintaining smooth transition between the forming tool and the material blank, three lubricants such as oil, grease, and combination of oil and grease are used. To quantitatively assess the selected lubricants influence on the produced part surface quality, the samples were examined using 3D nano surface profiler equipment. The surface roughness was computed as 0.56, 0.80, 0.66, and 0.64 μm for the original surface, oil, grease, and oil-grease combination, respectively. Here it is important to mention that the test conditions were chosen to be same for entire test cases. After investigating the surface roughness values of tested samples, a combination of oil and grease were chosen based on its advantage over low roughness and flexibility.

The experiments were designed using the design of experiments approach considering the central composite design with a face-centered option, and the DOE table is summarized in Table 2. Using Table 2, the real-time tests were performed, and the measured surface roughness value of tested samples is summarized in Table 2. The influence of forming parameters is investigated in detail against the response variable, surface roughness, using the response surface methodology, and the Analysis of Variance (ANOVA) from MINITAB 18 software.

TABLE I. Design Variables and Their Levels for Experimental Design.

Variables		**Levels**		
		low	**center**	**high**
Tool radius (mm)	X_1	2.0	2.5	3.0
Step-size (mm)	X_2	0.2	0.5	0.8
Feed rate (mm)	X_3	1000	2000	3000

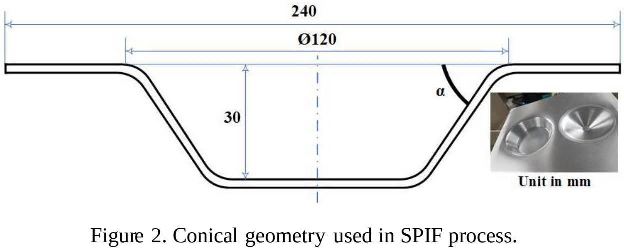

Figure 2. Conical geometry used in SPIF process.

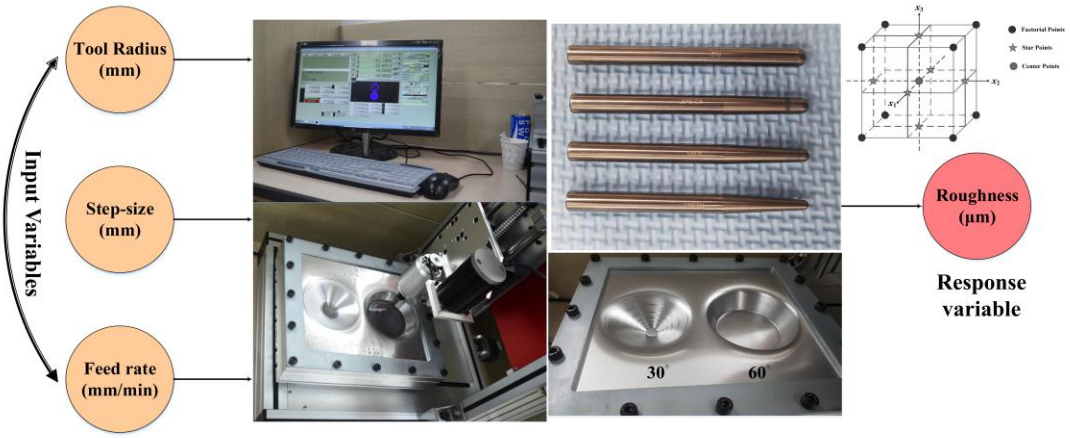

Figure 3. Experimental procedures for incremental forming process on CNC milling machine.

