Investigation of Surface Roughness in Incremental Sheet Forming of AA 2014-T6 using Taguchi’s Method

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Abstract. Aluminium alloy “AA 2014-T6” has widespread applications in aerospace industry and also used for making military weapons. This paper proposes incremental sheet forming as a newer and cost effective approach over the conventional die forming for making AA 2014-T6 components in lesser time. The quantitative effects of three levels of seven input parameters namely — type of tool path (profile and spiral), sheet thickness (1.2 mm, 2 mm and 2.3 mm), spindle speed (0 rpm, 100 rpm and 200 rpm), tool diameter (16 mm, 18 mm and 20 mm), step size (0.3 mm, 0.5 mm and 0.7 mm), feed rate (1500 mm/min, 2000 mm/min and 3000 mm/min) and type of lubrication (coolant, oil and grease) are analysed over the “surface roughness”. Further, Taguchi technique has been utilized for designing the experimentatio and finding the trends of variation in output response with change in individual factor. Sheet thickness and spindle speed emerged as the most influencing parameters in determining the final quality of fabricated parts. Zero spindle speed (free tool rotation) turned out most critical because at this level wear particles are stuck between sheet and tool, which degraded the surface due to unwanted abrasion.

1. Introduction

There are many traditional forming processes, which are used by industry; some of them are stamping, deep drawing etc. These processes need high initial investment and long set-up time [1]. Therefore, in order to address these issues existing in traditional forming processes, a new process called Incremental Sheet Forming (ISF) is being explored by researchers to establish it as low cost pragmatic solution on industrial scale. In this process a relative motion is provided between sheet metal and forming tool for shaping the sheets. This process can be efficiently used for small batch production without needing any extra machining set-up as general purpose machine tools like milling machine and lathe are easily available in small scale industries that can be used for ISF. ISF process is used to make complex 3-D parts with die-less tools and fixture. As there is no die used in this process, so, it provides economical alternative for small volume fabrication of components of various sizes especially the smaller to medium ones from metal sheets. Incremental sheet forming process also provides a good alternative for small batch production to deal with various needs like low die preparation time and low setup cost. Therefore low tooling cost without the need of dies give upper hand to ISF for making complicated parts and large diversified product.
Optimization of any process is much needed in the environment of worldwide competition. Therefore, to improve the quality of product and reduction of running costs it is necessary to optimize surface shining, shape, geometrical accuracy, weight and force required depending upon the product application.

In incremental sheet forming technique, principle of layer by layer deformation of sheet blank is applicable. In this process combined CAD/CAM system is used and locus of spherical tool moves through horizontal slices. This technique is performed by CNC milling, CNC lathe and special purpose machines. Fixture is used to clamp the sheet metal and hemispherical tip tool is moved on a predefined path as shown in Figure 1.

![Figure 1. Incremental sheet forming process [2]](image)

A number of researchers have made a significant contribution to improve the different aspects of ISF for its adaptation on industrial scale. Kopac et al. [3] worked on aluminum and steel sheets using tool diameter and lubrication as input parameters on CNC milling machine. It was reported that small ball tool with grease as lubricant produced better surface finishing. Further aluminum surface finishing was found superior to steel due to higher hardness of aluminum to steel. Cerro et al. [4] worked on CNC milling machine to optimize the surface quality using tool path, step size and lubrication as process parameters. Surface finishing was found much better with tool movement in horizontal direction than in perpendicular direction. Lubrication was also found more influencing parameter than the tool path and step size.

Attanasio et al. [5] worked with two variations of tool path. In first type of tool path, step size was kept constant with variation in scallop height. In second type scallop height was kept constant and step size was varying. In former case, surface quality was better while in later case surface quality was found to be unsatisfactory. M. Durante et al. [6] worked on aluminum AA7075-T0 sheets and studied the impact of geometrical changes in workpiece shape. Surface roughness was not found to correlate with shape effect i.e. changing in geometry of the part had no influence over surface roughness. L. C. C. Cavaler et al. [7] considered tool diameter and varying step depth as process variables in their study. Step depth was found to have a profound impact on surface finishing. Authors also verified that TiAlN coated tool generated superior surface finish than uncoated tool. S. Chehian Babu et al. [8] found that tool diameter was more influencing parameter on surface finish than step size. Authors further stated that influence of tool diameter on surface finish was 10 to 15% more than that of step size. Zhaobing Liu et al. [9] used “response surface methodology” as optimization technique while conducting experiments on AA 7075-T0. After finding the optimized process variables, authors could yield surface finish of 0.32μm.
Vishal Gulati et al. [10] worked on Aluminum-6063 alloy to optimize the formability and surface roughness using Taguchi’s technique. Author inferred that lubrication was most dominating process parameter in affecting the surface finish followed by sheet thickness and spindle speed respectively. Surface roughness and wall angle optimum value obtained were 1.03µm and 88.29˚ respectively. Suresh Kurra et al. [11] found the effect of process parameters on thickness distribution and wall angle using L9 orthogonal array. Tool diameter emerged as most significant parameter in affecting the process performance.

