

STUDY OF THE INFLUENCE OF PICUAL OLIVE OIL ON THE FORMABILITY AND SURFACE QUALITY OF PARTS MACHINED BY INCREMENTAL FORMING OF AEROSPACE ALUMINIUM ALLOYS

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Abstract: The current study aims to evaluate the impact of lubrication at the tool-workpiece interface on material formability, surface roughness of the machined part, and residual stresses in superficial layer in single point incremental forming of 6061-T4 and 2024-T3 aluminum alloys. Picual olive oil was used as a lubricant. The findings indicate that lubricated machining consistently produced superior outcomes compared to dry machining as it simultaneously increased part depth, improved surface roughness, and minimized residual stresses.

Keywords: AA2024-T3, AA6061-T4, dry machining, lubrication, SPIF, surface roughness, residual stresses

INTRODUCTION

As consumers become increasingly discerning, informed, and focused on uniqueness, companies are forced to adopt strategies centered on short product lifecycles, low-volume production, and mass customization. Business models like “fast fashion” demonstrate that the rapid delivery of trendy products for a limited time is more profitable than maintaining large inventories [1, 2]. In this competitive landscape, characterized by rapid change of needs, companies must shift from traditional mass production to more adaptable systems that facilitate flexible production [3]. This transition necessitates the implementation of flexible, smart, and interconnected technologies that enable the manufacture of one-off or small-batch products at costs and speeds comparable to those of mass production [4]. Furthermore, sustainability has evolved from merely being a regulatory requirement to becoming a competitive advantage, an operating system in which performance (i.e., lower energy consumption, reduced waste, and circularity) becomes the primary driver of value. Single point incremental forming (SPIF) is an emerging flexible sheet metal forming process that is ideally positioned on the path toward sustainable manufacturing. SPIF is a die-less, CNC-driven sheet forming method in which a very simple tool follows a predefined tool path over a clamped metal sheet, progressively shaping it into a three-dimensional geometry. The die-less characteristic of this process enables the production of complex geometries without the need for expensive dedicated tooling, making it particularly well-suited for small-batch and prototype production [5 – 7]. The localized nature of the deformation in SPIF allows for greater formability without premature failure, compared to traditional sheet metal forming processes. Additionally, the ability of the process to facilitate the use of recycled materials and minimize material waste aligns directly with the goals of a circular economy. Therefore, SPIF is expected to play a growing role for sustainable production across various sectors, especially aerospace, automotive, medical, and architectural industries [8, 9].

Despite the aforementioned advantages, several aspects still remain under study. One of the most significant challenges of SPIF is poor surface quality resulting from continuous contact between the forming tool and the sheet across the entire toolpath. Consequently, the application of lubricants and appropriate lubrication techniques is of great importance for achieving the desired surface quality. Inadequate lubrication leads to increased surface roughness, galling, tool wear, and premature failure of metal sheet [10, 11].

AA6061 and AA2024 are among the most used aluminum alloys in automotive, aerospace, and structural applications. Aluminum alloy 6061 is also widely utilized in food handling equipment and cookware due to its excellent corrosion resistance. This property is crucial for maintaining cleanliness and durability in environments that frequently encounter moisture and acidic substances. Furthermore, its superior machinability and weldability properties enable the precise and reliable manufacturing of various kitchen tools and equipment. The U.S. Food and Drug Administration (FDA) consider aluminum to be Generally Recognized as Safe (GRAS) for food contact and packaging, including aluminum foil and food-grade containers, when used as intended [12]. AA6061 alloy has been processed using single point incremental forming with various lubricants (e.g., mineral oils, greases/pastes [13], graphite, graphite-based anti-seize, MoS₂, copper-based anti-seize [14], sunflower, corn, soybean oil [11], hemp seed oil methyl ester [15]). In contrast, there are fewer studies that focus on the role of lubrication in the single point incremental forming of 2024 aluminum alloy [16].