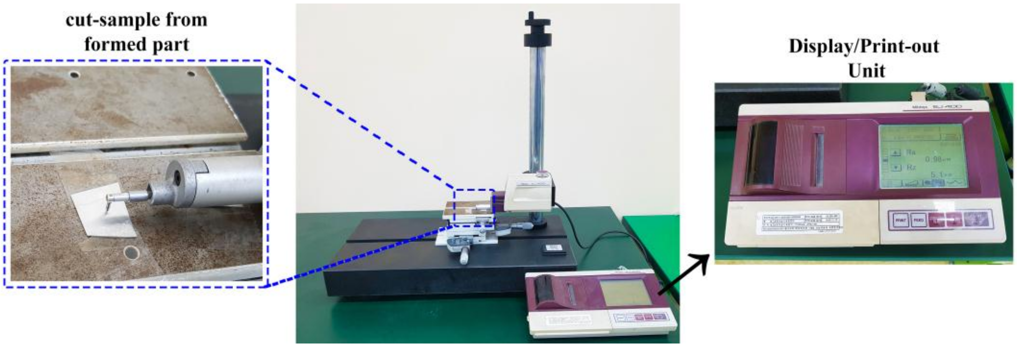

Figure 4. Surface roughness measurement in incrementally formed samples.

III. Results and Discussion

The experimental measurements and the standardized values are tabulated in Table 2 and Table 3. It was identified that the surface roughness values of 60^o truncated cone shape range from 0.587 µm to 4.237 µm. On the other hand, for 30^o truncated cone shape, it is found to be in a range from 0.717 µm to 3.463 µm, respectively. From the entire estimations, the outcomes revealed that the best surface finish was recognized for both forming cone angles in the experiment conditions of a 2.5 mm tool radius, a 0.2 mm step size, and a 2000 mm/min feed rate, respectively. Contrary, the low surface finish was observed for 60^o truncated cone shape in the test conditions of a 2.0 mm tool radius, a 0.8 mm step size, and a 1000 mm/min feed rate, whereas, for 30^o truncated cone shape, it was seen in a 2.0 mm tool radius, 0.8 mm step size, and 3000 mm/min. The predictive models for the average surface roughness are developed considering the process parameters, such as tool radius, step size, and feed rate, as shown in Eq. (3) and Eq. (4). The proposed prediction models are checked for their accuracy using statistical parameters such as R^2 and root mean square error (RMSE) [19-30]. Apart from numerical verification, the graphical verifications are modeled using the relationship, residual, and histogram plots. The 2nd order regression equation, including interaction effects, Eq. (3), is developed from the surface roughness measurements of 60^o truncated cone shape samples.

Moreover, ANOVA was conducted on the test data to recognize the input factor's statistical importance and how it affects surface roughness outcomes. The P values, which is smaller than 0.05, indicates that the fitted model terms are statistically meaningful. From Table 4 and Fig. 5(a), it is apparent in terms of F and P values that vertical step-size and the interaction between step-size and punch tool radius significantly influence the average surface roughness. Contribution (wt. in %) indicates that the proposed regression model in terms of step-size and interaction effect contributes almost 51 percentage and 19 percentage to the prediction outcome. In contrast, the model prediction error was almost 11 percentage, which is reasonable to consider. The effect of feed rate on surface roughness is not statistically significant. The coefficient of determination, R^2, provides the fitted model quality. Fig. 5(b) shows how strong the prediction against the experimental data, and it is estimated to be 0.889. Considering R^2 value, the randomness of residual, Fig. 5(c), and the residual normal distribution, Fig. 5(d), demonstrates that the regression model is adequately fitted with the test data.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_e^i - y_p^i)^2}{\sum_{i=1}^{n}(y_e^i - \bar{y}_e)^2} \quad (1)$$

$$\text{RMSE} = \sqrt{\sum_{i=1}^{n} (\text{test data}_i - \text{predicted data}_i)^2 / n} \quad (2)$$

$$\text{Ra } (\mu\text{m}) = -9.1 + 7.62\, x_1 + 16.72\, x_2 - 0.00400\, x_3 - 1.29\, x_1 \times x_1 + 0.55\, x_2 \times x_2 + 0.000001\, x_3 \times x_3 - 4.61\, x_1 \times x_2 + 0.000625\, x_1 \times x_3 - 0.001174\, x_2 \times x_3 \quad (3)$$

$$\text{Ra } (\mu\text{m}) = 6.83 - 5.40\, x_1 + 8.05\, x_2 - 0.00133\, x_3 + 1.47\, x_1 \times x_1 + 4.93\, x_2 \times x_2 + 0.000000\, x_3 \times x_3 - 4.10\, x_1 \times x_2 - 0.000036\, x_1 \times x_3 - 0.000570\, x_2 \times x_3 \quad (4)$$

TABLE II. EXPERIMENTAL DESIGN AND SURFACE ROUGHNESS MEASUREMENTS.

