Journal of Mines, Metals and Fuels, *73(7): 2241-2251; 2025. DOI: 10.18311/jmmf/2025/49266*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.co.in/index.php/jmmf*

Lubrication Study for Single Point Incremental Forming of Titanium

Shraddha S. Adewar[1] and Anand K. Bewoor[2]

[1]Mechanical Engineering Department, Zeal College of Engineering and Research, Narhe, Savitribai Phule Pune University, Pune - 411041, Maharashtra, India; shraddhaadewar84@gmail.com

[2]Mechanical Engineering Department, Cummins College of Engineering for Women, Pune - 411052, Maharashtra, India

Abstract

Lubrication plays a crucial role in reducing wear and heat between surfaces in relative motion, though these factors cannot be eliminated. This study investigates the most effective lubricant for enhancing surface finish and minimizing wear in the context of Single Point Incremental Forming (SPIF) of titanium sheets. SPIF is a versatile and cost-effective sheet metal forming process, but it often faces challenges in terms of surface quality and tool wear. The paper specifically focuses on the impact of different lubricants on surface roughness (Ra) and the maximum achievable sheet forming angle during titanium sheet deformation. Key independent parameters, including CNC spindle speed, tool step-down depth, hemispherical end tool diameter, and table feed rate, are systematically examined to optimize the SPIF process and identify the most effective lubricant. The objective is to determine which lubricant produces the best combination of surface finish, reduced tool wear and improved forming efficiency. Experimental results provide valuable insights into how these process parameters and lubricant types influence titanium sheet behavior, surface quality, and overall process performance. This study aims to contribute to the development of more efficient, precise, and sustainable SPIF processes for titanium, offering practical implications for advanced manufacturing applications.

Major Findings: *The study identified lubrication as the most influential factor affecting surface roughness during the Single Point Incremental Forming (SPIF) of pure titanium sheets, with coconut oil proving significantly more effective than water and SAE 30. Surface finish improved with larger tool diameters and optimal spindle speeds, while increased spindle speed negatively impacted formability. Lubrication had negligible influence on the maximum achievable forming angle, which was more sensitive to spindle speed. Overall, the research highlights the critical role of proper lubricant selection in enhancing surface quality and optimizing SPIF performance.*

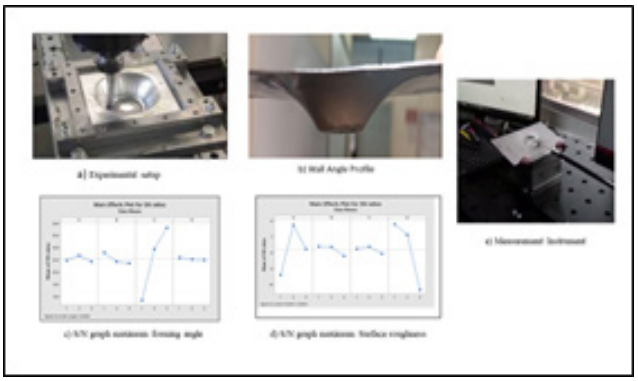
Keywords: *ANOVA, Lubricant, Maximum Sheet Forming Angle, Single Point Incremental Forming, Titanium Sheet Roughness (Ra)*

1.0 Introduction

Nowadays there are various applications of Single Point Incremental Forming. Most industries use this forming process. The SPIF process, as illustrated in Figure 1, involves the gradual deformation of a sheet metal using a single-point tool to achieve the desired three-dimensional shape.

This study experimentally examines the influence of process parameters on Surface Roughness (SR) variation. A validated predictive model was developed to identify optimal parameter levels that minimize SR

**Author for correspondence*



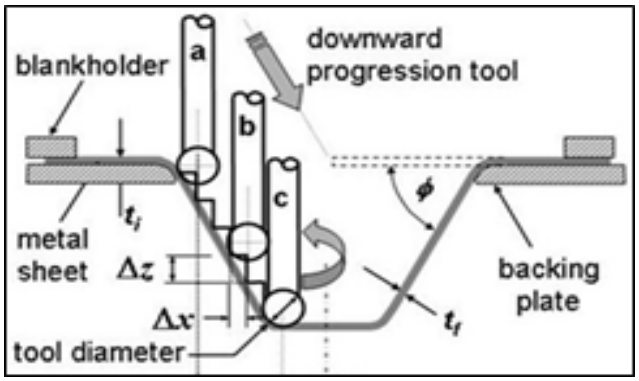


Figure 1. SPIF process[1].