The trend is replacing mineral oils (derived from crude oil) with vegetable oils (natural esters) due to their comparable or superior technical properties, including: high polarity, which allows vegetable oils to adhere strongly to metal surfaces and form an effective lubricating film; a better viscosity index than mineral oils, meaning they maintain stable viscosity across a wide range of temperatures; a significantly higher flash point (over 300 °C) compared to mineral oils, which reduces the risk of fires in industrial applications; and their extraction from renewable resources. Additionally, vegetable oils are biodegradable and non-toxic, presenting minimal environmental risks in the event of accidental leaks or spills, unlike mineral oils, which contribute to pollution [17, 18]. However, although they are very high performing, vegetable oils may exhibit lower oxidative stability at elevated temperatures (above 80 °C) when compared to mineral oils. This limitation can be effectively addressed using antioxidants and various chemical modifications, such as hydrogenation or transesterification, in modern production processes [19, 20].

The objective of this study is to evaluate how different lubrication conditions influence the formability, surface quality, and residual stress state of parts manufactured by single point incremental forming of 6061-T4 and 2024-T3 aluminum alloys. The study involved both dry machining and lubricated machining, utilizing Picual extra virgin olive oil from the Spanish harvest as the lubricant.

MATERIALS AND METHODS

Used materials and geometry of part

Two aluminum alloys were used to conduct experiments: AA2024-T3 and AA6061-T4. These two materials were chosen because of their wide applicability across various industrial sectors, particularly the automotive and aerospace industries, due to their unique properties. AA2024, a 2xxx series alloy based on copper, is known for its high strength and fatigue resistance, making it the primary choice for aircraft structural components. AA6061, a 6xxx series alloy, based on magnesium and silicon, is a versatile, general-purpose alloy, preferred for welded structures, automotive bodies, and components requiring good corrosion resistance. It is easy to machine and has very good weldability and high corrosion resistance.

Samples of 150×150 mm, with a thickness of 0.6 mm, were prepared from each material for testing purpose. The material properties and their chemical composition are presented in Table 1 and Table 2. A funnel geometry for the part was chosen as shown in Figure 1.

Table 1. Mechanical properties of materials

Materials	Yield Strength [MPa]	Ultimate Strength [MPa]	Modulus of elasticity [MPa]	Elongation [%]
AA2024-T3	310	448	73.1×10^3	15
AA6061-T4	145	241	68.9×10^3	22

Table 2. Chemical composition of materials

Materials	Al [%]	Mg [%]	Si [%]	Fe [%]	Cu [%]	Cr [%]	Mn [%]	Zn [%]	Others [%]
AA2024-T3	96.15	0.80	0.10	0.19	2.34	0.02	0.27	0.07	≤0.1
AA6061-T4	97.39	0.85	0.65	0.42	0.23	0.17	0.14	0.06	≤0.1