Runs	Coded Variables			Uncoded Variables			Roughness (μm)	
	X_1	X_2	X_3	X_1	X_2	X_3	Ra (60^o)	Ra (30^o)
1	-1	-1	-1	2.0	0.2	1000	0.743	1.323
2	+1	-1	-1	3.0	0.2	1000	0.705	1.778
3	-1	+1	-1	2.0	0.8	1000	4.237	3.403
4	+1	+1	-1	3.0	0.8	1000	2.600	2.203
5	-1	-1	+1	2.0	0.2	3000	0.713	1.260
6	+1	-1	+1	3.0	0.2	3000	3.093	2.450
7	-1	+1	+1	2.0	0.8	3000	3.967	3.463
8	+1	+1	+1	3.0	0.8	3000	2.410	1.383
9	-1	0	0	2.0	0.5	2000	0.637	0.850
10	+1	0	0	3.0	0.5	2000	2.020	1.533
11	0	-1	0	2.5	0.2	2000	0.587	0.717
12	0	+1	0	2.5	0.8	2000	2.815	1.820
13	0	0	-1	2.5	0.5	1000	2.625	1.240
14	0	0	+1	2.5	0.5	3000	2.270	1.253
15~20	0	0	0	2.5	0.5	2000	2.187	1.227

Besides, the main and interaction plots are plotted to illustrate the importance of control factors on the response variable. Fig. 7(a) clearly depicts that the process parameters such as tool radius and step-size provide a higher impact on the response variable than the feed rate. The interaction effect, Fig. 7(b), also indicates that the relationship between tool radius and average surface roughness depends on step-size. Even though small interaction is noticed in other combinations such as tool radius vs. feed rate and step-size vs. feed rate, it does not affect the response variable reasonably, as shown in Fig. 7(b).

Similarly, the same procedures are employed to construct the second-order quadratic regression model, including the factors interaction effects for surface roughness measurements of 30^o truncated cone shape. Eq. (2) clearly depicts the importance of the control factors in terms of quantity on the response variable. If the number is positive, it positively affects the response, and the quantity is negative, then it reduces the response, respectively. Eq. (4) shows that the main and interaction terms of tool radius and step size numbers are confirmed to influence the output factor, which is surface roughness. Besides independently examine the independent factors impacts on the response factor, the ANOVA table is developed and summarized in Table 5.

TABLE III. STANDARDIZED SURFACE ROUGHNESS DATA.

Runs	Uncoded Variables			Standardized Roughness Parameter	
	X_1	X_2	X_3	Ra (60^o)	Ra (30^o)
1	2.0	0.2	1000	0.043	0.221
2	3.0	0.2	1000	0.032	0.386
3	2.0	0.8	1000	1.000	0.978
4	3.0	0.8	1000	0.552	0.541
5	2.0	0.2	3000	0.035	0.198
6	3.0	0.2	3000	0.687	0.631
7	2.0	0.8	3000	0.926	1.000
8	3.0	0.8	3000	0.499	0.243
9	2.0	0.5	2000	0.014	0.048
10	3.0	0.5	2000	0.393	0.297
11	2.5	0.2	2000	0.000	0.000
12	2.5	0.8	2000	0.610	0.402
13	2.5	0.5	1000	0.558	0.190
14	2.5	0.5	3000	0.461	0.195
15~20	2.5	0.5	2000	0.438	0.186

The ANOVA results indicate that the parameter, step-size, and the input factor combination, namely tool radius (x_1) and step-size (x_2), provides the better impact on the surface roughness rather than that of other factor and their combinations. Apart from that, F and P values also depict the input factor's influence on the response variable by holding a higher F value and a lower P value, notably less than 0.05. The proposed second-order quadratic model prediction error is also around ten percentage, which is considerable because the prediction range of surface roughness is quantitatively small. It is essential to mention that the error percentage will alter based on the response variable working range, so the graphical validations also have to be carried out rather than numerical verifications. As illustrated in Fig. 6(a-d), the constructed regression model tends to have a strong correlation, error randomness without too many outliers, and the normal distribution in terms of residuals.