in fabricated components. Each parameter was analyzed at three distinct levels to assess its impact on surface quality. Titanium alloys retain considerable strength even at elevated temperatures, making them more difficult to machine compared to metals like aluminium or steel. Another challenge is their tendency to undergo work hardening during machining, where the material becomes harder with each pass, exacerbating tool wear and complicating dimensional accuracy[2] Surface Roughness Measurement Techniques. Equation 1 described is measured in terms of a tangent line from the unformed blank to the deformed part of the surface, determined by sine law,

$$Ra=1/L\int_0^L Y(x)dx \quad (1)$$

where ti and tf are the initial and final thicknesses of the part, respectively, and α is the semi-cone angle. Many Industries use some simple parameters like SR, *i.e.*, surface roughness. Figure 2 graphically describes average roughness as the area between the irregular roughness profile and its mean value. The integral of the absolute value of the roughness height over the sampling length can also be used to Equation 2 explain this. Mathematically, Ra is defined as:

$$t_f = t_i \frac{\sin\left(\frac{\pi}{2}\right)}{\sin\alpha} \quad (2)$$

where,

Ra = average deviation from mean

Y = ordinate of the profile curve

L = sampling length[3]

SR can be approximated on specimens by eye even by fingertip. Microscopes, profile tracing instruments, or stylus instruments can also be used.

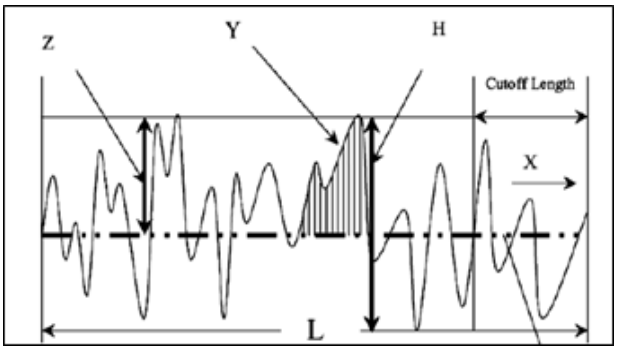


Figure 2. SR profile[4].

Manufactured with the help of a computer-controlled tool[5]. In this paper, we studied the Lubrication study for Single Point Incremental Forming of Titanium, by using lubricants such as coconut oil, water, and SAE30. From this, we get a better result. The Single Point Incremental Forming effect on Formed titanium sheet roughness (Ra) and maximum sheet forming angle are measured. In the SPIF process, lubrication reduces friction between the forming tool and the sheet metal.Proper lubrication minimizes tool wear, prevents excessive heat generation, and improves surface finish by ensuring smoother tool movement. Different lubricants, such as oils, greases, and solid lubricants, are used depending on the material and forming conditions to enhance formability and reduce the risk of defects like tearing or surface roughness. Optimal lubrication can also reduce the force required for forming and extend tool life[6-8]. In SPIF, the process begins with a flat sheet of material placed on a forming surface. A tool is

moved along a programmed path, incrementally forming the sheet in discrete steps. The tool usually moves in both the vertical direction (to achieve depth) and along the surface (to trace the geometry). As the tool advances, each pass creates a small incremental deformation at a point, which accumulates to form the entire geometry. The process is governed by a number of key parameters, including tool path, tool geometry, material properties, and process conditions[9].

2.0 Material and Methodology

In this research, the lubrication parameters used in the SPIF process were thoroughly investigated. The material selected for the SPIF process was titanium alloy (Ti-6Al-4V) with a specific thickness[10,11]. Chosen for its desirable mechanical properties in incremental forming applications. A variety of lubricants were tested during the forming process, including oil-based, grease-based, and solid lubricants, to evaluate their impact on formability, surface finish, and tool wear[12]. The forming tool was made of High-Speed Steel (HSS), which was selected for its durability and resistance to wear. The tool's geometry, such as conical,was designed to enhance material flow and reduce friction, factors that directly influence lubrication effectiveness and tool performance. To determine the most suitable lubricant for the SPIF process, the effects of different lubricants were analyzed using Analysis of Variance (ANOVA), which enabled a comparison of performance metrics across the various lubricant types[13,14].

2.1 Material

Titanium offers a unique combination of lightweight and high mechanical strength, making it ideal for applications where weight reduction is critical. Titanium forms a stable oxide layer that protects it from corrosive environments, making it suitable for aerospace, medical, and chemical industries. Titanium is not as ductile as aluminum or steel, which poses challenges during SPIF, requiring specific temperature and lubrication considerations. The material used for this study is Titanium. Titanium is one of the applications in the sheet metal industry[15]. To its survivability titanium is heavily utilized and associated with the aerospace, medical, power, oil, and gas industries[16]. Some less thought-of industries for which titanium has also been sourced are the automotive, electrics, and desalination industries. Titanium alloys at very low to elevated temperatures allow weight savings in aerospace structures and other high-performance applications[17,18]. The material properties are presented below in Table 1.