Swagatika Mohanti et al. [12] worked on estimation of effect of tilted angle on wall angle and surface roughness. Surface roughness decreased with increase in tilted angle. It was also reported that with increment in tilt angle, surface roughness first decrease and increase after the critical value of tilt angle. Zhidong Chang et al. [13] estimated the effect of friction mode, feed rate and speed on surface roughness. It was inferred that poor lubrication and unsuitable combination of feed rate and tool rotation severely degraded the surface quality.

From the literature survey it can be concluded that there is scarcity of experimental investigation on ISF of aluminium alloy “AA 2014-T6”. Therefore, effect of various process parameters are little known on AA 2014-T6. Furthermore no previous study has investigated the combination of the process parameters namely types of tool path, tool diameter, sheet thickness, spindle speed, feed rate and type of lubricants on ISF performance in terms of surface roughness. Therefore, this study is an attempt to process the aluminium alloy AA 2014-T6 using ISF to observe the surface roughness of components under the abovementioned process variables.

2. Experimental Work

2.1. Workpiece material

AA 2014-T6 aluminum alloy sheets with thicknesses of 1.2mm, 2mm and 2.3 mm are used, which has widespread applications in manufacturing sector especially the aerospace industry. Other than that, It also used for making subparts of military vehicles, bridges, machinery, weapons and structural application. Therefore, its processing with incremental sheet forming process will add a valuable impact over industrial applications. It has high hardness and high strength as mentioned in table 1, so high amount of force is required to form a part using single point incremental forming.

| Sr. No | Property             | Value (Units) |
|-------|----------------------|---------------|
| 1     | Density              | 0.101 Lb/cu.in. |
| 2     | Specific Gravity     | 2.8           |
| 3     | Melting point        | 950 F         |
| 4     | Modulus of Elasticity| 72.4 GPa      |
| 5     | Shear Modulus        | 28 GPa        |
| 6     | Brinell Hardness     | 135           |
| 7     | Annealing Temperature| 775 F         |

2.2. Experimental equipment

Experiments has been performed on the BRIDGEPORT 2216 CNC milling machine as shown in Figure 2. The machine is 5-axis CNC vertical milling machine (VMC2216XV) with a maximum workspace of 550×400×500 mm3 and is capable of possessing maximum feed rate of 8000 mm/min. The process parameters that have been used for experimental investigation are given in table 2. Except the two levels of tool path, the remaining parameters have three levels. The range of these process parameters was based upon the preliminary experimentation and past literature as well [9, 10, 12, 14-16].
Figure 2. Experimental machine tool

Table 2. Process parameters and their levels

| Process Parameters (Units) | Levels         |
|----------------------------|----------------|
|                            | L₁  | L₂  | L₃  |
| Tool Path                  | Spiral | Profile | --- |
| Tool Diameter (mm)         | 16   | 18   | 20  |
| Sheet Thickness (mm)       | 1.2  | 2    | 2.3 |
| Step Size (mm)             | 0.3  | 0.5  | 0.75 |
| Spindle Speed (rpm)        | 0    | 100  | 200 |
| Feed Rate (mm/min)         | 1500 | 2000 | 3000 |
| Lubrication                | Coolant | Oil | Grease |

The hemispherical tip tool as shown in Figure 3(a) has been used for applying the forming forces on workpiece sheets. The lubricants used are machine oil, grease and coolant, which are mainly sprayed over the blank before the forming. Fixture used for rigidly holding the metal sheet has been shown in Figure 3(b).