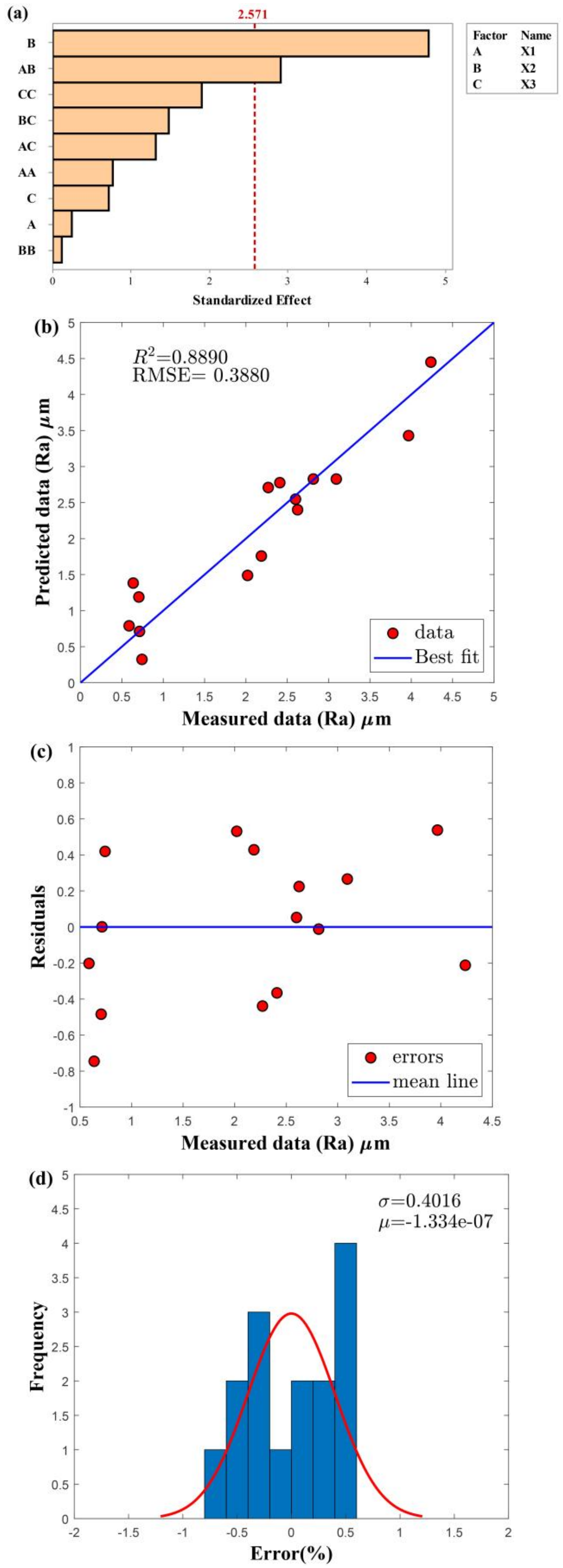

Figure 5. (a) Pareto chart of standardized effects (b) Relationship plot (c) Residual plot (d) Histogram.

