Advances in Mechanical and Materials Engineering

Volume 40, 2023, Pages 113-123
https://doi.org/10.7862/rm.2023.12

THE FACULTY OF MECHANICAL ENGINEERING AND AERONAUTICS
RZESZOW UNIVERSITY OF TECHNOLOGY

Original Research

Influence of Input Parameters on the Coefficient of Friction during Incremental Sheet Forming of Grade 5 Titanium Alloy Sheets

Marcin Szpunar [1,*], Paulina Szawara [2], Piotr Myśliwiec [2], Robert Ostrowski [2]

[1] Doctoral School of Engineering and Technical Sciences at the Rzeszow University of Technology, Rzeszow University of Technology, al. Powst. Warszawy 12, 35-959 Rzeszów, Poland
[2] Department of Materials Forming and Processing, Rzeszow University of Technology, al. Powst. Warszawy 8, 35-959 Rzeszów, Poland; p.szawara@prz.edu.pl (P. Szawara); p.mysliwiec@prz.edu.pl (P. Myśliwiec); rostrows@prz.edu.pl (R. Ostrowski)

* Correspondence: d547@stud.prz.edu.pl

Received: 2 June 2023 / Accepted: 28 July 2023 / Published online: 4 September 2023

Abstract

This research paper focuses on investigating the influence of input parameters on the coefficient of friction (COF) during incremental sheet forming (ISF) of grade 5 titanium alloy sheet. Titanium alloys are widely used in various industries due to their corrosion resistance and strength to weight ratio. ISF is a flexible and cost effective process for producing complex shapes. The aim of this study was to gain insight into the frictional conditions during ISF that affect formability, surface quality, and overall process performance. The experiments were carried out using a combination of MoS_2 lubrication and friction stir rotation-assisted heating. COF was measured using a high precision piezoelectric dynamometer, taking into account axial and horizontal components of forming force. A split-plot design was used and 25 runs were performed to obtain the COF for each run. The results of the study provide valuable information on the relationship between input parameters and COF, contributing to the understanding of the frictional conditions in the ISF.

Keywords: ANOVA, coefficient of friction, incremental sheet forming, titanium alloys

1. Introduction

Titanium alloys are widely used in a variety of industries, including aerospace, automotive, orthopaedic, and dental, because of their exceptional corrosion resistance and impressive strength-to-weight ratio. Among the various techniques used to form titanium and its alloys, incremental sheet forming (ISF) stands out as a flexible and advantageous process compared to traditional sheet forming methods. It plays an important role in modern manufacturing by enabling the production of complex shapes at reduced cost (Oleksik et al., 2021). Using a universal set of tools, ISF allows the creation of a wide variety of shapes, resulting in increased production flexibility and reduced tooling costs. It also makes it easier to achieve higher levels of stress. However, it is most economically viable for low-volume production. This includes metal (Trzepieciński et al., 2022a), polymer (Rosca et al., 2021) and composite (Harhash & Palkowski, 2021) sheets. The main advantages associated with ISF include the ability to form elements on conventional CNC machines such as lathes or milling machines (Cheng et al., 2020; Jadhav et al., 2003).

In the ISF process, a circular forming tool gradually shapes the sheet by executing a coordinated motion around the stationary workpiece, The tool then performs a depth movement with a specified step size, forming the component by traversing the next horizontal trajectory at a feed rate (Harfoush et al., 2021; Patel and Gandhi, 2022). In ISF, friction plays a critical role in the interaction between the tool and the workpiece (Duflou et al., 2017). Friction not only influences the forming limit, but also the surface quality of the resulting parts (Szewczyk and Szwajka, 2023; Więckowski et al., 2023). As surface quality has a significant impact on the aesthetics, performance and service life of metal structures, it warrants serious attention.