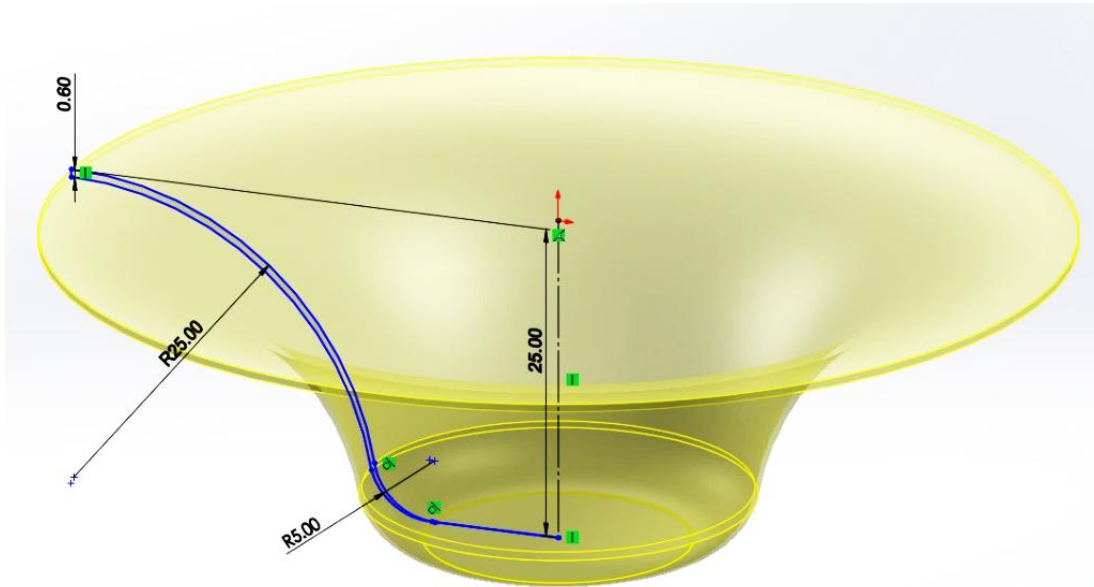


Figure 1. Geometry of part

Experimental set-up and process parameters

Experimental tests were carried out on a LAGUN L850 vertical machining center, according to a factorial optimal (custom) design, using a spherical-head tool of 10mm diameter, made by tungsten carbide (Figure 2). Three input factors were investigated: one numerical and two categorical factors. The numerical factor, namely tool vertical step (Δz), has three levels of variation (Table 3). The categorical factors are lubrication conditions, with two levels of variation (dry and lubricated machining), and the workpiece material with two levels of variation (AA2024-T3 and AA6061-T4). The feed rate of 600 mm/min, and the spindle speed of 30 rpm were kept constant.

For the lubricated condition, Picual extra virgin olive oil (the most widely cultivated olive variety globally, representing approximately 30 % of total olive oil production [21, 22]) sourced from the Spanish harvest was applied manually to the upper surface of the sheet prior to each test, ensuring full coverage of the contact area between the tool and the workpiece. No reapplication was made during the forming process. The exact quantity of lubricant was not measured, as lubrication was treated as a qualitative binary factor (presence vs. absence), with the focus placed on its effect on the measured outputs rather than on its quantitative tribological characterization. Details regarding its fatty acid profile can be found in Table 4 [23]. The high oleic acid content contributes to excellent oxidative stability and a significant ability to form boundary lubrication films, both of which are crucial for SPIF.