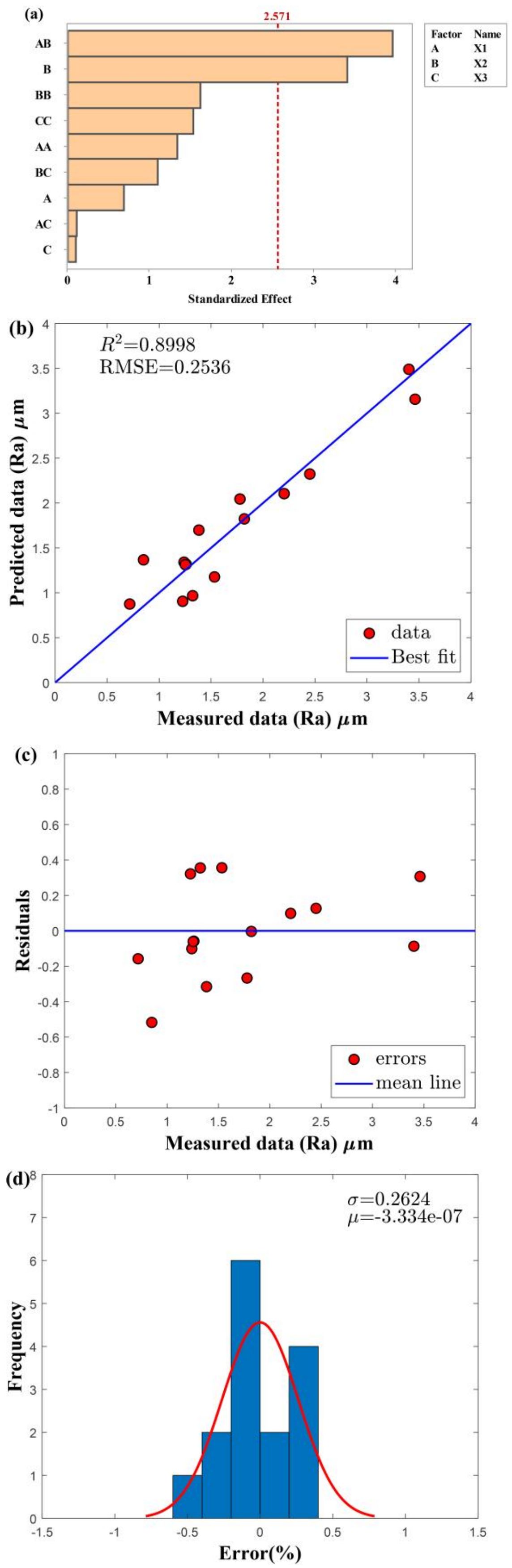

Figure 6. (a) Pareto chart of standardized effects (b) Relationship plot (c) Residual plot (d) Histogram.

TABLE IV. ANOVA FOR SURFACE ROUGHNESS MEASUREMENTS OF 60O TRUNCATED CONE SHAPE SAMPLES.

Source	DF	Adj SS	Adj MS	F-value	P-value	Contribution (%)
Model	9	18.0959	2.0107	4.45	0.057	**88.905**
Linear	3	10.6458	3.5486	7.86	0.024	52.302
X1	1	0.0282	0.0282	0.06	0.813	0.139
X2	1	10.3795	10.3795	22.98	0.005	**50.994**
X3	1	0.2381	0.2381	0.53	0.500	1.170
Square	3	1.8465	0.6155	1.36	0.355	9.072
X1*X1	1	0.2678	0.2678	0.59	0.476	1.316
X2*X2	1	0.0064	0.0064	0.01	0.910	0.031
X3*X3	1	1.6304	1.6304	3.61	0.116	8.010
2-Way Interaction	3	5.6036	1.8679	4.14	0.080	27.530
X1*X2	1	3.8309	3.8309	8.48	0.033	**18.821**
X1*X3	1	0.7800	0.7800	1.73	0.246	3.832
X2*X3	1	0.9926	0.9926	2.20	0.198	4.877
Error	5	2.2584	0.4517			**11.095**
Total	14	20.3543				

