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The Effects of Process Parameters on Residual Stresses in Single Point Incremental Forming of A1050 Aluminum Using ANOVA Model

Abstract- *Incremental sheet metal forming is a modern technique of sheet metal forming in which a uniform sheet is locally deformed during the progressive action of a forming tool. The tool movement is governed by a CNC milling machine. The tool locally deforms and by this way the sheet with pure deformation stretching. The aim of the present work is to inspect, experimentally, the state of the residual stresses induced in SPIF parts made by A1050 aluminum. The forming surface was measured at four different angles using a ORIONRKS 6000 test (the X-ray diffraction technology was used to detect the residual stress) measuring instrument with the angles (0o, 15o, 30o and 45o) and the average residual stress value is recorded in (MPa), the residual stress in original blanks is (-6.29MPa). This specialized stress analysis system using the side-inclination method includes stress analysis software, the stress analysis sample stand and X-ray tube. A comparison study is made for tabulated values and experimental values for residual stress by using ANOVA model with the contribution of rotational speed, feed rate and forming depth with respect to residual stress is (63.7, 4.3 and 32)% respectively..*

Keywords- *ANOVA, CNC milling machine, machining parameters, residual stress, Taguchi method.*

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1. Introduction

Single point incremental forming (SPIF) used simple and cheaply made tools to locally deform a sheet of metal along a pre-defined tool path without using of dies. This process can be carried out by CNC milling and requires very simple tooling. The important process parameters that affect the product properties using this method of forming process are rotational speed, step depth, tool diameter, feed rate, wall angle, friction, and tool path. The limitations of this process are less geometrical accuracy and more processing time over conventional forming types; so many researchers attempted to solve this problem by using different types of analysis methods to predict and optimized the best process parameters that give good surface accuracy and mechanical properties. Figure 1 illustrates the diagram of incremental sheet forming (ISF). [1]

There are several optimization methods such as simulated annealing algorithm, genetic algorithm, neural network, Taguchi technique etc. to find optimum forming variables. Taguchi technique is best method to be defined and also easy to performed.

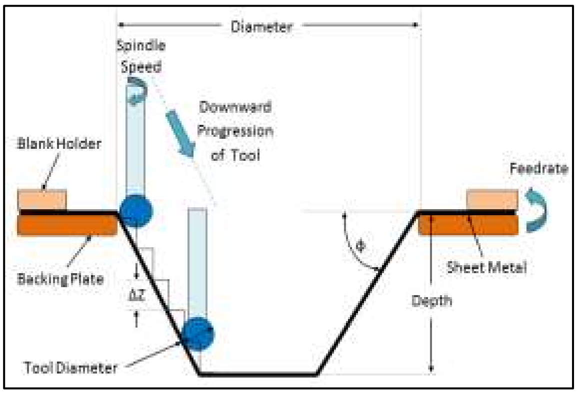

Figure 1: Principle of the single point incremental forming process.

2. Literature survey

There are several issues that need separate discussion as peoples around the world are trying to optimize the ISF process the governing process parameters. The concerned issues (forming forces, formability, geometric accuracy, surface quality, and mechanical properties etc.) are discussed briefly.

Radu (2012) [2], analyzed the relation between the accuracy of parts product by SPIF and the distribution of residual stresses induced in

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material as a function of different values of forming parameters. The hole drilling strain gauge method is used to find the residual stresses distribution in sheet thickness and the results are correlated with the standard deviations of formed parts. The experimental tests are performed for DC01 carbon steel.

Fontanari, et al. [3] investigated their work by means of a numerical and experimental approach. A Finite Element (FE) model has been developed and validated by comparison with experimental data measured during the process (forming forces) and on the finished component (strain distribution and final shape). Radu et al. [4] presented the distribution of residual stressed in part formed by single point incremental forming (SPIF) to determine its influence on the part accuracy and as a function of the working parameters. Crina et al. [5] showed that the residual stresses founded in SPIF part made by Al-alloy. They studied a double cone. The experimental measurement of the residual stresses was applied using the hole drilling method.

