Lubricant Selection and Post Forming Material Characterization in Incremental Sheet Forming

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Abstract. Single Point Incremental Forming (SPIF) is a flexible, novel and rapid sheet forming process to deform extra thin to the thick sheet with the help of computer numerical control unit, hemispherical tool and fixture. A tool follows a series of small incremental steps which deforms the sheet into the desired shape. Despite of recent development occurred in past, the little literature was reported which investigate the effect of various types of lubricants in SPIF process. This study aims to address the distinct type of lubricant to accomplish better surface roughness and formability of final parts while incremental forming of aluminium 5052 H32 sheets. After the forming process, the fractographies of the specimen were studied at optimal condition. The study is also extended to determine residual stresses generated due to incremental deformation and its effect on corrosion phenomenon with the environment. It has been found that the fracture zone material is likely to corrode more rapidly due to increased plastic deformation than the material at initial and middle forming zones.

1. Introduction
Incremental Sheet Forming (ISF) is an unconventional metal forming process which is extensively used to manufacture products with free form shapes without using any specialized dies. A computer numerical controlled (CNC) tool traces a series of contour, after completing each contour, the tool takes a small depth and deforms the sheet into the product. Single Point Incremental Forming (SPIF) is a highly flexible sheet metal forming process which uses rapid prototyping techniques to produce parts in small batches economically. The working principle of the SPIF process has been explained in the published article [1]. The basic components of the process are sheet metal blank, blank holder, backing plate and hemispherical tool. The blank holder is generally used in holding and clamping of the blank metal sheet during the process. The backing plate acts as a support to sheet metal to avoid initial sheet bending and also provides the open area during forming. The single point tool rotates over the sheet and its incremental depth forms the sheet. The incremental depth and movement of the tool are controlled by CNC machine control unit. During the forming process, die sets are not used, hence, it is a cheaper process. The process is still under its development due to some limitations such as slow operation, geometrical inaccuracy, no uniform thinning of formed sheet and wavy surface texture.

Some researchers have paid attention to investigate the effect of SPIF process parameters on the response of sheet metal by incorporating various strategies. Cerro et al. [2] investigated the SPIF process by the numerical and experimental techniques to predict the surface roughness and stress distribution in the sheet during forming. Hussain et al. [3] have found that the good surface quality of deformed pure titanium sheet is obtained by using surface hardened high-speed steel tool and molybdenum disulphide paste with petroleum jelly in a specific proportion. Shanmugananatan and Senthil Kumar [4] carried out an experimental and numerical simulation to investigate maximum wall angle, surface roughness and sheet thinning of Al 3003(O). Zhaobing et al. [5] studied the impact of input parameters on surface roughness using the design of experiments (DOE) along with multi-objective function. Thickness distribution and failure limited diagram are studied by Malwad and Nandedkar [6] to understand the deformation mechanism behaviour of commercial AA8011. Desai et al. [7] presented one factor at a time approach for dieless rapid prototyping process to study the effect...
of process parameters on forming characteristics. Yanle et al. [8] performed some tests using RSM with Box-Behnken design to study the effects of input parameters on both deformation energy and geometrical accuracy in ISF process. Golabi and Hossain [9] statistically analyzed the incremental forming of SS304. They studied the effect of some parameters on forming the height of the component. Gulati et al. [10] concluded the effect of six different input process parameters like tool radius, sheet thickness, tool rotational speed, feed rate and lubrication on performance measures using Taguchi’s method. Aeren et al. [10] devised a novel technique to predict the developed forces in SPIF process based on the results obtained from experiments and finite element analysis. The ultimate goal of the work was to obtain an equation for different materials, which could help in the prediction of forces generated during forming. Five different materials and sheet blanks having different thickness were used to form a truncated cone. Equations were developed with the partial involvement of regression modelling techniques, results of finite element analysis and physics of the ISF process. Zhang et al. [12] investigated the more suitable lubricants and lubricating methods to be employed in case of magnesium alloy AZ31 sheet with warm negative incremental forming. The combined effect of tool size and lubricants was also discussed in the literature. The effect of lubrication, punch material and spindle velocity on the surface finish with CP titanium Gr.2 sheet of 1.0 mm thickness for SPIF of biomedical devices was studied by Fiorentino et al. [13]. Micari et al. [14] also studied the shape and dimensional accuracy of formed geometry by SPIF process. They defined the geometrical error as the distance between the ideal and actual profile. Bending of the sheet, spring back and the pillow effect at the base of formed geometry are some of the errors associated with SPIF process. They also addressed some strategies for error minimization in SPIF process. Mugendiran and Gnanavelbabu [15] compared the measurement accuracy of the developed plastic strain in SPIF using conventional, least-square and digital-based processing method. The result shows that the digital-based processing method is found to be more accurate than the other two. They claim that the strain measurement accuracy can be improved using digital-based processing method. Allwood et al. [16] proposed a novel blank shape, termed as partially cutout blanks to improve the accuracy of the final part. They observed that partially cutout blanks did not provide many benefits in the improvement of dimensional accuracy of the formed components. However, the use of stiff backup plate was the key solution in enhancing the part accuracy than the partial cut-outs.