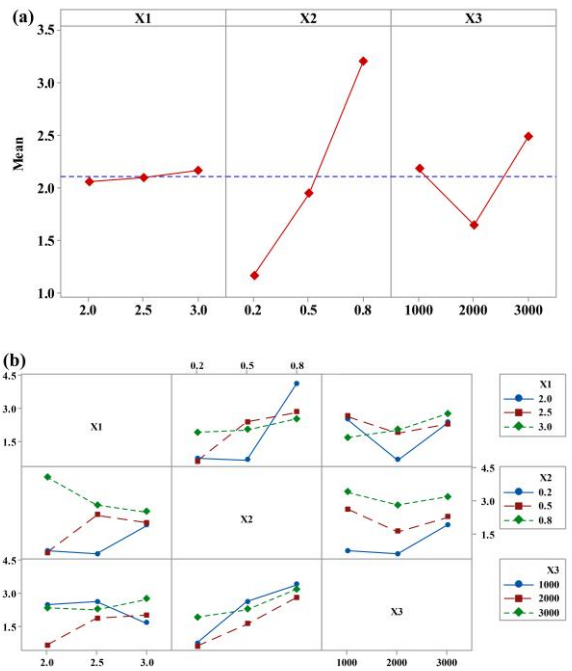

Figure 7. (a) Main effects plot (b) Interaction plot.

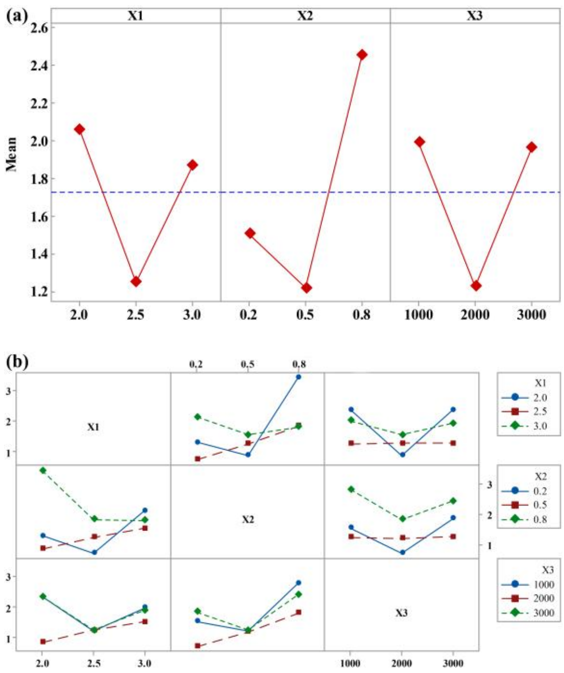

Figure 8. (a) Main effects plot (b) Interaction plot.

TABLE V. ANOVA FOR SURFACE ROUGHNESS MEASUREMENTS OF 30O TRUNCATED CONE SHAPE SAMPLES.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution (%)
Model	9	8.65717	0.96191	4.99	0.046	**89.977**
Linear	3	2.34309	0.78103	4.05	0.083	24.352
X1	1	0.09063	0.09063	0.47	0.524	0.942
X2	1	2.25055	2.25055	11.67	0.019	**23.391**
X3	1	0.00190	0.00190	0.01	0.925	0.020
Square	3	3.04523	1.01508	5.26	0.053	31.650
X1*X1	1	0.34613	0.34613	1.79	0.238	3.597

X2*X2	1	0.50667	0.50667	2.63	0.166	5.266
X3*X3	1	0.45769	0.45769	2.37	0.184	4.757
2-Way Interaction	3	3.26885	1.08962	5.65	0.046	33.974
X1*X2	1	3.03195	3.03195	15.72	0.011	**31.512**
X1*X3	1	0.00263	0.00263	0.01	0.912	0.027
X2*X3	1	0.23427	0.23427	1.21	0.321	2.435
Error	5	0.96441	0.19288			**10.023**
Total	14	9.62158				

Further, one more graphical verification, Figure 8, is performed to identify the input parameters effect on the output, surface roughness. The main effects, x_1, x_2, and x_3, displayed the same response, whereas the factor, x_2, showed a more robust influence than that of others. The interaction terms, x_1x_2 show a significant effect on the average surface roughness than other combinations. Therefore, this statistical study indicates that one factor, step-size, has a unique effect; one interaction, tool radius vs. step-size, has combined effects on the average surface roughness.