The aim of this work is to inspect, experimentally, the state of the residual stresses induced in SPIF parts made by A1050 aluminum. After that, a comparison study is made for tabulated values and experimental values for residual stresses by using ANOVA model with the contribution of rotational speed, feed rate and forming depth with respect to residual stress.

3. Experimental Work

I. Material and Process

Samples of (Al 1050) aluminum metal sheets, 225 x 225 x 0.9 mm, were used to perform the experiments (9-samples). The geometry of part is shown in figure (2).

The experimental work was applied using oil lubricant on a C-tek three-axis (KM-80D), CNC milling machine equipped with a maximum rotational speed of 6000 rpm, feed rate of 10 m/min. CNC part programs for tool path was created. The experimental work of the work piece for hem-spherical tool is illustrated in Figure 3. The chemical composition and mechanical properties of this Aluminum (Al 1050) is illustrated in tables 1 and 2. For forming operation, the tool used for performing is tool steel (12mm diameter). While the experimental steps of the present work is illustrated in Figure 4.

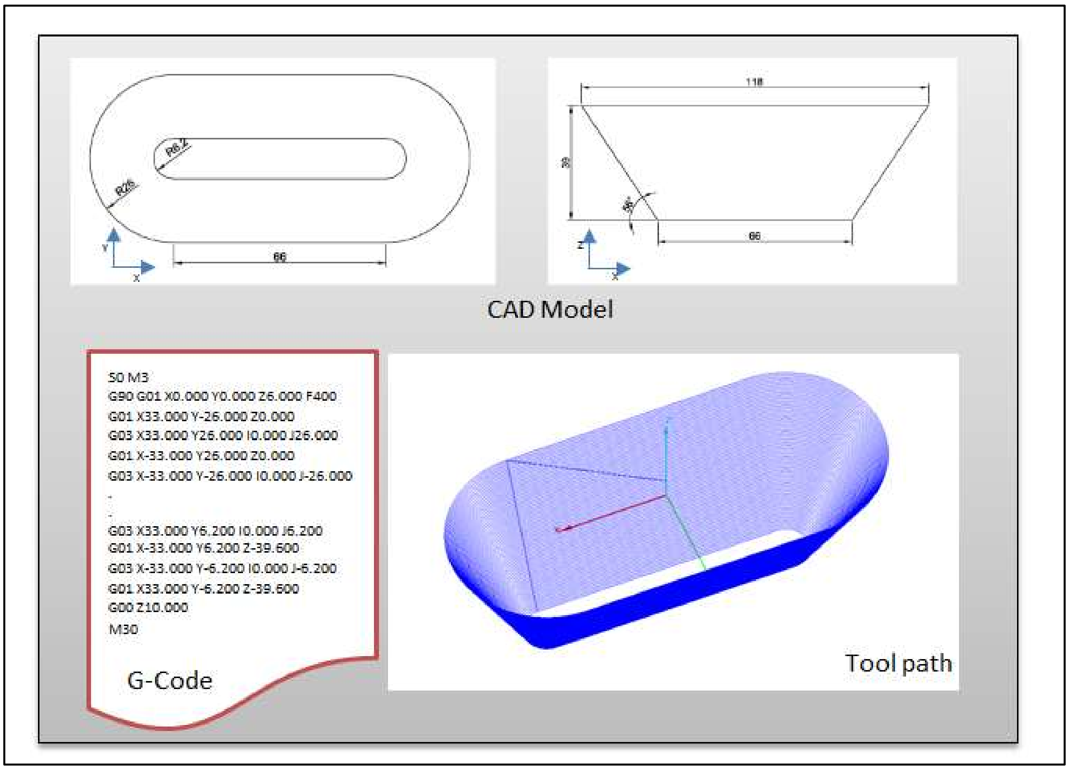


Figure 2: Geometry of part and part program

Figure 3: The experimental setup and nine-samples

Table 1: Chemical composition of Al 1050 alloy (wt %)

Elements	Al	Cr	Cu	Fe	Mg	Mn	Si	Ni	Zn
Percentage %	99.5	0.001	0.013	0.315	0.001	0.013	0.142	0.003	0.006