The metal forming industries are moving towards customized production of sheet metal parts. In recent years, sheet metal industries demand flexibility, a novelty in the products to satisfy diversified customers worldwide. A lot of studies had reported to investigate dimensional accuracy, execution time, part formability and surface integrity of the deformed part. The attention was also sought for process optimization, FE simulation, material characterization, high speed, multi-sheet- and, multi-step- SPIF process. However, not much work had reported on the prerequisite lubrication condition and post investigations of parts resulting out of SPIF process. The use of suitable lubricant is the vital step to improve forming performance. The several experiments were performed and authors have identified set of process parameters to achieve better process performance in terms of minimum surface roughness value and maximum formability. The corrosion and residual stress behaviour study were carried out at optimized conditions of process parameters.

2. Selection of proper lubricant

The ASTM D4172-94 standard was used to select proper lubricant for the SPIF process to evaluate antiraw characteristics of several lubricants using four-ball tester (Model: TR-30L-IAS, Make: DUCOM) as shown in Figure 1. In the tests, three 12.7 mm diameter steel balls made of AISI standard steel No. E-52100 with Grade 25 EP (Extra Polish) are clamped together and covered with the lubricant to be evaluated. A top steel ball of the same diameter will be the fourth ball which presses into the cavity made by the three clamped balls for three-point contact. The test load, duration, temperature and rotational speed are defined in accordance with set standards. As shown in Figure 2, the real-time data of frictional torque vs. time data was recorded. The average scar diameter on the bottom three balls is obtained using an image acquisition system. An optional scar measuring image acquisition system with an image sensor allows acquiring scar images on the computer. The ability of
the lubricant to avoid wear can be indicated by the area of the scar. A larger diameter of wear scar indicates poor wear resistance of the lubricant and vice versa.

![Four-Ball tester equipment](image1)

**Figure 1.** Four-Ball tester equipment

![Frictional torque vs. time](image2)

**Figure 2.** Frictional torque vs. time

The lubricants such as 10W30, 5W30, 20W40 and 15W40 have been considered for the investigation. The lubricants are compared by using the average size of the scar diameters worn on the three lower clamped balls. From Figure 3 and Figure 4, it has been found that the coefficient of friction value obtained with 10W30 lubricant is relatively less as compared to other synthetic lubricants. For 5052 H32 aluminium, tests reveal that the 10W30 oil gives the best surface finish than other oils. The coefficient of friction of 0.11013 was obtained with 10W30 oil which has lesser in magnitude. The efforts have also extended by comparing synthetic oil with grease and dry lubricating techniques. The synthetic oil lubricant is found to be a good choice for SPIF process to get a finished surface and formability of deformed specimen as compared to dry, grease and paste of graphite and grease.
At the same forming condition, the process shows different behavior with a change in the lubricant as illustrated in Figure 5. The formability has been indicated by the maximum angle of forming without getting a fracture in SPIF process with varying wall angle conical frustum. According to the results obtained, it was possible to note that 10W30 provides better results during forming operation. The 10W30 oil has a viscosity of 71.5 mm²/s at 40°C, the relative density of 0.856 g/ml at 15°C. Servo 10W30 oil lubricant gives good results as compared to other oil lubricants. It is viscous oil generally used in automobile engine to attain lubrication in the service conditions. Hence, the synthetic oil 10W30 was used in the experimental investigation.

