STATISTICAL ANALYSIS OF THE MAIN INCREMENTAL FORMING PROCESS PARAMETERS THAT CONTRIBUTE TO CHANGE THE ROUGHNESS IN AN EXPERIMENTAL GEOMETRY

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STATISTICAL ANALYSIS OF THE MAIN INCREMENTAL FORMING PROCESS PARAMETERS THAT CONTRIBUTE TO CHANGE THE ROUGHNESS IN AN EXPERIMENTAL GEOMETRY

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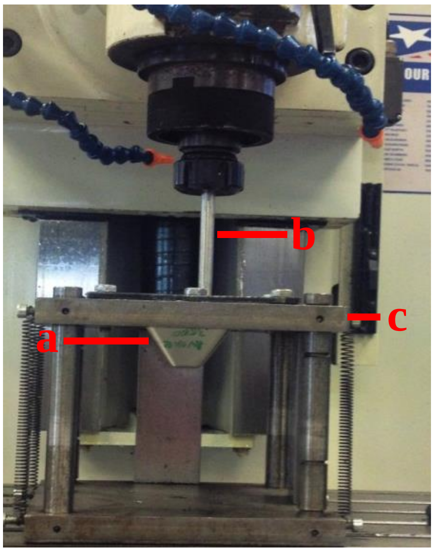
ABSTRACT:
Over time the process of incremental deformation of sheet metal without matrix in its variant (SPIF), has been developed in different countries with the aim of meeting the needs of flexible production with no investment in tooling and low production costs. As in any manufacturing process is important to obtain a surface quality of the part that meets customer needs, this variable is evaluated by the average roughness (Ra). For this reason the purpose of this study is to investigate the influence of the variation of three process parameters and determine which of them contributes in greater proportion to the change in the average roughness (Ra) measured parallel and perpendicular to the path followed by the tool. Besides this, it wants to validate the impact that has the spindle speed in the analyzed variable and the orange peel defect. To this end, a full multifactorial design of experiments with three factors and two levels (2^3) and three replicates were performed, in order to obtain greater reliability in the model. Subsequently, an analysis of variance is executed and the results are formalized, finding which parameters influence more than others in changing roughness and how the orange peel defect depends on the spindle speed. Additionally, the results are compared with the authors cited. The aspects developed in this study highlight the importance of improving quality variables in any field of sheet metal processing in the international industrial environment.

Keywords: Incremental forming, SPIF, Roughness, Statistical analysis, Design of experiments, CAD, CAM; Parameters, Spindle speed, feed rate, depth increase.

1. INTRODUCTION

In order to achieve significant savings in time, money, tools and materials over the years, it has justified the eagerness that have the industry to make its manufacturing processes ever more efficient and flexible. That is why today the sheet metal incremental forming process is presented as a practical and reliable alternative for prototyping and low production batches with multiple advantages over conventional processes. [1-3], besides this, to be a numerically controlled process, it can deform sheets of different materials in different complex forms [4]. One of the proposed variants of this process is the single point incremental forming (SPIF) [5-6] that consists in the progressive deformation of the sheet metal by a spherical tip tool, which follows a predefined trajectory, and ends with obtaining the desired geometry. This process is shown in Fig. (1).



(a) Deformed sheet, (b) Tool, (c) Sheet support

Fig.1. Graphical representation of SPIF process.

Studies on the process and the influence of different parameters on output or control variables, such as surface quality, forming forces, formability, geometric precision, among others, have been made by different authors over time. Ham and Jeswiet [7-8] presented research formalized by factorial design experiments to identify the effects on the formability of various aluminum alloys that has the parameters feed rate, spindle speed, depth increase and wall angle, they concluded that at higher speeds of the spindle, the formability of the sheet improves and the depth increase has a little effect on the maximum angle obtained. Duflou et al. [9] investigated the influence on the formability forces that have the parameters tool diameter, depth increase, sheet thickness and wall angle, and exhibited that has a strength increase with the increase of all these parameters. Also, Arfa et al. [10] presented a modeling by finite elements to find the influence of the above parameters and the material strength on the said forces. Bahloul et al. [11] executed a design of experiments along to finite element analysis to determine the influence of the parameters: tool diameter, sheet thickness, depth increase and wall angle on the thickness changes and strength exerted on the tool. Likewise, Bagudanch et al. [12] analyzed using a design of experiments the importance that have the depth increase, the spindle speed, the feed rate, the tool diameter and sheet thickness, on the formability forces, on the greatest depth reached and surface quality in polyvinyl chloride sheets (PVC). Additionally, Radu et al. [13] evaluated the efficiency of two optimization methods in order to improve dimensional accuracy by setting an appropriate combination of parameters. Finally, other authors [14-16] have focused their research on finding the greater formability angles and Centeno et al. [17] concluded that SPIF formability increases when the diameter of the tool is reduced.