Table 2: Mechanical properties of Al 1050 alloy

Ultimate Strength (MPa)	Yield Point (MPa)	Elongation (%)	Hardness (HBR)
80-100	65-78	35-42	20-30

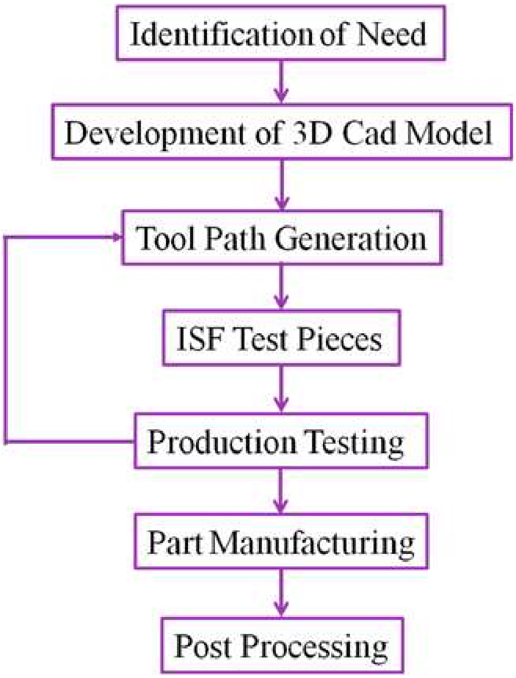


Figure 4: Sequence of the present work.

II. Theoretical consideration of residual stresses

Residual stresses are those that stay in a structure that is fixed and at equilibrium with its circumference. They can affect the mechanical action interact with external loads, with respect to how residual stresses react with exterior force; they can impact on life time of components and the mechanical behavior in negative or a positive way. For instant surface compressive residual stresses will get better fatigue strength since the residual stress and applied stress are additive compared with the tensile residual stresses are detrimental to fatigue resistance and in the presence of a corrosive medium may cause stress corrosion cracking, even in the absence of an applied load. [6]

The main limitation in sheet metal forming is the effect of residual stresses that cause reduced product accuracy of a product due to distortion. In (SPIF) this effect is even more pronounced since no support for the metal sheet is used during forming and, then, large value of forming occur, which in turn, induce highly non-uniform residual stresses. [7].

III. Residual stress test

The forming surface was measured at four different angles using a ORIONRKS 6000 test (the X-ray diffraction technology was used to detect the residual stress) measuring instrument with the angles (0o, 15o, 30o and 45o) and the average residual stress value is recorded in MPa that illustrated in Figure 5, the residual stress in original blanks is (-6.29) MPa.

This specialized type of stress analysis system using the side-inclination method includes stress analysis software, the stress analysis sample stand and X-ray tube. X-ray stress analysis is widely used to measure the level of stress in substances. In the X-ray diffractometry of stress, very small changes in the lattice space are measured from the X-ray diffraction pattern profile. The precise measurement of the residual stress allows the use of the special stress analysis stand associated with the side-inclination method. Free of absorption error is used in this technique. The software includes the following functions, as measurement, peak position calculation, width at half height and stress calculation depending on the type of reflective plane and sample, either the Co tube or Cr X-ray tube is necessary.

The acting single stress measure in four ways in the surface σϕ shows an isotropic solid that the strain along an inclined line according to elasticity theory (m3 in Figure 5) is [8]:

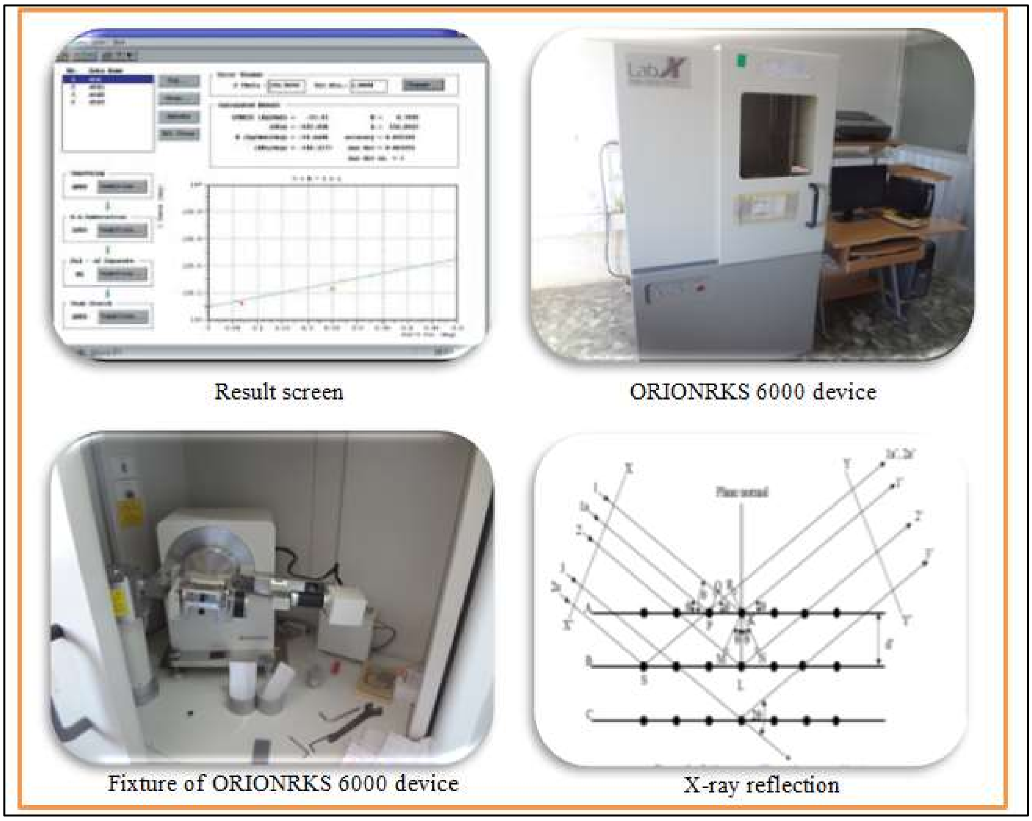
$$\varepsilon_{\phi\psi} = \frac{1+\nu}{E}\left(\sigma_1 \cos^2\phi + \sigma_2 \sin^2\phi\right)\sin^2\psi - \frac{\nu}{E}\left(\sigma_1 + \sigma_2\right) \qquad (1)$$

The strains are used to evaluate the stresses when take the strains in terms of inter-planar spacing and then it can be shown that

$$\sigma_\phi = \frac{E}{(1+\nu)\sin^2\psi}\left(\frac{d_\psi - d_n}{d_n}\right) \qquad (2)$$

ϵϕψ: Strain measured in the ϕψ direction
v: Poisson's ratio
E: Elastic modulus (GPa)
σ1, σ2: Principal stresses (MPa)
ϕ: Angle between the direction the sample and the projection in normal of the diffracting plane (deg.)
ψ: Angle between the normal of the diffracting plane and the normal of the sample.(deg.)
dψ: Inter-planar spacing at angle ψ (Å)
dn: Inter-planar spacing of normal surface (Å)

Eq. (2) is used to determine the stress from two strain measurements made in the direction of the stress to be found and a plane normal to the surface. At different psi tilts, a number of XRD measurements are made. The 2-theta peak position or inter-planar spacing is tested and plotted that illustrated in Figure 5.



Result screen ORIONRKS 6000 device
Fixture of ORIONRKS 6000 device X-ray reflection

Figure 5: Set up for residual stress measurement and residual stress analysis result screen

4. Design of experiments

Taguchi algorithm became a good tool to improve productivity through research and development in recent years, thus at low cost that can be produced High-quality products rapidly. With a small number of experiments Taguchi method uses a special design of orthogonal arrays to study the entire parameter space. At three levels the methodology of Taguchi is used for three factors that implementation of the plan of testing. To define the nine trial conditions, the six degrees of freedom was used at this study and Taguchi's (L9) orthogonal array. The levels and process parameters are illustrated in table 3. The average response and Replicated twice values for each of the nine trials or process designs are used for this work. Table 4 illustrates the present work and the tests results, and Figure 6 presents the relationship between experimental data.