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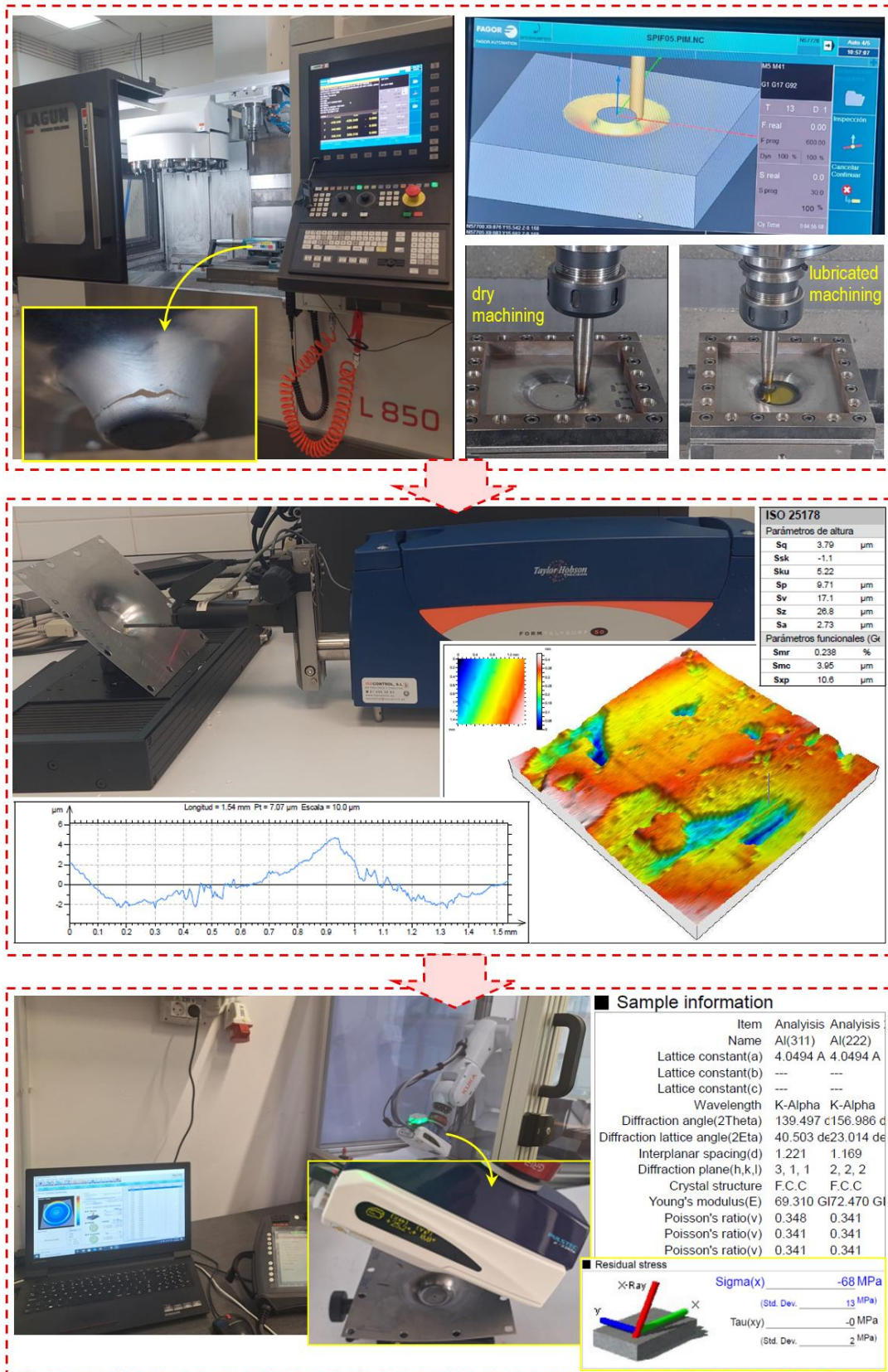


Figure 2. Experimental set-up used to conduct experimental tests

Table 3 Variation levels of the input parameters

Process Variables	Variation Levels		
	Level 1	Level 2	Level 3
Tool vertical step, Δz [mm]	0.25	0.5	0.75
Lubrication conditions	Dry machining		Lubricated machining
Workpiece material	AA2024-T3		AA6061-T4

Table 4. Fatty acid composition of Picual extra virgin olive oil

Fatty acid	Type	Carbon chain	Content [%]
Oleic acid	Monounsaturated (MUFA)	C18:1	$\approx 79-82$
Palmitic acid	saturated	C16:0	$\approx 11-12$
Linoleic acid	Polyunsaturated (PUFA)	C18:2	$\approx 3-5$

The depth of the part, surface roughness (S_a), and residual stresses in the superficial layer were analyzed as output parameters to assess the formability of materials and the surface quality of the formed parts, based on the input parameters. Surface roughness was measured using a Taylor Hobson FORM TALYSURF 50 stylus profilometer (Taylor Hobson, AMETEK, UK) at three different locations on each part. In each location, three measurements were taken over a scanned area of 1.5×1.5 mm, and an average value was calculated. Residual stresses were measured using a μ -X360s residual stress analyzer (Pulstec Industrial Co., Ltd., Japan), as illustrated in Figure 2. Three measurements were conducted for each part, and the average of these measurements was used for the analysis of the results.