Several parameters mentioned above contribute to obtain different surface quality values, which are measured in microns (µm) by the characterization of the average roughness Ra. It is defined as the set of irregularities that has a surface during the manufacturing process. [18] This being a key control variable in the process, several authors have focused their efforts particularly on how to obtain a better surface finish with specific parameters. Studies by Ham et al [19] showed that the internal roughness is affected by the tool diameter and depth increase. Hagan and Jeswiet [20] analyzed the parameters of spindle speed and depth increase and concluded that the surface finish can be seen as ripples on a large scale created by the tool paths, which disappear with the decrease of the depth increase. Echrif and Hrairi [21] in addition to examining the two parameters above, analyzed the feed rate and the tool diameter, obtaining that the feed rate and spindle speed are not significant in changing the roughness. Liu et al [22] considered the parameters: feed rate, depth increase, tool diameter and sheet thickness, proposed an optimization model and concluded that the sheet thickness is the parameter that most influences the roughness followed by the depth increase. Durante et al. [23] considered the depth increase, tool diameter and the wall angle. They evaluated the roughness and conducted a predictive model. The results were compared experimentally, thus obtaining an error below 10%. Powers et al. [24] chosen speed rate and path direction and showed that the roughness is greater in the marks left by the tool perpendicular

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to the path direction. Lasunon et al. [25] evaluated the effects of the three parameters using a factorial design and showed that the depth increase, wall angle and the interaction between them are significant in changing the roughness.

Moreover authors as Caddell and Hosford [26] ensure that the internal roughness affects the external surface finish as a defect known as orange peel. Also, Hamilton et al. [27] have investigated the influence of the feed rate and high spindle speeds in such defect. This occurs on the outside of the part when the forming tool is in contact with only the inside part and is characterized by giving a rough appearance to the surface which can be seen with the naked eye.

By the above, it is known that in the process (SPIF) some of the parameters are more related to the change in the roughness than others, for that reason the purpose of this study derived from research project funded by the Universidad EAFIT and entitled: "Development and simulation of the forming process of sheet metal SPIF - DPIF" is to investigate the influence that has the variation of three process parameters and determine which of them contributes in greater proportion to the change in the average roughness (Ra) measured parallel and perpendicular to the path followed by the tool independently. In the first, it wants validate the effect on the texture of the surface which leaves the feed rate and spindle speed and in the second, to validate the effect given by the depth increase on this control variable. In addition, it wants to confirm the impact that has the spindle speed in the orange peel defect.
The design of experiments (DOE) is taken as a methodology for statistical analysis, because it is widely applied to the study of production processes. This has a variety of suitable experimental strategies to generate the information sought, full factorial design 2^k is one of them. This is apt to know what effect have k factors on a response variable.

2. TOOLS Y METHODS

2.1 DESIGN OF EXPERIMENTS AND PARAMETERS

It is performed a design of experiments full multifactorial with three factors, two levels (2^3), and three replicates which are the number recommended by the literature, these are the reiteration of the measure roughness. With this, the effects of uncontrolled variables can be compensated. The chosen factors and the experimental domain are shown in Table 1. These have been regarded as important parameters in the process and the values taken by the levels are within the range of values used by several of the aforementioned authors. The experimental domain of a factor is expressed by the minimum and maximum values that can take the parameter evaluated, and the coded notation -1 to lower level and +1 to upper is assigned. Additionally the value of (RPM) zero to evaluate the process with and without spindle speed is included.