Table 1. Material property

Property	Minimum Value (S.I.)	Maximum Value (S.I.)	Units (S.I.)
Tensile Strength	862	1200	MPa
Density	4.429	4.512	Mg/m3
Young's Modulus	110	119	GPa
Resistivity	168	170	10-8 ohm.m

Titanium has high elastic recovery, leading to dimensional inaccuracies. High strength and abrasiveness can wear tools faster. Requires careful control of forming parameters like step-down depth and feed rate. The heat generated during forming can affect tool life and material properties. Process parameters like tool size, feed rate, and step size significantly affect the material flow and forming limits in SPIF. Their work provides useful insights into the optimization of these parameters to improve formability[19,20].

2.2 SPIF Tool and Machine

SPIF tests were carried out on a three-axis CNC milling vertical machining center at room temperature in Figure 3. One benefit of single-point incremental forming is that it requires less setup costs for the machine and may be performed on CNC equipment with cheap fixtures and tools. All testing was carried out using a variable feed rate range of 1000 to 2000 mm/min and a square clamping frame with a free edge of 100 mm.

2.3 Lubrication

A study evaluated the influence of various lubricants on aluminum 1050 and DP780 steel sheets during SPIF. The research highlighted that the choice of lubricant significantly affects surface quality and formability, with specific lubricants performing better for different

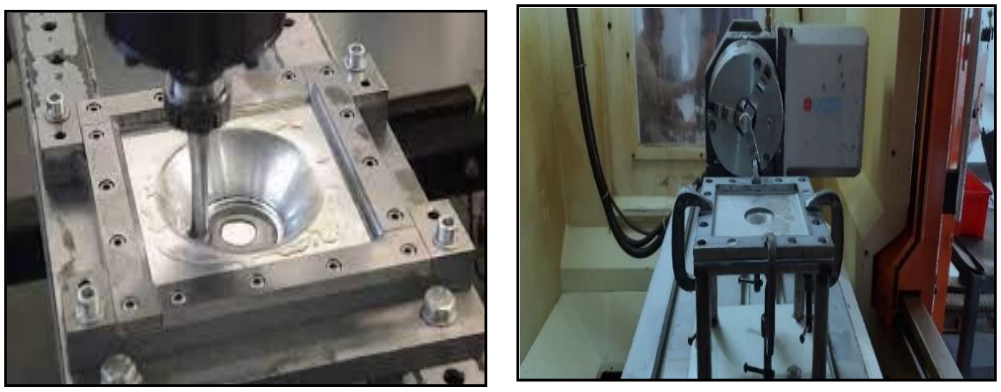


Figure 3. Experimental setup.

Table 2. List of lubrication used

Lubricant	Base	State	Viscosity (mm/s^2) @40°C
Coconut Oil	Fatty acids	Oil	30
SAE 30	Refined mineral oil	Oil	12.5
Water	Water	Liquid	0.65

materials[21]. Research on near-dry machining in SPIF introduced nano-powder mixed solid lubricants, promoting effective lubrication with minimal environmental impact. This approach demonstrated potential in reducing friction and improving surface finish[22]. A study examined the influence of lubrication and cooling on the quality of SPIF-processed parts. The findings indicated that appropriate lubrication and cooling techniques could enhance surface quality and dimensional accuracy[23]. This Single Point Incremental Forming Tools are made up of AISI H13. Coconut oil is used as a lubricant, to reduce friction and sticking effect at the tool-workpiece interface and, consequently, the risk of failure[24]. The lubricant chemical composition are presented in Table 2.