### 3. Experimental investigations

The experimental setup of SPIF forming fixture mounted on CNC machine bed (Model: Surya VF 30 CNC VS, Make: Bharat Fritz Werner LTD, Bangalore, India). The experiments were carried out to evaluate the effect of input process parameters such as spindle speed (N), table feed (f), step depth (p), tool diameter (d) and sheet thickness (t₀) on surface finish and formability. The process parameters and their levels have been shown in Table 1. The SPIF experiments were performed on AA5052 H32 material as per Taguchi L₂⁷ design of experiments. The experimental setup, specimen geometry, fixture and statistical analysis can be found in the article [1]. According to the investigation carried out by the author and his team, the table feed and step depth have a major contribution in affecting the surface finish of 71.11% and 18.24% among the total value. The spindle speed has played very little role in affecting the surface finish and sheet formability. Table 2 depicts the percentage error corresponding to average surface roughness and the maximum forming angle at their optimum conditions. The optimized conditions for average surface roughness and formability are N₃f₀p₀dₐ(τ₀)₁.
and $N_3f_2p_1d_1(t_o)_3$, respectively. In notation $N_3$, ‘$N$’ indicates spindle speed whereas ‘3’ indicates level three. The prediction model was developed within 95% of confidence level. It has been found that the experimental response values obtained within a specified range of input process parameters were closely matched with the predicted outcome. It is also understood that the optimum combinations suggested are reasonably acceptable. Analysis of S/N ratio concludes that the optimum forming parameters are spindle speed at 3500 rpm, table feed at 600 mm/min, step depth at 0.2 mm, tool diameter 10 mm, and sheet thickness at 0.8 mm for optimum value of average surface roughness (1.42 μm) while the optimum value of the maximum forming angle was found to be 85.40 degrees at spindle speed of 3500 rpm, table feed of 1400 mm/min, step depth of 0.2 mm, tool diameter of 8 mm, and sheet thickness of 1.2 mm. The parts obtained from the confirmation experiments have shown in Figure 6.

Table 1. SPIF input parameters and their levels

| Sr. no. | Factors        | Units     | Symbol | Low   | Medium | High   |
|---------|----------------|-----------|--------|-------|--------|--------|
| 1       | Spindle speed  | rpm       | N      | 1500  | 2500   | 3500   |
| 2       | Table feed     | mm/min    | f      | 600   | 1400   | 2200   |
| 3       | Step depth     | mm        | p      | 0.2   | 0.4    | 0.6    |
| 4       | Tool diameter  | mm        | d      | 8     | 10     | 12     |
| 5       | Sheet thickness| mm        | $t_o$  | 0.8   | 1      | 1.2    |

Table 2. Results of confirmation experiments

| Responses                        | Optimum conditions | Predicted Values | Experimental Values | % of error |
|----------------------------------|--------------------|------------------|---------------------|------------|
| Surface Roughness                | $N_3f_2p_1d_1(t_o)_3$ | 1.35             | 1.42                | 4.24       |
| Maximum forming angle            | $N_3f_2p_1d_1(t_o)_3$ | 85.40            | 84.26               | 1.35       |

Figure 6. Confirmation experiments (a) average surface roughness (b) maximum forming angle

4. Fractography analysis

SEM micrographs of the cross-sectional view of SPIF fractured surface have been taken with the help of VEGA3TESCAN, Scanning Electron Microscope (SEM), TESCAN, CZECH REPUBLIC. After SPIF forming, the fractured surfaces at optimum conditions were cut precisely at fracture using wire Cut EDM to analyze fracture surface. The fracture surface of the incrementally formed part has analyzed using SEM photographs. The SEM images of the fractured surface at a magnification of ×500 at the optimum condition of surface roughness and formability are shown in Figure 7 (a) and 7 (b), respectively. The scanning electron microscope (SEM) photographs of the fractured surface of surface roughness and formability at ×2500 magnification are shown in Figure 8 (a) and 8 (b), respectively. The cup-like impressions (dimples) can be observed from the microstructure and they are nearly circular holes on the ruptured surface. Due to the presence of live local stresses and state of
strain, the dimples of various sizes appeared on the yielding fracture surface. It indicates that the fracture is predominantly ductile in nature. In ductile fracture, damage accumulates due to nucleation, growth and coalescence of voids [17]. The fracture has occurred during the process after a considerable degree of deformation called severe plastic deformation. The results depict that the material deformed plastically before the fracture has happened.