	Factors	Experimental domain	
		Level (-)	Level (+)
A:	Spindle speed (RPM)	0	1500
B:	Feed rate (mm/min)	2000	3500
C:	Depth increase (mm)	0.5	1

Table I. Factors y experimental domain.

To see the effects of the factors is sufficient to vary them together between the ends of the experimental domain [28]. This will show whether the effect on the change of roughness depends on the combination of all factors or is independent, as indicated in the matrix of experiment shown in Table 2.
Subsequent to obtain measurements of the roughness in three replicates provided, it proceeds to execute a variance analysis using a statistical software.

2.2 MATERIALS AND PROCEDURE

The SPIF process begins of the design of a geometry in a system of computer-aided design (CAD), for the case study is chosen a pyramidal shape. After, a simulation process is performed in a system of computer aided manufacturing (CAM) and it is obtained the paths which the tool will travel. They were created two paths with value of depth increase of 0.5 to 1 mm. Finally, the assembly is running on a computer numerical control (CNC) milling center with three axes

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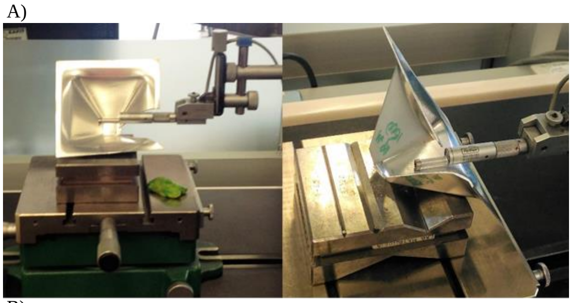
and parameters are programmed with respect to the experiments matrix. Supply used is aluminum sheet AL1100-H0 of dimensions 110 mm x 110 mm with a thickness of 1 mm and mechanical properties E (GPa) = 69, Y (MPa) = 62, UTS (MPa) = 90 εr (%) = 35. The tool is a round shaft of spherical tip of hardened steel of 8 mm in diameter and as a lubricant cooling oil is used. The above and geometries obtained are shown in Fig. (2a).

2.3. - SURFACE ROUGHNESS MEASUREMENT

The device for measuring the roughness is known as roughness tester, this comprises a diamond-tipped probe with a radius of 2.5 or 10 µm. which runs a small sampling length on the studied surface as shown in Fig. (2b). The normalized values of said length are 0.08, 0.25, 0.8, 2.5, 8 and 25 mm, 2.5 mm is chosen for measurement in the pieces obtained.


A)

B)
Fig.2. (A) CAD design, CAM paths, assembly and geometries obtained.
(B) Measurement the average roughness Ra horizontally (left) and perpendicular (right) to the tool path.

With this device are obtained the average roughness (Ra), which is specified as the sum of the absolute values of the areas enclosed by the roughness profile and its mean line divided by the sample length; average roughness (Rz), defined as the value obtained by averaging the resulting difference between the highest peak and the deepest pothole in each of the five sections in which the sample length is divided; and roughness (Ry) stated as the maximum distance between the highest peak and the deepest pothole [18]. The average roughness (Ra) was chosen as the parameter measurement due to use in the most manufacturing processes. This will be measured in parallel to the toolpath direction, because what is sought is to evaluate the influence of the feed rate and spindle speed on the tracks obtained in the material after executing the process and see the effect that has the combination of the parameters in the orange peel default. Additionally it will be measured perpendicular to the trajectory in order to compare the results with previous studies cited.

2.4. - STATISTIC ANALYSIS

With the data obtained by measuring the roughness and the matrix exposed in Table 2, the analysis of variance (ANOVA) with significance level of 5% ($\alpha = 0.05$) is performed, this employs the reason of estimates F created by mathematician Ronald Fisher (1890-1962). The analysis is performed in order to check the following hypothesis:

H0: The effects of A, B, C, AB, AC, BC, ABC are zero; not significant.

H1: One of them is different from zero.