3.0 Results and Discussion

3.1 SPIF Control Parameter

Single Point Incremental Forming (SPIF) is a versatile sheet metal forming process where a tool incrementally deforms a clamped sheet to achieve the desired geometry without the need for dedicated dies. The quality and

Table 3. SPIF parameter

No	Factors	Unit	Symbol	Low	Medium	High
1	Tool diameter	mm	d	1	2	3
2	Spindle speed	rpm	N	1000	2000	3000
3	Table feed	mm/min	f	1000	1200	1500
4	Step down depth	mm	z	0.3	0.4	5
5	Lubrication			Coconut Oil	SAE30	Water

accuracy of SPIF are significantly influenced by various control parameters. Larger tool diameters generally lead to reduced surface roughness and forming forces, enhancing surface quality. However, they may limit the achievable geometric intricacies. Optimization of tool diameter, along with other parameters, has been shown to influence forming forces and part accuracy[25]. Studies indicate that sheet thickness significantly affects forming forces and the quality of the formed parts.The relationship between step depth and surface roughness has been analyzed, showing that optimal step depth selection is crucial for balancing quality and efficiency. Proper lubrication reduces friction between the tool and sheet, decreasing forming forces and tool wear while improving surface finish. Studies have highlighted the importance of lubrication in minimizing surface roughness and enhancing formability[26].

These SPIF parameters and their qualities appearin Table 3. Improvement of parameters is finished with sign-to-noise (S/N) proportion according to Taguchi's strategy[27]. The bigger the rate association of the parameter to the absolute contrast, the bigger the capacity of that parameter to impact the S/N proportion[24]. The ideal blend of factors is acquired from the greatest estimation of the mean S/N proportion for separate parameters. The more the S/N proportion better the presentation[28].

3.2 Surface Roughness

Preliminary experiments were conducted to evaluate the effects of tool shape, tool diameter, lubricant viscosity, and spindle speed. The fluctuation of the step depths of progressively created shaped sheets, tool diameters, for various lubrication, spindle speeds table feeds, and measure a maximum forming angle, and its signal to noise ratios[29]. It has been seen that when depth step and table feed rates increase, the roughness decreases. The importance of toolpath strategies in minimizing surface roughness. A zigzag toolpath generally leads to more pronounced surface roughness compared to spiral or contour toolpaths, which create smoother surface transitions[30]. It is also necessary to consider other geometric factors, such as form accuracy and dimensional tolerances. The study presents empirical models for predicting surface roughness in ISF based on tool geometry and material properties[31]. The surface roughness measurements, as presented in Table 4. provide the Ra values recorded for different test conditions or samples.

3.3 Taguchi Analysis

Single Point Incremental Forming (SPIF) is a flexible and cost-effective sheet metal forming process, particularly advantageous for materials like titanium and its alloys due to their high strength-to-weight ratio

Table 4. Readings for surface roughness (Ra)

Expt. No.	Spindle Speed	Table Feed	Step down dept	Lubrication	Average surface roughness	S/N ratio
1	1000	1000	0.3	Coconut Oil	2.379	-7.5279
2	1000	1200	0.4	SAE30	2.544	-8.1103
3	1000	1500	0.5	Water	4.249	-12.5657
4	2000	1000	0.4	Water	2.6250	-8.3826
5	2000	1200	0.5	Coconut Oil	1.727	-4.7458
6	2000	1500	0.3	SAE30	1.917	-5.6524
7	3000	1000	0.5	SAE30	2.207	-6.8760
8	3000	1200	0.3	Water	3.185	-10.622
9	3000	1500	0.4	Coconut Oil	2.082	-6.3696

and corrosion resistance. Optimizing SPIF parameters for titanium is crucial to enhance formability, surface finish, and dimensional accuracy. The Taguchi method, a statistical approach for the design of experiments, has been effectively applied to determine optimal SPIF parameters for titanium. The study identified that specific combinations of tool diameter, step depth, and feed rate significantly influence surface roughness and formability. Optimal settings were determined to enhance the quality of the formed parts[32]. The study provided a synthesis of optimal process parameters, demonstrating the effectiveness of combining Taguchi and Grey relational analysis for multi-response optimization in SPIF[33].

SR versus Spindle Speed, Table Feed, Step down depth, Lubrication

The feed rate is the amount of time (in ms) that the forming tool travels across the sheet surface. For surface roughness, more Taguchi analysis is conducted[34]. Figure 4. illustrates how the spindle speed climbed from 1000 to 2000 rpm and then increased from 2000 rpm when the surface roughness started to decrease. Surface roughness increases with tool diameter increases from 1 mm to 2 mm and decreases with tool diameter increases from 2 mm to 3 mm. Surface roughness increases when coconut oil is used as a lubricant.The Signal to Noise Ratios for surface roughness under various conditions are summarized in Table 5. highlighting the influence of process parameters on surface quality.