RESULTS AND DISCUSSION

The analysis of variance (ANOVA) was employed for the statistical evaluation of the experimental results. All tests were performed at a significance level of $\alpha = 0.05$ (95% confidence level), meaning that a factor was considered to have a statistically significant effect on the response if its associated p-value was less than 0.05. Regression models were subsequently derived for each output response to describe the influence of the significant input parameters on the experimental results. All three models were found to be statistically significant ($p < 0.05$). The predictive capability of the models was assessed using the coefficients of determination R^2 , adjusted R^2 , and predicted R^2 , which together provide a comprehensive evaluation of model fit and generalization ability. A difference smaller than 0.2 between the adjusted R^2 and predicted R^2 is recommended by the software, indicating that the model is not overfitted and retains good predictive capability. For all three regression models, this condition was satisfied (Table 5). The part depth model and residual stresses model showed very high predictive capability, while a moderate fit was obtained for the surface roughness model. Although the three R^2 values are lower compared to the other two models, the difference between adj. R^2 and pred. R^2 remains within the recommended threshold ($0.1713 < 0.2$), confirming that the model is not overfitted and is statistically valid. The lower R^2 is consistent with the well-documented complexity of this response in SPIF [24 – 26].

Table 5. Fit statistics

Model	R ²	Adjusted R ²	Predicted R ²
Depth of the part	0.9865	0.9828	0.9735
Surface roughness, Sa	0.6472	0.5884	0.4171
Residual stresses	0.9937	0.9903	0.9808

Effects of the input factors on depth of the part

The ANOVA results for depth of the part are presented in Table 6. A linear model was generated for determining influences. The model F-value of 267.04 indicates that the model is significant, with only a 0.01 % probability that such a large value could occur due to noise. The most influential factors on part depth are C-material, B-Lubrication conditions, and A-Step size.

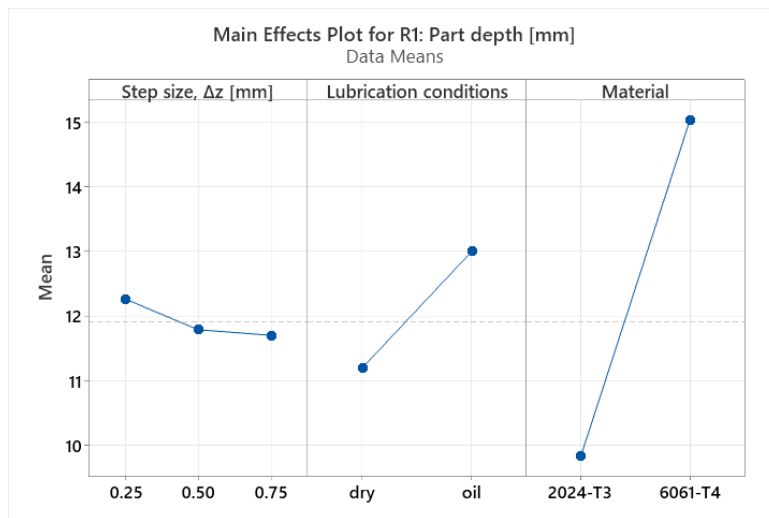
Table 6. ANOVA results for depth of the part

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	101.49	3	33.83	267.04	< 0.0001
A-Step size, Δz	0.7992	1	0.7992	6.31	0.0289
B-Lubrication conditions	3.26	1	3.26	25.74	0.0004
C-Material	88.96	1	88.96	702.17	< 0.0001
Residual	1.39	11	0.1267		
Cor Total	102.89	14			