The null hypothesis assumes that if all effects at all levels of the factors are zero, all the means of all groups considered are equal and equal to the overall average and not have any interaction. If the proof value (P-value) obtained in the analysis is less than α is concluded that the corresponding effect is statistically different from zero, that is to say, this effect has a significant influence on the response and the smaller the value, the more important is this effect. It can also be concluded by comparing the calculated F value with the respective table. H0 is rejected, if the calculated F is greater than F of the table.

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3. RESULTS

In Fig. (3) surface finishes on parts obtained are presented. Good results are obtained in terms of formability, since no cracks and wrinkles occurred. Additionally the appearance of orange peel defect on the outside of the workpieces with (RPM) equal to 1500 (pieces 2, 4, 6 and 8) is evidenced.

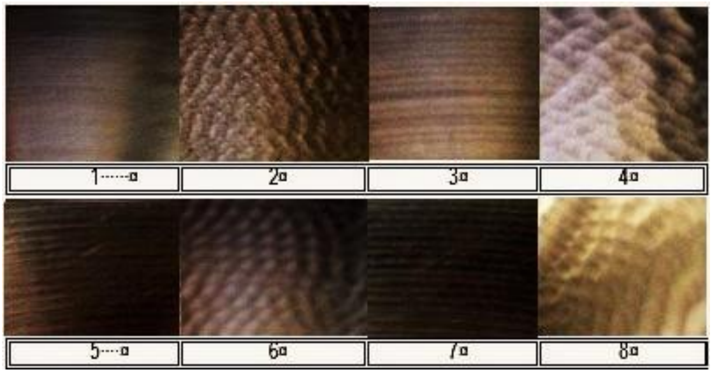

Fig.3. Surface finish obtained in experimental pieces.

The results of measurement parallel and perpendicular to the path are shown in Table 2, significant differences in the average roughness values (Ra) between both measurements are perceived.

Experiments matrix				Experimentation			Horizontal measurement (µm)			Vertical measurement (µm)		
	X1	X2	X3	Spindle speed (RPM)	Feed rate (mm/min)	Depth increase (mm)	Replica I	Replica II	Replica III	Replica I	Replica II	Replica III
1	-	-	-	0	2000	0,5	0	0,1	0,1	1,3	1,2	1,4
2	+	-	-	1500	2000	0,5	0,9	0,7	0,8	2,2	1,8	1,7
3	-	+	-	0	3500	0,5	0,1	0,1	0,1	1,1	1,2	1
4	+	+	-	1500	3500	0,5	0,3	0,3	0,4	2,9	2,9	3
5	-	-	+	0	2000	1	0,1	0,1	0	3,1	2,9	3
6	+	-	+	1500	2000	1	0,9	0,7	0,9	2,8	2,9	3
7	-	+	+	0	3500	1	0,1	0	0,1	2,7	2,9	2,8
8	+	+	+	1500	3500	1	0,6	0,3	0,4	2,4	2,7	2,9

Table 2. Experiments matrix, experiments performed and results of average roughness Ra measurements horizontal and vertical.

The analysis of results of the design of experiments based on the parallel measurements are presented in Fig. (4).The Pareto diagram Fig. (4a) showing the absolute value of the effects with the reference line indicating if the effect is greater than her is important, it is inferred that the parameters that contribute to change in the roughness of the workpiece are only spindle speed with a value of effect of 14.85, the feed rate with a value of 5.84 and finally the interaction between them with value of 6.36. Also, it shows that the depth increase has no significant effect, this was expected since roughness measurement was performed parallel to the path. The contribution by percentage of the effects and their interactions are shown in standardized effects graphic, spindle speed reaches a value of 90%, the feed rate of 64% and the interaction between them 78%. The proximity of the blue dots to the fitted line due to parameters and interactions that have no effect.