Response Table for Signal-to-Noise Ratios

Smaller is better

Table 5. Signal to noise ratios for roughness

Level	Speed	Feed	depth	Lubrication
1	-9.401	-7.596	-7.748	-6.214
2	-6.26	-7.639	-7.621	-6.88
3	-7.769	-8.196	-8.063	-10.337
Delta	3.141	0.6	0.442	4.122
Rank	2	3	4	1

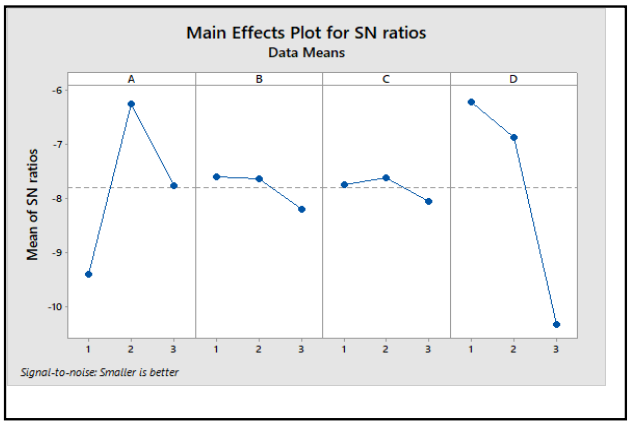


Figure 4. S/N graph for average surface roughness.

Table 6. ANOVA: Average surface roughness values versus tool dia., speed, feed and step size

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	3.23934	0.80983	0.16	0.0237
A	1	0.48053	0.48053	0.28	0.0321
B	1	0.17923	0.17923	0.48	0.0527
C	1	0.08213	0.08213	0.22	0.0664
D	1	2.49744	2.49744	0.66	0.061
Error	4	1.49995	0.37499		

3.4 Maximum Forming Angle

The maximum forming angle was calculated based on the depth at which the fracture occurred and comparing the equivalent angle for the same depth in the CAD geometry. Here, as can be seen in Table 7. there is no significant effect of lubrication on the maximum forming angle[35]. However quantitatively, it can be stated that the lubrication has negligible positive effect on the maximum forming angle. Experimental study focuses on determining the maximum forming angle for a range of materials, including aluminum, brass, and steel. The authors conducted incremental forming experiments with different tool diameters and feed rates to measure the maximum angles achievable[36]. Table 8 presents the Signal-to-Noise Ratios for the forming angle, indicating the effect of different process parameters on the formability in the SPIF process.

Table 7. Maximum forming angle

Expt No.	Spindle Speed	Table Feed	Step down depth	Lubrication	Max forming angle (Φmax)	S/N ratio (Forming Angle)
1	1000	1000	0.3	CO	35.9256	31.10808
2	1000	1200	0.4	SAE30	43.6092	32.79156
3	1000	1500	0.5	Water	47.6558	33.56232
4	2000	1000	0.4	Water	46.3458	33.32021
5	2000	1200	0.5	Coconut Oil	49.7072	33.92839
6	2000	1500	0.3	SAE30	34.7167	30.81077
7	3000	1000	0.5	SAE30	49.9803	33.97598
8	3000	1200	0.3	Water	33.9067	30.60571
9	3000	1500	0.4	Coconut Oil	43.3011	32.72998

Table 8. Signal to noise ratios for forming angle

Larger is better

Level	Speed (rpm)	Feed (mm/min)	Depth (mm)	Lubrication
1	32.49	**32.80**	30.84	**32.59**
2	**32.69**	32.44	32.95	32.53
3	32.44	32.37	**33.82**	32.50
Delta	0.25	0.43	2.98	0.09
Rank	3	2	1	4

4.0 ANOVA Analysis

ANOVA helps in determining which process parameters significantly affect the outcomes in SPIF. By analyzing the variance within experimental data, it identifies the influence of each parameter and their interactions on specific response variables, such as formability, surface roughness, and wall angle.

The study revealed that step depth and tool diameter significantly influence the formability and surface quality of titanium sheets in SPIF. Optimal parameter settings were determined to enhance the process outcomes[37]. The analysis indicated that parameters such as tool rotation speed and feed rate have a significant effect on the

Table 9. ANOVA: Maximum Forming Angle values versus tool dia., speed, feed, and step size

Source	DF	Seq SS	Contribution %	Adj SS	Adj MS	F-Value	P-Value
Regression	4	312.613	95.31	312.613	78.153	0.30	0.006
A	1	0.001	0.000	0.000	0.000	0.012	0.000
B	1	7.212	2.20	7.212	7.212	0.87	0.243
C	1	305.225	93.05	305.225	305.225	0.29	0.001
D	1	0.175	0.05	0.175	0.175	0.05	0.841
Error	4	15.399	4.69	15.399	3.850		
Total	8	328.011	100.0				

thickness distribution and surface finish of the formed titanium parts[38].