Figure 7. SEM photographs of fractured surface at ×500 magnification (a) average surface roughness (b) maximum forming angle

Figure 8. SEM photographs of fractured surface at ×2500 magnification (a) average surface roughness (b) maximum forming angle

5. Corrosion resistance and residual stress
The corrosion leads to material degradation, wastage of valuable resources, and loss in material efficiency. Polarization methods are faster experimental techniques as compared to classical weight loss estimation. All electrochemical measurements have been performed on the computerized electrochemical analyzer (supplied by Autolab Instruments, Netherlands). AA5052 H32 deformed sheets were used as the working electrode with a platinum wire as the counter and a saturated calomel electrode as the reference electrode. The AA5052 was cleaned initially and about 2 cm² of surface area was used for sample testing as the working electrode. Polarization measurements were taken after exposure to the 3.5% NaCl solution. The potential was scanned between −1 V to +1 V at a rate of 10 mV/s. The electrochemical measurements were carried out at room temperature (25°C). For an electrochemical reaction under activation control, polarization curves exhibit linear behaviour in the E vs. log (i) plots called Tafel behaviour. The results obtained for the deformed SPIF parts at optimum conditions are shown in Figure 9(a) and 9(b).

The deformation of the AA5052 H32 sheet can significantly affect the corrosion resistance. As like other cold forming techniques, SPIF can also introduce residual stresses. The magnitude and significance of such stresses are always underestimated. The combination of induced stress and the
corrosive atmosphere has a synergistic effect and the material corrodes faster than if unstressed. The combined effect is generally called as stress-corrosion or environmentally assisted cracking. From Figure 9, these results indicate that the degradation of the localized corrosion resistance can be caused by increases in the level of residual stress due to the incremental deformation. The residual stresses are always caused by inhomogeneous elastic and/or elastic-plastic changes of grain shape.

Figure 9. Tafel plots for the AA5052 optimum samples in 3.5% NACL solution (a) average surface roughness (b) maximum forming angle.

Figure 10. Residual Stress (a) average surface roughness optimum condition (b) formability optimum condition (c) as-received sheet.
The non-destructive x-ray diffraction method is used to find induced residual stress due to the forming operation. It has been found that the corrosion rate of the fully deformed sheet is higher than that of the initial deformed sheet in case of SPIF. It is well known that stress is a major factor in the rate of corrosion. Presence of any stress in the material will accelerate corrosion phenomena with the environment. Therefore the study is further extended to determine residual stresses present near to fracture zone. It was observed that residual stresses are developed in the material due to forming operation which eventually leads to lower corrosion resistance than as-received material (See Figure 10).

6. Conclusions

Even if the geometrical, forming and material parameters are the most significant parameters, the use of a proper lubricant may significantly improve the SPIF process performance. The preliminary study presented here provides a base for research engineer on lubricant should they select in the SPIF process. The research work contributes to understand the lubricant selection, residual stress and corrosion behavior. The following conclusions are drawn from the research results presented in this study.

1. It has been found that the performance 10W30 lubricant is relatively better to get a smooth surface and formability of deformed specimen as compared to dry, grease and paste of graphite and grease. The synthetic oil lubricant is found to be a good choice for incremental forming of AA5052 H32 alloy.

2. The fracture surfaces with respect to optimum conditions contained large and wide voids and dimples indicating fracture occurred at larger plastic strains.

3. Presence of any stress in the material will accelerate corrosion phenomena. It was observed that residual stresses are developed in the material due to forming operation which eventually leads to lower corrosion resistance than as-received material.

4. The accumulation of residual stress near fracture leads to generate rapid corrosion as compared to middle and initial zone specified in the study.

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