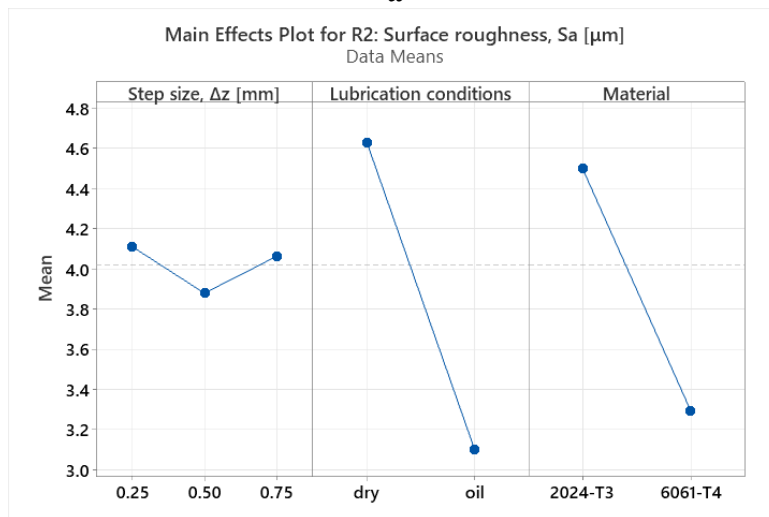
The effects of input factors on the depth of part are illustrated in Figure 3a. The superior formability of the AA6061-T4 aluminum alloy enables the manufacturing of deeper parts compared to the 2024-T3 aluminum alloy, achieving a depth increase of up to 34.27 % in lubricated machining and 37.6 % in dry machining. Lubrication conditions notably affect the depth of the part when machining the 2024-T3 aluminum alloy; in this case, the depth of the part increased by 16.56 %, while it only increased by 5.24 % for the 6061-T4 alloy. Additionally, employing a smaller vertical tool step led to greater part depths, with increases of 6.57 % for the 2024-T3 alloy and 7.35 % for the 6061-T4 aluminum alloy.

Effects of the input factors on surface roughness, Sa

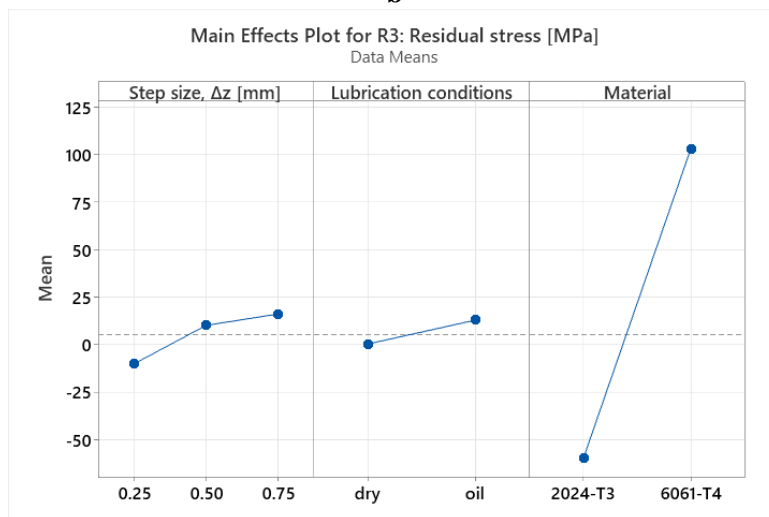
The ANOVA results for surface roughness are presented in Table 7. A linear model was generated for determining influences. The model F-value of 11.1 indicates that the model is significant, with a 0.19 % probability that such value could occur due to noise. The most influential factors on part depth are B-Lubrication conditions and C-material.



a



b



c

Figure 3. Main effects of the input factors on the output results

Table 7. ANOVA results for surface roughness, Sa

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	11.76	2	5.88	11.01	0.0019
B-Lubrication conditions	6.55	1	6.55	12.26	0.0044
C-Material	3.33	1	3.33	6.22	0.0282
Residual	6.41	12	0.5343		
Cor Total	18.17	14			

The effects of input factors on the surface roughness, Sa, are illustrated in Figure 3b. For the 2024-T3 aluminum alloy, dry machining led to an increase in surface roughness up to 47.71 % compared to lubricated machining. In contrast, dry machining of the 6061-T4 aluminum alloy resulted in a smaller increase in surface roughness, reaching up to 30.56 % compared to lubricated machining.

The workpiece material also plays an important role in influencing surface roughness. Specifically, for the 2024-T3 aluminum alloy, surface roughness values were found to be up to 47.74 % higher for dry machining and up to 40.39 % higher for lubricated machining when compared to the 6061-T4 alloy.