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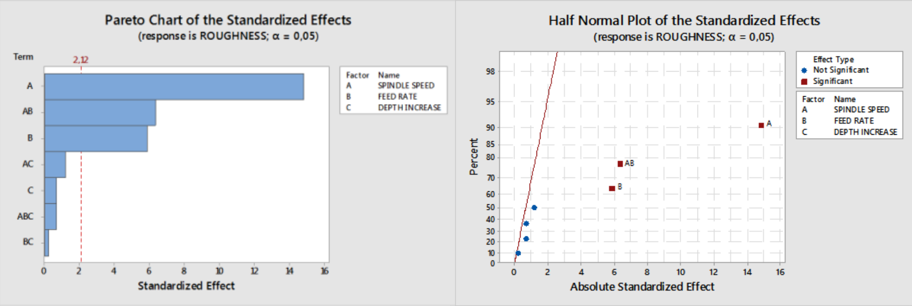
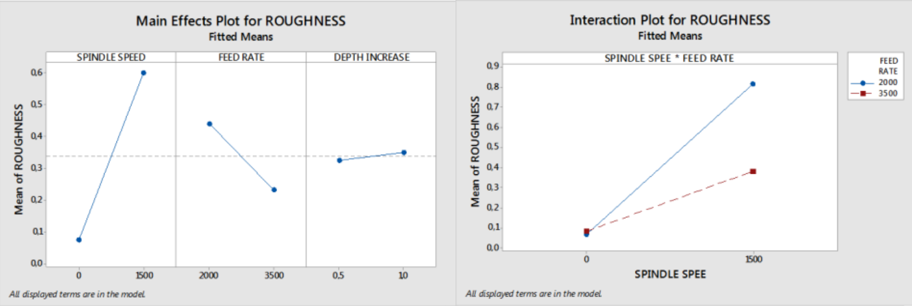


A)



B)

Fig.4. (A) Pareto Chart (left) and Standardized effects (right). (B) Main effects plot (left) and interaction plot of the analyzed parameters (right).

The main effects plot Fig. (4b) follows that the spindle speed affects in good proportion to the average roughness measurement as its slope is really steep. When rotation of the tool had a value of 1500 (RPM), the pieces showed an average roughness of 0.6 µm, however, when the tool did not have rotation a measurement of 0.1 µm was obtained. The effect of the feed rate is less than the previous parameter because it has a moderate inclination of its slope, in fact with this variation, average measurements from 0.25 to 0.45 µm is reached. The interactions graph shows the average roughness values with the combination of both significant parameters; with the parameters in their levels +1 average roughness values of 0.35 µm are reached, with these in levels -1 values of 0.1 µm are obtained and the spindle speed at +1 and feed rate at -1 values of 0.9 µm are achieved.

The results of the (ANOVA) are presented in Table 3. This shows the results of the sum of squares (SS) of the mean squares (MS), the test statistic F and proof values (P-value) for each parameter and interactions.
For the significant parameters it is observed that the (P-value) is zero, this compared with the significance level $\alpha = 0.05$, makes the null hypothesis is rejected, the alternative hypothesis is accepted and it is concluded that the effects of the two parameters set forth and their interaction are statistically significant in the change of average roughness (Ra).

ANALYSIS OF VARIANCE

Components	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	2,2363	0,3195	42,6	0
Linear	3	1,9179	0,6393	85,24	0
Spindle speed	1	1,6538	1,6538	220,5	0
Feed rate	1	0,2604	0,2604	34,72	0
Depth increase	1	0,0038	0,0038	0,5	0,49
2-way interactions	3	0,3146	0,1049	13,98	0
Spindle speed * Feed rate	1	0,3038	0,3038	40,5	0
Spindle speed * Depth increase	1	0,0104	0,0104	1,39	0,256
Feed rate * Depth increase	1	0,0004	0,0004	0,06	0,817
3-way interactions	1	0,0038	0,0038	0,5	0,49

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Spindle speed * Feed rate * Depth increase	1	0,0038	0,0038	0,5	0,49
Error	16	0,12	0,0075		
Total	23	2,3563			

Table 3. Result of analysis of variance.

The analysis of results of the design of experiments based on the perpendicular measurements are shown in Fig. (5). According Pareto diagram, the parameters that influence the change of roughness are depth increase, the spindle speed, the respective interaction between them and the interaction between all the parameters, with effect values 16.57, 8.81, 10.69 and 5.08 respectively. Similarly, it is evident that the feed rate parameter by itself has no a significant effect. In the graph of standardized effects the biggest percentage contribution is given by the depth increase, followed by the interaction between this and the spindle speed, and the latter, with values of 90.54, 77.03 and 63.51% respectively. All interactions provide values lower than 50% and the feed rate has only an effect of 9.46%.