Table 3: Forming parameters and their levels

Parameters	Unit	Level 1	Level 2	Level 3
Rotational Speed (S)	Rev/min	0	400	800
Feed Rate (F)	mm/min	400	700	1000
Depth Size (D)	mm	0.3	0.6	0.9

Table 4: Experimental layout using L9 orthogonal array and corresponding results

Exp. No.	Forming Parameters			Average Response Values
	Spindle speed rev/min	Feed rate mm/rev	Depth of cut mm	Residual Stresses
1	1	1	1	70.495
2	1	2	2	50.187
3	1	3	3	67.825
4	2	1	2	33.937
5	2	2	3	56.606
6	2	3	1	28.344
7	3	1	3	58.854
8	3	2	1	53.389
9	3	3	2	49.922

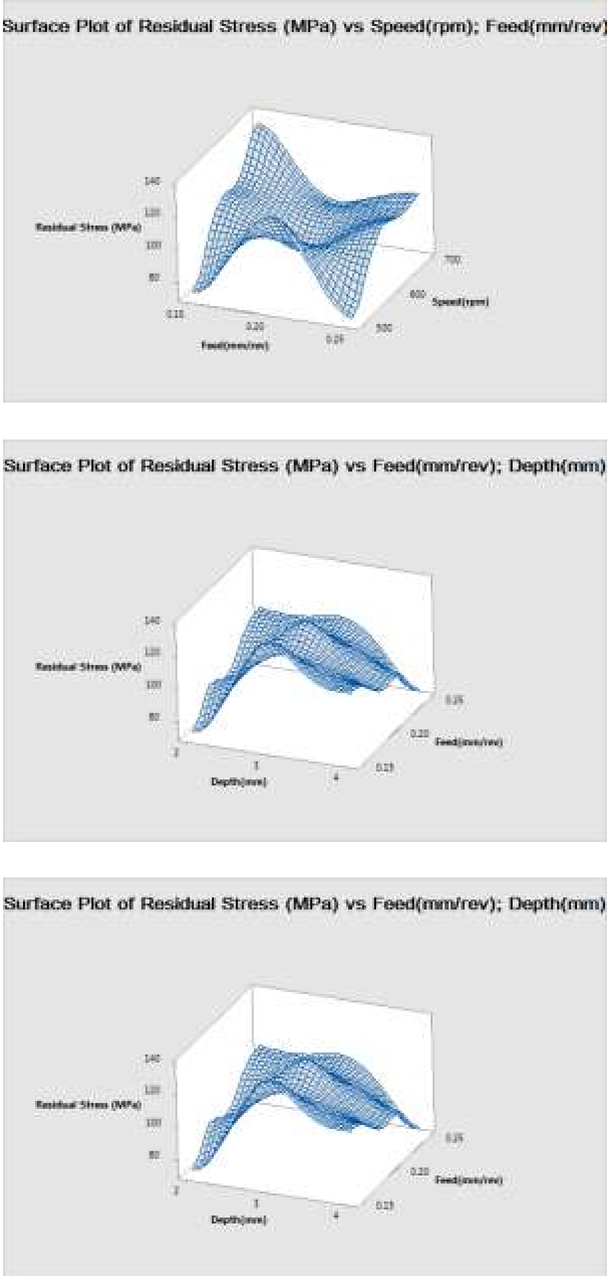


Figure 6: Relationship between residual stress and process parameters.

5. Optimization of forming parameters

To gather the experimental data, Taguchi approach is employed. Then, the best set of forming parameters has been found according to signal to noise (S/N) ratio. Using these parameters values, the residual stress of Al1050 parts may predict, optimum process parameters that are required that found for efficient use of forming tools. The SPIF process parameter optimization is time consuming and highly complex. Taguchi parameter optimization methodology is applied in this work to optimize process parameters in SPIF process.

As stated above, for performance characteristics there are three categories, i.e., the higher-is-better, the nominal-is-better and the lower-is-better. For optimal performance conditions, they should take the lower-is-better performance characteristic for residual stress. Equation (3) is used to calculate the (S/N) ratio. Since the experimental design is orthogonal, it is then possible to separate out the influence of each process parameter at various levels. For each level of the process parameters the mean S/N ratio can be computed that called the mean S/N response table for residual stress and summarized in table 5. In addition, the ANOVA results for the nine experiments is also calculated and listed in table 6.