Figure 3. (a) Hemispherical tip tool & (b) Fixture for ISF

2.3. Surface roughness measurement
The surface roughness of formed part is measured using digital instrument (Mitutoyo Surftest SJ-201P) as per ASTM standards [17]. The equipment has measuring range from 350µm (-200 µm to +150 µm)
and stylus material is of diamond, which traces the surface of formed parts and calculates the surface roughness as illustrated in figure 4.

![Surface tester and formed part](image)

**Figure 4.** Surface roughness tester

### 2.4. Research methodology

In ISF process, progressive deformation of sheet blank is carried out using single tool on CNC milling machine. 3-D profile is made by controlled movement of tool. Product is made using the standard procedure of 3-D CAD. A part programming used to exchange the data from CAD model to CAM, which is read by CNC milling machine to guide the tool to move along specified path. Fixture is used to attach the sheet material on machine table with the help of blank. To reduce the complexity of fixture design the component shape fabricated in current work was kept limited to truncated cone as shown in Figure 5. Taguchi technique has been used for statistical analysis and graphical representation to examine the effects of process parameters on surface finishing of fabricated components. Furthermore, graphs were generated using Minitab software package (version 17.0) to understand the variation in levels of process parameters on output response surface roughness.

![Truncated cone](image)

**Figure 5.** Truncated cone (Shape of part)

Tool path used during the forming process are Profile and Spiral both the tool path shown in Figures 6 and 7 respectively.

![Profile tool path](image)

**Figure 6.** Profile tool path [18]
2.4.1. Design of experimentation

Taguchi optimization technique differs from the factorial design of experimentation because it can reveal the process behaviour with the minimum number of trials; thus saving a lot of time as well as valuable resources [19].

Taguchi technique is used for modeling, analysis and optimization. Orthogonal arrays are used for modeling of the experiments. Degrees of freedom (DOF) for current study were 14, So, L18 orthogonal array is selected as the orthogonal array as the experimental array should be greater than the DOF [20]. Otherwise full factorial design would have given 1,458 (3^6 × 2) different configuration, making it tedious task for conducting the experimentation. Taguchi technique yielded only 18 experiments [19]. The experimental setting and corresponding surface roughness values have been logged in table 3. The quality of final component has been depicted in Figures 8 (a), (b) and (c) corresponding to experiment number 2, 4 and 8 respectively.

Table 3. Taguchi L18 Orthogonal Arrays with details of experimental data.

| Trial No. | Tool path | Tool Diameter (mm) | Sheet thickness (mm) | Step Size (mm) | Spindle Speed (rpm) | Feed Rate (mm/min) | Lubrication | Surface Roughness (µm) |
|-----------|-----------|--------------------|----------------------|----------------|---------------------|-------------------|-------------|-----------------------|
| 1         | Spiral    | 16                 | 1.2                  | 0.3            | 0                   | 1500              | Coolant     | 1.49                  |
| 2         | Spiral    | 16                 | 2                    | 0.5            | 100                 | 2000              | Oil         | 0.86                  |
| 3         | Spiral    | 16                 | 2.3                  | 0.75           | 200                 | 3000              | Grease      | 1.40                  |
| 4         | Spiral    | 18                 | 1.2                  | 0.3            | 100                 | 2000              | Grease      | 0.69                  |
| 5         | Spiral    | 18                 | 2                    | 0.5            | 200                 | 3000              | Coolant     | 1.26                  |
| 6         | Spiral    | 18                 | 2.3                  | 0.75           | 0                   | 1500              | Oil         | 1.28                  |
| 7         | Spiral    | 20                 | 1.2                  | 0.5            | 0                   | 3000              | Oil         | 1.13                  |
| 8         | Spiral    | 20                 | 2                    | 0.75           | 100                 | 1500              | Grease      | 1.17                  |
| 9         | Spiral    | 20                 | 2.3                  | 0.3            | 200                 | 2000              | Coolant     | 1.19                  |
| 10        | Profile   | 16                 | 1.2                  | 0.75           | 200                 | 2000              | Oil         | 0.95                  |
| 11        | Profile   | 16                 | 2                    | 0.3            | 0                   | 3000              | Grease      | 1.17                  |
| 12        | Profile   | 16                 | 2.3                  | 0.5            | 100                 | 1500              | Coolant     | 1.06                  |
| 13        | Profile   | 18                 | 1.2                  | 0.5            | 200                 | 1500              | Grease      | 0.65                  |
| 14        | Profile   | 18                 | 2                    | 0.75           | 0                   | 2000              | Coolant     | 1.22                  |
| 15        | Profile   | 18                 | 2.3                  | 0.3            | 100                 | 3000              | Oil         | 1.45                  |
| 16        | Profile   | 20                 | 1.2                  | 0.75           | 100                 | 3000              | Coolant     | 0.70                  |
| 17        | Profile   | 20                 | 2                    | 0.3            | 200                 | 1500              | Oil         | 0.75                  |
| 18        | Profile   | 20                 | 2.3                  | 0.5            | 0                   | 2000              | Grease      | 2.35                  |