The lubricants used in ISF are the same as those used in conventional sheet metal forming processes and are selected mainly on the basis of factors such as pressure values, material grade of the workpiece/tool material pair and tool speed (Najm et al., 2021). Several factors come into play when considering the potential use of the ISF method and ensuring forming accuracy. These include technological parameters (e.g., tool diameter, step size, tool rotational speed, friction conditions), product design factors (e.g., sheet thickness, die geometry) and mechanical parameters of the workpiece (e.g., work hardening, material anisotropy, Young's modulus) (Najm and Paniti, 2020). Higher tool rotational speeds allow greater plastic deformation to be applied to the sheet material without the risk of cracking, making them ideal for forming thin sheets with limited plasticity (Martins et al., 2008; Sbayti et al., 2020).

The challenge of achieving suitable forming conditions arises from the contact between relatively low strength materials and high hardness, high strength tools (Pepelnjak et al., 2022). Najm and Paniti (2021) used an artificial neural network to investigate and determine the formability of the workpiece and the geometry of the forming tools. They also derived an analytical equation for each output based on the weight and bias of the most accurate network prediction. Tooling characteristics were found to play an essential role in all predictions and to have a significant impact on the final products. Najm et al. (2021) investigated the effect of forming tool diameter, tool rotational speed, feed rates and coolant type on the hardness of EN AW-1100 aluminium alloy sheets in ISF. Various coolant oils and greases were analysed at the same feed rates and the study showed that the use of coolant oil increased hardness whereas the use of grease decreased hardness. Milutinović et al. (2021) fabricated a X6Cr17 stainless steel denture base plate for a full maxillary prosthesis using a lost wax technique. An ordinary form of mineral oil was selected as the lubricating agent in this particular case. Experimental tests on the surface roughness of the inner surface of the cup showed that the step size had a significant influence on the surface quality. Machine learning based procedure to predict result of surface roughness parameters (Ra, Rz) for heat assisted ISF titanium grade 5 was proposed by Bautista-Monsalve et al. (2021). The authors confirmed algorithm prediction potential with an experiment results. Sbayti et al. (2022) investigated the ISF process of a Ti6Al4V titanium alloy acetabular cup at high temperatures using finite element based simulations and an optimisation procedure. The effects of four key process parameters – coefficient of friction (COF), processing temperature, step depth and tool diameter - on the final part were analysed. The computational results showed that moth-flame optimisation, multiverse optimisation and Harris Hawk optimisation provided highly competitive geometry optimisation results. Popp et al. (2021) investigated the sheet bending mechanism in the ISF of AlCu4PbMgMn aluminium alloy blanks using finite element based analysis. The study showed that the shape of the retaining rings significantly influenced the final geometric accuracy of the parts produced by ISF. A novel method was presented by McPhillimy et al. (2022). The authors applied laser metal deposition to thicken locally titanium grade 2 sheet before incremental forming process. Such a treatment allowed them to improve drawpiece thickness homogeneity, but also caused early fracture phenomenon especially at high wall angles.

Numerous research studies have focused on parameter optimisation for incremental sheet forming of pure titanium sheets. Hussain et al. (2008) found that increasing the feed rate or incremental step depth reduced the formability, while increasing the tool diameter improved it. Ajay (2020) also confirmed that these input factors had the most significant influence on process parameters such as, wall angle, surface roughness and thickness. The increased relative tool speed was found to be critical to generate forming forces and ensuring successful forming commercially pure titanium sheets without cracking (Zwolak et al., 2022). However an elevated tool rotation causes increase in surface roughness Rz parameter of the formed sheets, while step size is a key factor affecting axial and in-plane forming force components (Szpunar et al., 2021). Trzepieciński et al. (2022b) studied input parameters of ISF titanium grade 5 sheets to find optimal one. The authors found that proper feed rate and tool rotational speed setup allows to achieve greater deformation. Kim et al. (2022) developed an CPB06ex2 anisotropic and asymmetric yield function for the titanium grade 5 sheet. The excellence was presented by the correlation with the experiment and finite element method results of the surface profile. Naranjo et al. (2017) conducted the analysis of ISF titanium grade 5 at elevated temperatures. They found not significant correlation between the temperature and surface quality. Ambrogio et al. (2018) investigated super plastic forming and ISF to obtain titanium protests without failure. On the other hand Racz et al. (2018) presented decision-making method to select the most favourable manufacturing method for titanium Ti6Al4V alloy dedicated for medical devices with forming at room temperature inclusion. Other studies have investigated the microstructural effects after ISF of pure titanium sheets. Kumar et al. (2020) investigated the magnitude and state of residual stresses in commercially pure grade 2 titanium after forming. They observed that increasing wall angles and incremental step depth resulted in higher residual tensile stresses. Li et al. (2023) carried out and experiment with titanium grade 1 perforated sheets. The authors found the limit for the wall angle as 60°, while with 45° good thickness distribution and geometric accuracy can be obtained. Mishra et al. (2021) analysed the evolution of microstructure and texture and found that prismatic slip dominated in the ISF of pure titanium, while twinning occurrence varied with several parameters and was heterogeneous. Yoganjaneyulu et al. (2021) analysed the effect of tool rotation on mechanical properties and microstructure and found that grain elongation and orientation followed the incremental step depth. They also found that tool rotation did not affect grain size, but higher rotation rates induced an effect of strain hardening by denser in dislocations.