The vertical step of the tool, contrary to expectations, had the least impact on surface roughness. For the 2024-T3 aluminum alloy, increasing the vertical tool step from 0.25 mm to 0.5 mm led to a reduction in roughness by 36.91 % in lubricated machining and by 17.23 % in dry machining. This variation can be attributed to the deposits of workpiece material that formed on the tool-head surface during the initial experimental tests when a vertical step size of 0.25 mm was used. These deposits were analyzed using an Olympus SZX7 stereo microscope. The tool-head surface was then cleaned and reexamined, as shown in Figure 4. In contrast, when machining the 6061-T4 alloy, increasing the vertical tool step caused an increase in roughness, with up to 22.65 % in the case of lubricated machining and up to 35.05 % in dry machining.

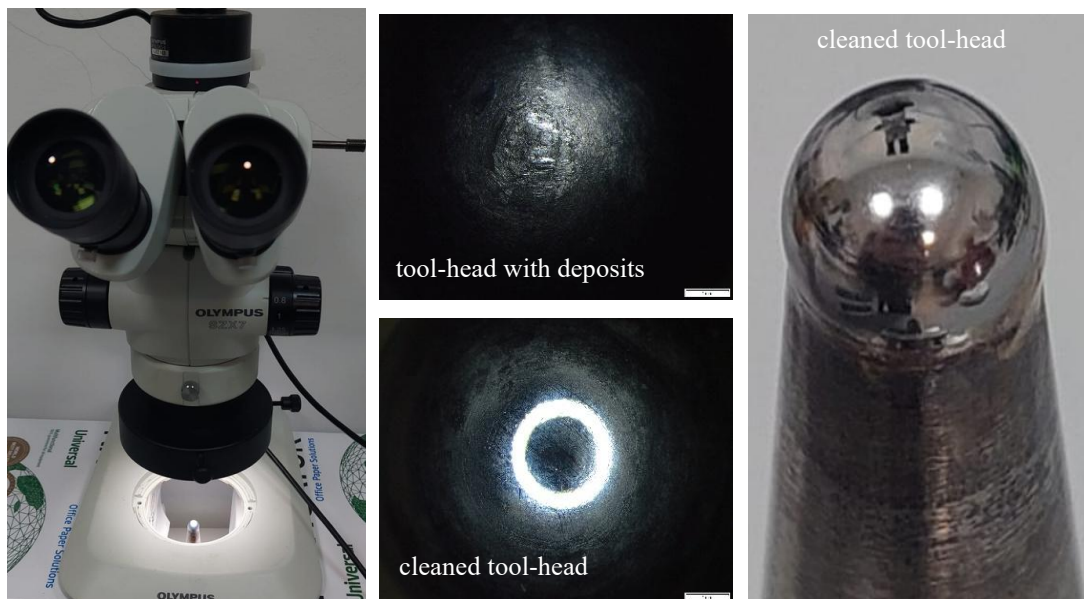


Figure 4. Evaluation of the tool-head state

Effects of the input factors on residual stresses

The ANOVA results for residual stresses are presented in Table 8. A reduced two-factors iteration model was generated for determining influences. The model F-value of 286.13 implies the model is significant. There is only a 0.01 % chance that an F-value this large could occur due to noise. The most influential factors on part depth are C-material, A-Step size, and B-Lubrication conditions. There are also significant interactions: AC and BC.

Table 8. ANOVA results for residual stresses

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	1.054E+05	5	21072.82	286.13	< 0.0001
A-Step size, Δz	2720.27	1	2720.27	36.94	0.0002
B-Lubrication conditions	1348.67	1	1348.67	18.31	0.0021
C-Material	88320.86	1	88320.86	1199.23	< 0.0001
AC	3345.07	1	3345.07	45.42	< 0.0001
BC	4002.38	1	4002.38	54.34	< 0.0001
Residual	662.83	9	73.65		
Cor Total	1.060E+05	14			