Applying ANOVA in the study of SPIF for titanium sheets allows for a systematic evaluation of process parameters, leading to improved formability and surface quality. The referenced studies demonstrate the effectiveness of ANOVA in identifying significant factors and optimizing the SPIF process for titanium and its alloys. To statistically evaluate the influence of process parameters on surface roughness and forming angle, ANOVA was applied. The F-test served as the primary threshold for determining significance, distinguishing critical factors from those with negligible effects. Below is an ANOVA study of surface roughness and forming angle. Table 9 shows the ANOVA results for maximum forming angle values, analyzing the significance of tool diameter, speed, feed rate, and step size on the formability in the SPIF process.

4.1 Confirmation Run

Response parameters	Optimum conditions
Surface Roughness	A2B1C2D1
Forming Angle	A2B1C3D1

5.0 Conclusion

The study investigated the influence of process parameters spindle speed, table feed, step-down depth, and lubrication on Figure 5 illustrates the Signal-to-Noise (S/N) graph for the maximum forming angle, showing the impact of various process parameters on formability in the SPIF process.surface roughness and forming angle during the SPIF of pure titanium sheets. Using an L9 orthogonal array design, the experiments revealed that coconut oil significantly outperformed water and SAE 30 lubricants in minimizing surface roughness, highlighting lubrication as the most critical factor for surface finish. However, lubrication conditions showed no measurable impact on the forming angle. The experimental investigation into the SPIF process revealed critical insights into how various process parameters influence both surface roughness and formability of the formed components. among the parameters studied, lubrication emerged as the most influential factor affecting surface roughness. its presence significantly reduced friction between the tool and the workpiece, resulting in smoother surfaces. following lubrication, spindle speed, feed rate, and step size were also found to impact surface roughness, though to a lesser extent and in that descending order of influence. additionally, the tool diameter played a crucial role; increasing the diameter beyond 2 mm led to noticeable improvements in surface quality, likely due

to better load distribution and reduced tool penetration depth.when evaluating formability, which in this context is characterized by the maximum achievable wall angle without failure, a different trend was observed. higher spindle speeds were associated with a reduction in formability, potentially due to increased thermal effects or dynamic instabilities at elevated rotational speeds. interestingly, unlike its pronounced impact on surface roughness, lubrication showed negligible influence on formability. this suggests that while lubrication is essential for enhancing surface characteristics, it does not significantly contribute to the material's ability to undergo plastic deformation at steep angles.

To reinforce these observations, a comprehensive statistical analysis was performed using response tables and ANOVA. The results of this analysis confirmed that lubrication is the dominant parameter affecting surface finish, affirming its importance in minimizing roughness. On the other hand, spindle speed was identified as the most critical parameter influencing formability, underscoring the need for careful control of rotational speed during the SPIF process. These findings provide a detailed understanding of parameter interactions and offer practical guidance for process optimization in SPIF, enabling manufacturers to tailor surface quality and formability according to specific application requirements.