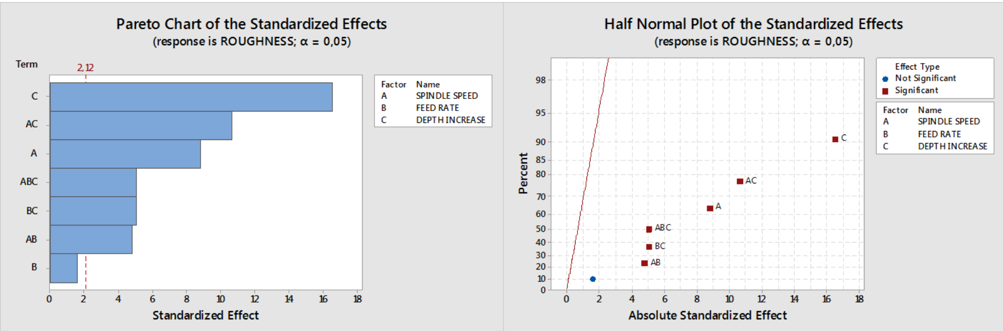

Fig.5. Pareto chart and Standardized effects plot.

4. - DISCUSION

According to the results in the tables and the analysis of experiments, it follows that the average roughness (Ra) measured parallel to the toolpath is greatly affected by the parameter spindle speed followed by feed rate, and the workpieces worked without spindle speed (pieces 1, 3, 5,7) exhibit no undulations marks. Values average roughness (Ra) were obtained much lower than those obtained when spindle speed was used as 1500 (RPM) (see Table 2), this contrasts with the statements made for the authors Durante et al. [29]. Also making a qualitative analysis of the orange peel defect in the pieces obtained, is evidenced that it disappears on the outer face of the parts listed above, so the use of the process without spindle speed it is advisable. However, this also opens the way to investigate as hypothesis for future research, the effects involved making the SPIF process with the tool without rotation, for which it plans to conduct detailed studies on the microstructure of the worked sheet, studies also analyze if a critical tool wear occurs during the process, and assess whether significant energy savings are obtained when the process is performed without spindle speed. All this in order to make a greater and enriching scientific contribution to continue arguing the applicability of the process and increasingly strengthening its industrial viability.

As proposed by Powers et al. [24], the analysis of roughness measurements performed in both directions indicate higher values of this for measurements made perpendicular to the path followed by the tool. Table 2 shows that for parallel measurement roughness values between 0 and 0.9 µm were obtained, and for those made perpendicularly values were reached between 1.1 and 3.1 µm. Meanwhile the analysis of the (DOE) executed to the perpendicular measurements states that the depth increase is the parameter that most affects the change in roughness and the feed rate is the only parameter that has no significant effect, this confirms what said by the aforementioned authors [19-22], [25]. However for the developed study case in this research, the spindle speed parameter also has a significant effect according to Fig. 5, situation that requires a future detailed analysis.

5. CONCLUSIONS

A multifactorial design of experiments was developed in order to evaluate the influence that has the change in roughness the parameters spindle speed, feed rate and depth increased. It was found that the spindle speed affects the

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value of this measured both perpendicular and parallel with a greater effect in the latter. It was also revealed that the feed rate only affects the obtained roughness in a parallel direction. Similarly, it was found that by not using (RPMs) the orange peel defect is not presented, since in the internal face of the part, undulations marks left by the tool when is in rotation are displayed as they presented in the workpieces with spindle speed.

The feed rate has a significant effect only in the change of roughness measured parallel but is insignificant as far perpendicular. Besides this, the roughness values obtained perpendicular are significantly higher than those achieved in parallel, this is because the depth increase generates a highly significant effect on the measurements and is not considered in parallel measurement.

The interaction between all the parameters in the design of experiments shows that these have effects between 20 and 50% on the change of roughness measured perpendicularly. Moreover only the interaction between the parameters spindle speed and feed rate generates an effect on the change of roughness measured parallel.

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