By using the best type, the response is given by:

$$S/N\ ratio = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} Y_i^2\right] \quad (3)$$

Where, i = no. of trial,

Yi = measured value of quality characteristic for ith trial condition,

n= no. of repetitions.

$$DOF\ withingroup = E - 1 - S \quad (4)$$

Where E=No. of experimental tests.

S=Sum of degree of freedom for process parameters.

Using above equation, the signal to noise ratios for each of the nine experimental conditions are calculated. In terms of mean response and in terms of S/N ratio can be separated the factors affected out.

The relationship among forming parameters and the mean response and S/N ratio are illustrated in Figures 7 and 8 respectively. Figure 9 illustrates the variance of residual stress with respect to three process parameters.

Table 5: Results for individual characteristic of mean response and S/N ratio

	Mean response			S/N ratio		
	Speed	Feed	Depth	Speed	Feed	Depth
Level 1	36.90	47.80	51.07	28.44	32.71	33.54
Level 2	28.50	27.30	25.80	28.44	27.84	27.60
Level 3	28.830	19.13	17.37	28.43	24.76	24.17
Delta	8.40	28.67	33.70	0.01	7.95	9.36
Rank	3	2	1	3	2	1

Table 6: ANOVA results of residual stress.

Source of variance	Degree of freedom	Sum of squares, ss	Variance, V	Contribution on (P), %
Rotational Speed (S)	2	823.759	411.879	63.7
Feed Rate (F)	2	55.984	27.992	4.3
Depth Size (D)	2	413.289	206.645	32
Within group	2	262.799	131.399	20.3
Total	8	1555.831		100