6.0 References

1. Baharudin BTHT, Azpen QM, Sulaima S, Mustapha F. Experimental investigation of forming forces in frictional stir incremental forming of aluminum alloy AA6061-T6. Metals. 2017; 7(11):484. https://doi.org/10.3390/met7110484
2. Festas A, Ramos A, Davim JP. Machining of titanium alloys for medical application - A review. Proc Inst Mech Eng Part B J Eng Manuf. 2022; 236(4):309-318. https://doi.org/10.1177/09544054211028531
3. Singaravel B, Shekar K, Reddy G, Sunkeswram DP. Experimental investigation of vegetable oil as dielectric fluid in Electric discharge machining of Ti-6Al-4V. Ain Shams Eng J. 2019; 11. https://doi.org/10.1016/j.asej.2019.07.010
4. Nalbant M, Gökkaya H, Sur G. Application of Taguchi method in the optimization of cutting parameters for surface roughness in turning. Mater Des. 2007; 28(4):1379-1385. https://doi.org/10.1016/j.matdes.2006.01.008
5. Crina R. New configurations of the SPIF Process - A review. J Eng Stud Res. 2010; 16(4).
6. Echrif SBM, Hrairi M. Research and progress in incremental sheet forming processes. Mater Manuf Process. 2011; 26(11):1404-1414. https://doi.org/10.1080/10426914.2010.544817
7. Behera AK, Verbert J, Lauwers B, Duflou JR. Tool path compensation strategies for single point incremental sheet forming using multivariate adaptive regression splines. Comput-Aided Des. 2013; 45(3):575-590. https://doi.org/10.1016/j.cad.2012.10.045
8. Agrawal MK, Singh P, Mishra P, Deb RK, Mohammed KA, Kumar S, *et al*. A brief review on the perspective of a newer incremental sheet forming technique and its usefulness. Adv Mater Process Technol. 2024; 10(2):506-516. https://doi.org/10.1080/2374068X.2023.2168288
9. Jain PS, Kagzi SA, Patel S, Vasava J. An analysis of the effect of various parameters on surface roughness, springback and thinning while performing single point incremental forming on polypropylene sheet. Proc Inst Mech Eng Part E J Process Mech Eng. 2021; 09544089211047203. https://doi.org/10.1177/09544089211047203
10. Hagan E, Jeswiet J. A review of conventional and modern single-point sheet metal forming methods. Proc Inst Mech Eng Part B J Eng Manuf. 2003; 217(2):213-225. https://doi.org/10.1243/095440503321148858
11. Lisowicz J, Krupa K, Leksycki K, Rusinek R, Wojciechowski S. Analysis of tool wear in finish turning of titanium alloy Ti-6Al-4V under minimum quantity lubrication conditions observed with recurrence quantification analysis. Materials. 2025;18(1). https://doi.org/10.3390/ma18010079 PMid:39795724 PMCid:PMC11721966
12. Oleksik V, Trzepieciński T, Szpunar M, Chodoła Ł, Ficek D, Szczęsny I. Single-point incremental forming of titanium and titanium alloy sheets. Materials. 2021; 14(21):6372. https://doi.org/10.3390/ma14216372 PMid:34771897 PMCid:PMC8585273
13. Dabwan A, Ragab AE, Saleh MA, Anwar S, Ghaleb AM, Rehman AU. Study of the effect of process parameters on surface profile accuracy in single-point incremental sheet forming of AA1050-H14 aluminum alloy. Adv Mater Sci Eng. 2020; 2020(1):7265941. https://doi.org/10.1155/2020/7265941
14. Fan G, Sun F, Meng X, Gao L, Tong G. Electric hot incremental forming of Ti-6Al-4V titanium sheet. Int