For illustrating the proposed model's usefulness, the experimental data are compared against the predicted data in Fig. 9(a) and 9(b). The comparison clearly shows that the predicted data lies very close to the experimental data in most cases. In observations 7 to 9, they were noticed to have a little deviation but reasonably acceptable, and both constructed models displayed the same prediction response. Overall, the statistical approach presented in this research work can be devised for predicting the surface roughness for the chosen material to manufacture the product with better surface finish by investigating manufacturing process parameters carefully.

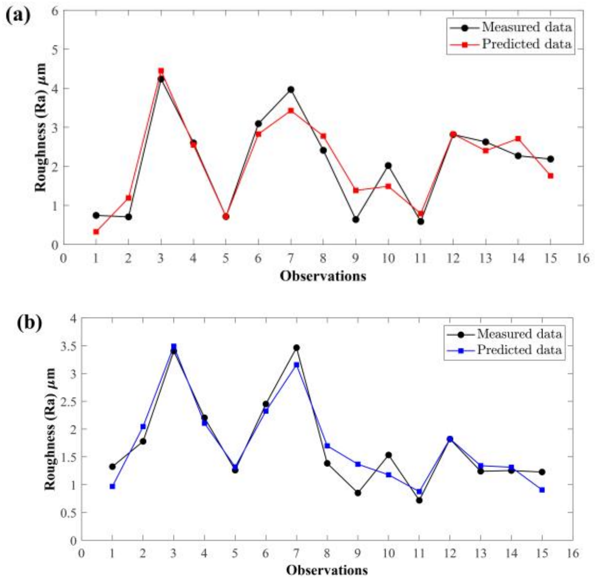

Figure 9. Comparison plot of experimental vs. predicted data (a) 60^{o} (b) 30^{o}.

IV. CONCLUSIONS

This research work experimentally investigated the surface quality of incrementally formed commercial aluminum alloy (AA3003-H18) parts, considering the forming factors such as tool radius, step size, and feed rate in the forming process. The effect of forming process parameters in the surface quality was examined using the response surface methodology, adopting the central composite design to model the experiments. The lubricant, a combination of oil and grease, was significant compared to the lubricants such as oil and grease, so a combination of oil and grease was utilized in the forming process for improving the surface quality of formed components. The average surface roughness of formed parts was determined using the Mitutoyo Surftest SJ-400 surface roughness tester. The statistical parameters were used to confirm the proposed model adequacies on the surface roughness prediction of performed test parts. From the entire surface roughness measurements, the results displayed that the excellent surface finish was identified for both cone angles in the test conditions of a 2.5 mm tool radius, a 0.2 mm step size, and a 2000 mm/min feed rate, respectively. On the other hand, the low surface finish was seen in the forming conditions of a 2.0 mm tool radius, a 0.8 mm step size, and a 1000 mm/min feed rate. The proposed models were verified using numerical and graphical validations; the results were meaningful with a higher correlation coefficient and lower prediction error. Moreover, the graphical plots, such as residual and histogram graphs, were identified to have randomness in the error pattern and the normal distribution for both tests forming cone angle. From the analysis of variance (ANOVA) outcomes, the process parameters, tool radius, and step size were recognized as the most significant parameters in the forming process. This present research can be used to implement the model surface quality in real-time industrial applications. Moreover, the statistical approach presented here can be used as a guideline to understand the forming process in terms of surface finish; it will also be useful to perform the SPIF process to improve product accuracy for any chosen material.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

In this research, the parts, such as conceptualization, methodology, experimental, programming, investigation and validation, original article writing and editing, were done by Mohanraj Murugesan, Krishna Singh Bhandari, and Muhammad Sajjad, and the supervision was carried out by Dong-Won Jung.

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