It can be clearly seen that the final quality of fabricated component does not solely depends upon the individual values of input variables, rather the combined interaction of all the input variables as it dictates the resultant forming forces. If forming forces crosses the fracture limit of the component, result might be partial or complete tearing of metal sheet at any stage of the processing as observed for experiment number 4 and 8. The current study is limited to cast light on the main effects only. The
interaction effect and more versatile fixture design are under consideration as future research objectives.

![Figure 8. Formed parts](image)

(a) for Exp. no 2, (b) for Exp. no. 4 & (c) for Exp. no 8

3. Results and discussion

3.1. Effects of parameters on SR

Graphs (mean effect plot) shown in Figure 9 has been generated by putting the experimental data in Minitab software. These graphs are displaying the main effects of input variables on process outcome i.e. surface roughness.

![Figure 9. Main effects plot for surface roughness](image)
Profile tool path causes scars as can be seen in Figure 10 on formed part while Spiral tool path gives no scars. Due to downward penetration of tool in single vertical direction the profile tool path leaves a scare on formed part.

In spiral tool path tool moves in both vertical and horizontal plane at the same time, this moment causes the larger area of deformation in single cycle. Except the generation of scars with profile tool path, both the tool paths generated components with very little difference in values of surface roughness. Therefore, spiral tool path is recommended to prevent the formation of scars on surface of components.

In case of thick sheet, higher forming forces are required. This significant increase in forces led to profound increase in friction and wear of material during forming process. Therefore, lower sheet thickness of metal sheets yielded better surface finishing comparative to thicker one. At low spindle speed, rate of wear was less that caused the improvement in surface finish. But at high spindle speed, friction between tool and sheet become high that caused excessive wear of material and rough surface was formed. An irregular behavior was observed at free spindle speed, where wear particle instead of moving out came between sheet and tool. These wear particles resulted in unwanted abrasion of workpiece surface causing degradation in its finishing quality.

Smaller tool diameter caused bending of sheet material and sharp point penetration during deformation; because of less contact area between tool and sheet, while increase in diameter leads to increase in area between sheet and tool which causing stretching and strain hardening of material. Therefore, Surface roughness decreases with increase in tool diameter up to a point. But for further increase in tool diameter both bending and stretching caused increase in surface roughness.

Smaller step size leads to closer punch passes, which causes work hardening of sheet material. Hardened material undergoes less wear rate during forming process so surface finishing during the application of smaller step size yielded superior surface finish as compared to larger step size.

Surface finish was superlative when oil was applied over workpiece surface as lubricant than coolant and grease. This might has happened due to flow of wear-out particles with application of oil and while in case of grease wear particle experienced stick-slip phenomenon due to higher viscosity. Consequently, contact between tool and sheet blank caused more wear that deteriorated the surface finish. With increase in feed rate, surface roughness decreased as higher feed leads to application of higher forming force for smaller time.
4. Conclusions

In current study, aluminium alloy AA 2014-T6 has been processed with Incremental sheet forming process. The effect of seven input variables has been explored on surface roughness of conical shaped components using the Taguchi’s approach. The findings of this research work can be summarized as follows:-

- Sheet thickness dominated all the other parameters in affecting the surface roughness of formed parts. Surface roughness increased sharply with little variation in sheet thickness.
- After sheet thickness spindle speed affected the SR most but variation trend didn’t followed specific trend.
- Free tool rotation caused trapping of wear particle between forming tool and sheet metal that caused abrasion of sheet material and damaged the surface. So, judicious selection of spindle speed is very critical to get superior surface finish.
- Other parameters namely tool diameter, tool step size, lubricant type and feed rate have moderate impact over the surface finish of formed part and trends between these variables and SR were irregular.
- Although Tool path didn’t affected the surface roughness significantly, but use of spiral tool path is recommended as it prevents the formation of scars that are frequently formed in case of profile tool path.

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