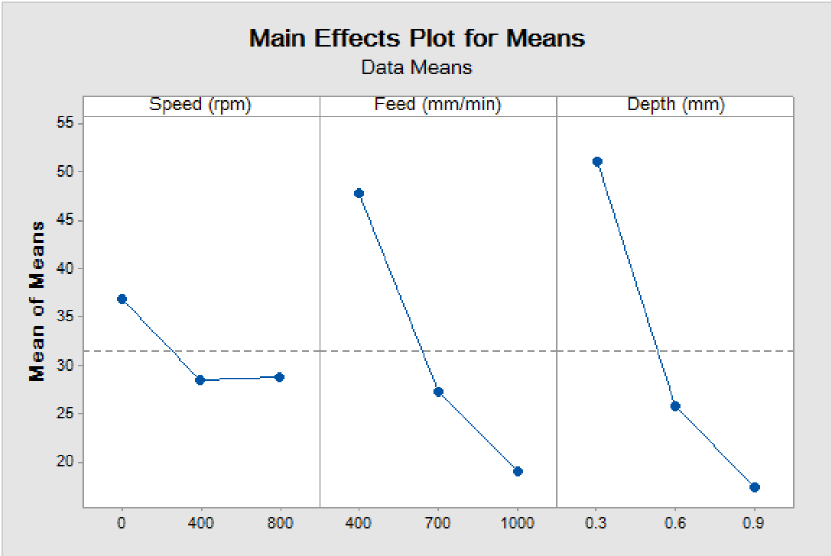


Figure 7: Relationship among mean residual stress and process parameters

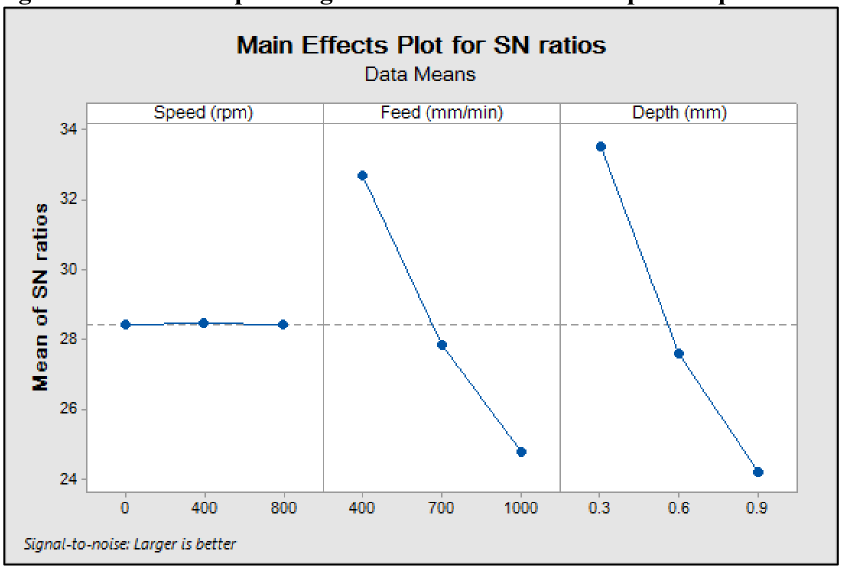
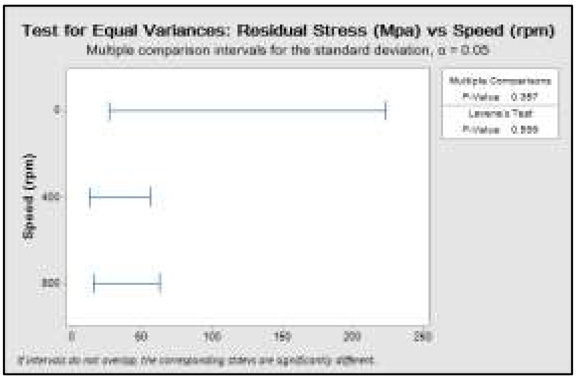
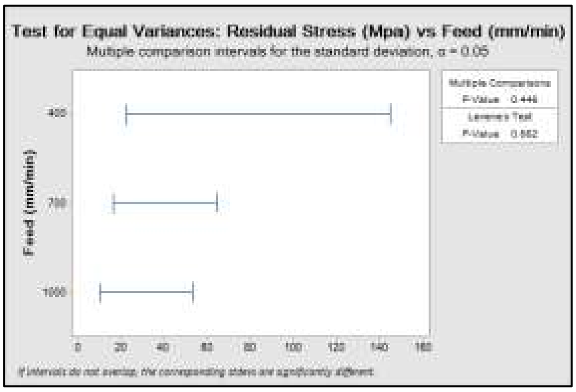


Figure 8: Relationship between S/N ratio and process parameters





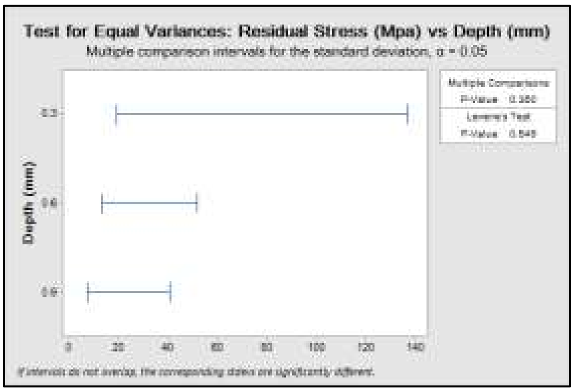


Figure 9: Variance of residual stress with respect to process parameters

6. Conclusions

1. The optimum parameter level for minimized residual stress at 1st level is rotational speed (S) parameter, the 2nd level is feed rate (F) parameter and 3rd level is forming depth (D) parameter. The level of parameters that implies at designated levels as S1, F2 and D3 are the best combination to get minimized residual stress in SPIF process of Al1050.
2. High values of the forming depth led to high values of residual stresses which in turn caused high values of standard deviations of the formed parts geometry from the theoretical geometry.
3. The increase of rotational speed causes a more uniform distribution of residual stresses which amounted to a slight increase of part accuracy.
4. A comparison study is made for tabulated values and experimental values for residual stress by using ANOVA model that indicated the contribution of rotational speed, feed rate and forming depth with respect to residual stress is (63.7, 4.3 and 32)% respectively.
5. The analysis of variance showed that the rotational speed is definitely the most important parameter, followed by the feed rate and forming depth that influences the multiple performance specifications.

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