Workpiece material has the greatest influence on residual stress. It has been observed that, under identical machining conditions, stresses characteristics differ between the two materials. The residual stresses in the surface layer of the 2024-T3 aluminum alloy are compressive, while those in the 6061-T4 aluminum alloy are tensile. This difference can be attributed to the distinct mechanical properties of the two materials and their different work-hardening behaviors: AA2024-T3 is a high-strength, copper-alloyed aluminum known for its exceptional fatigue resistance, with a yield strength exceeding 300 MPa. During the SPIF process, the combination of local heat generation, intense localized compression, and the material resistance to deformation can lead to local surface hardening and thermal contraction. These phenomena contribute to the development of residual compressive stresses on the surface (which justify the high fatigue resistance of material). In contrast, AA6061-T4, which is alloyed with magnesium and silicon, has a lower yield strength (approx. 150 MPa). The deformation and thermal cycles during SPIF may cause surface tensile stress in 6061-T4 alloy, as the lower-strength material cannot sustain the same localized compressive deformation as 2024-T3 alloy (under the same working conditions). In addition, 6061-T4 alloy exhibits higher residual stresses compared to 2024-T3 alloy, with up to 45.19% in lubricated machining and up to 59.76 % in dry machining.

Lubrication conditions also influence the residual stresses value. Specifically, dry machining leads to an increase in residual stresses of up to 32.35 % for the 2024-T3 alloy and up to 67.67 % for the 6061-T4 alloy.

Increasing the vertical step of the tool generally results in higher residual stresses. For the 2024-T3 alloy, residual stresses increased up to 15.79 % in lubricated machining and up to 14.17 % in dry machining. Similarly, for the 6061-T4 alloy, higher tool step values resulted in greater residual stresses, with up to 65.21 % in lubricated machining and up to 27.81 % in dry machining.

CONCLUSIONS

The experimental results demonstrate that across all response variables and both alloys, lubricated machining consistently produced superior outcomes compared to dry machining. Lubrication with Picual extra virgin olive oil simultaneously allows for higher part depth, reduced surface roughness, and minimized residual stress magnitudes. Lubrication increased forming depth by up to 16.56 % for AA2024-T3 and 5.24 % for AA6061-T4, while significantly reducing surface roughness by up to 47.71 % and 30.56 % respectively, confirming the critical role of lubrication in reducing tool-sheet friction and suppressing surface defect formation. Regarding residual stresses, lubrication reduced their magnitude for both alloys; however, this effect must be interpreted in the context of stress nature: for AA2024-T3, which develops compressive residual stresses, the higher stress magnitudes observed under dry conditions could be considered advantageous from a fatigue resistance perspective, while for AA6061-T4, which develops tensile residual stresses, lubrication is clearly preferable as it limits the development of potentially detrimental tensile stresses.

These findings underscore the necessity of adopting appropriate lubrication strategies in industrial SPIF applications and provide a strong motivation for the investigation of sustainable lubricant alternatives, including bio-based and waste-derived oils, as environmentally responsible substitutes for conventional mineral lubricants.

Limitations of the study

The present study has several limitations that should be acknowledged. First, the lubrication condition was treated as a qualitative binary factor (presence vs. absence), and the exact quantity of lubricant applied was not measured or controlled, which limits the ability to draw quantitative tribological conclusions. Second, the experimental design considered a limited number of process parameters (i.e., workpiece material, lubrication condition, and vertical tool step) while other potentially influential factors (e.g., spindle speed, feed rate, and sheet thickness) were kept constant. Third, the moderate predictive capability of the regression model for surface roughness ($R^2 = 64.72\%$) suggests that additional uncontrolled variables influence this response. Finally, only two aluminum alloys were investigated, which restricts the generalizability of the findings to other materials commonly used in the aerospace industry.

Future direction of study

Based on the findings and limitations of this study, some directions for future research can be identified. First, a dedicated tribological investigation should be conducted to quantify the effect of lubricant amount, viscosity, and application method on SPIF process outputs, enabling a more rigorous characterization of lubrication conditions. Second, the oxidative stability and thermal behavior of the Picual extra virgin olive oil under the thermal and mechanical conditions encountered during SPIF should be assessed, as lubricant degradation during forming may influence surface quality and tool wear. Third, the potential reuse of waste olive oil as a bio-lubricant in SPIF represents an environmentally sustainable research direction, offering insights into both tribological performance and ecological impact.

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