J Adv Manuf Technol. 2010; 49(9):941-947. https://doi.org/10.1007/s00170-009-2472-2
15. Li W, Chang Z, Chen J. Impact of strain gradient on the structural refining and hardening in a CP-Ti through double sheet-assisted incremental sheet forming method. J Alloys Compd. 2025; 1010:177598. https://doi.org/10.1016/j.jallcom.2024.177598
16. Vanhove H, Mohammadi A, Duflou JR. Incremental forming of aluminium alloys in cryogenic environment. AIP Conf Proc. 2016; 1769(1):070020. https://doi.org/10.1063/1.4963473
17. Trzepieciński T, Oleksik V, Pepelnjak T, Najm SM, Paniti I, Maji K. Emerging trends in single point incremental sheet forming of lightweight metals. Metals. 2021; 11(8):1188. https://doi.org/10.3390/met11081188
18. Hu B, Yuan S, Zou Z, Ren Z, Tang P, Zhao X, *et al*. Mechanical analysis prior to the steady-state cutting of TC4 titanium alloy. Measurement. 2025; 244:116461. https://doi.org/10.1016/j.measurement.2024.116461
19. Kumar A, Gulati V, Kumar P. Effects of process parameters on surface roughness in incremental sheet forming. Mater Today Proc. 2018; 5:28026-28032. https://doi.org/10.1016/j.matpr.2018.10.043
20. Deokar S, Jain P, Tandon P. Formability assessment in single point incremental sheet forming through finite element analysis. Mater Today Proc. 2018; 5:25430-25439. https://doi.org/10.1016/j.matpr.2018.10.348
21. Azevedo NG, Farias JS, Bastos RP, Teixeira P, Davim JP, Alves de Sousa RJ. Lubrication aspects during Single Point Incremental Forming for steel and aluminum materials. Int J Precis Eng Manuf. 2015; 16(3):589-595. https://doi.org/10.1007/s12541-015-0079-0
22. Diabb J, Rodriguez C, Mamidi N, Sandoval J, Taha-Tijerina J, Martinez-Romero O, *et al*. Study of lubrication and wear in Single Point Incremental sheet Forming (SPIF) process using vegetable oil nanolubricants. Wear. 2017; 376-377:777-785. https://doi.org/10.1016/j.wear.2017.01.045
23. Beşliu-Băncescu I, Slatineanu L, Dodun O, Nagit G. Influence of lubrication and cooling on the quality of Single-Point Incremental Forming parts of polycarbonate sheets. J Manuf Mater Process. 2021; 5:75. https://doi.org/10.3390/jmmp5030075
24. Ai S, Long H. A review on material fracture mechanism in incremental sheet forming. Int J Adv Manuf Technol. 2019; 104(1):33-61. https://doi.org/10.1007/s00170-019-03682-6
25. Yan Z, Hassanin H, El-Sayed M, Eldessouky H, Rizki J, Djuansjah P, *et al*. Multistage tool path optimisation of Single-Point Incremental Forming process. Materials. 2021; 14(22):6794. https://doi.org/10.3390/ma14226794 PMid:34832197 PMCid:PMC8620775
26. Habeeb H, Jweeg M, Abbar A. Effect of the Single-Point Incremental Forming process parameters on the surface roughness of aluminum alloy Al 2024-O draw pieces. Adv Sci Technol Res J. 2023; 17:155-163. https://doi.org/10.12913/22998624/174364
27. McAnulty T, Jeswiet J, Doolan M. Formability in single point incremental forming: A comparative analysis of the state of the art. CIRP J Manuf Sci Technol. 2017; 16:43-54. https://doi.org/10.1016/j.cirpj.2016.07.003
28. Afonso D, Alves de Sousa R, Torcato R. Integration of design rules and process modelling within SPIF technology-A review on the industrial dissemination of single point incremental forming. Int J Adv Manuf Technol. 2018; 94(9):4387-4399. https://doi.org/10.1007/s00170-017-1130-3
29. Lu H, Liu H, Wang C. Review on strategies for geometric accuracy improvement in incremental sheet forming. Int J Adv Manuf Technol. 2019; 102(9):3381-3417. https://doi.org/10.1007/s00170-019-03348-3
30. Trzepieciński T, Kubit A, Dzierwa A, Krasowski B, Jurczak W. Surface finish analysis in Single Point Incremental Sheet Forming of rib-stiffened 2024-T3 and 7075-T6 alclad aluminium alloy panels. Materials. 2021; 14(7). https://doi.org/10.3390/ma14071640 PMid:33801612 PMCid:PMC8038002
31. Bhattacharya A, Singh S, Maneesh K, Nallagundla VR, Cao J. Formability and surface finish studies in single point incremental forming. J Manufact Sci Eng. 2011; 133. https://doi.org/10.1115/1.4005458
32. Vahdani M, Mirnia MJ, Gorji H, Bakhshi-Jooybari M. Experimental investigation of formability and surface finish into resistance Single-Point Incremental Forming of Ti-6Al-4V titanium alloy using taguchi design. Trans Indian Inst Met. 2019; 72(4):1031-1041. https://doi.org/10.1007/s12666-019-01577-4
33. Henia A, Hassine H. Taguchi grey relational analysis for parametric optimization of incremental forming process of bimetallic Steel-CP Titanium composite sheet. 2023.
34. Rauf A, Khan MA, Jaffery SHI, Butt SI. Effects of machining parameters, ultrasonic vibrations and cooling conditions on cutting forces and tool wear in meso scale ultrasonic vibrations assisted end-milling (UVAEM) of Ti-6Al-4V under dry, flooded, MQL and cryogenic environments - A statistical analysis. J Mater Res Technol. 2024; 30:8287-8303. https://doi.org/10.1016/j.jmrt.2024.05.202

35. Behera AK, Lauwers B, Duflou JR. Advanced feature detection algorithms for incrementally formed sheet metal parts. Trans Nonferrous Met Soc China. 2012; 22:s315-s322. https://doi.org/10.1016/S1003-6326(12)61725-7
36. Kumar Y, Kumar S. Experimental and analytical evaluation of incremental sheet hydro-forming strategies to produce high forming angle sheets. Heliyon. 2019; 5(6):e01801. https://doi.org/10.1016/j.heliyon.2019.e01801 PMid:31193947 PMCid:PMC6551419
37. Marcin S, Ostrowski R, Trzepieciński T, Kascak L. Central composite design optimisation in Single Point Incremental Forming of truncated cones from commercially pure titanium Grade 2 sheet metals. Materials. 2021; 14:3634. https://doi.org/10.3390/ma14133634 PMid:34209927 PMCid:PMC8269636
38. Kim M, Lee H, Park N. Evaluation of deformation for titanium alloy sheet in single point incremental forming based on asymmetric yield function. Int J Mater Form. 2022; 15(5):66. https://doi.org/10.1007/s12289-022-01712-5