A review of the literature indicates that research into the ISF of titanium sheets has focused primarily on investigating the influence of input parameters on geometric accuracy and mechanical properties. However, studies that specifically investigate friction conditions, quantified by COF, are relatively limited. Therefore, the aim of this research is to investigate the influence of the ISF input parameters: cavity pressure, tool rotational speed, feed rate and step size on the COF between a hemispherical solid carbide tool and a grade 5 titanium alloy sheet. By analysing the COF, this study aims to gain insight into the frictional conditions during the ISF process, which play a crucial role in the formability limits, surface quality and overall process performance.

2. Materials and Methods

The experimental material used was a 0.8-mm-thick Ti-6Al-4V titanium alloy sheet. At room temperature, the microstructure of this alloy is predominantly hexagonal closed packed (HCP) for the α phase and body centred cubic (BCC) for the β phase. The chemical composition of the sheets material presents Table 1.

Table 1. Chemical composition of the sheets material within % weight content (Titanium, 2023).

Component	Al	V	Fe	O	C	N	H	Ti
Wt. %	5.5−6.75	3.5−4.5	<0.4	<0.2	<0.08	<0.03	<0.015	remainder

This Ti-based alloy, known as a two-phase (α-β) alloy, is widely used in various fields such as turbine blades, discs, rings and structural components in the aerospace industry. Furthermore, Ti-6Al-4V is widely used as a biocompatible implant in medical applications. It has desirable properties such as high corrosion resistance, good weldability, excellent strength and a low modulus of elasticity. However, due to its complex microstructure at room temperature, this alloy is typically formed at elevated temperatures. Mechanical properties of the sheets material is presented in Table 2.

Table 2. Basic mechanical properties of the sheets material (Titanium, 2023).

Density	Ultimate Tensile Strength	Yield Tensile Strength	Elastic modulus	Hardness
4.43 g/cm^3	950 MPa	880 MPa	113.8 GPa	349 HV

The experiments involved the forming of drawpieces using a combination of ISO 6743/12 QB oil-based lubrication and friction stir rotation-assisted heating in a warm ISF. A die consisting of a housing and a blank holder were used to secure the displacement of the workpiece flange. Figure 1 shows the experimental setup. The blank holder was securely mounted with screws. An electric oil heater was placed within the die cavity and the oil pressure was maintained at a constant level during the forming process through a valve. The forming device was mounted on the bed of a PS95 CNC vertical milling machine. A 100 mm diameter workpiece was used to form conical truncated cones with varying wall angle from (Fig. 2). A tungsten carbide material was selected for the tool with a rounded tip with a radius of 4 mm. The tool was mounted in the face mill using an ER32 collet. To minimise friction, in the experiments a dry grease-free antifriction spray containing MoS_2 was used. This lubricant is temperature resistant from −185°C up to 400°C. Before applying the lubricant, the surfaces were thoroughly cleaned and degreased. During the process, the tool followed a spiral path as it indented into the workpiece. The path of the tool (Fig. 1), was generated using NX CAM software. The tool path was generated based on a numerical model that represents the desired shape of the part.

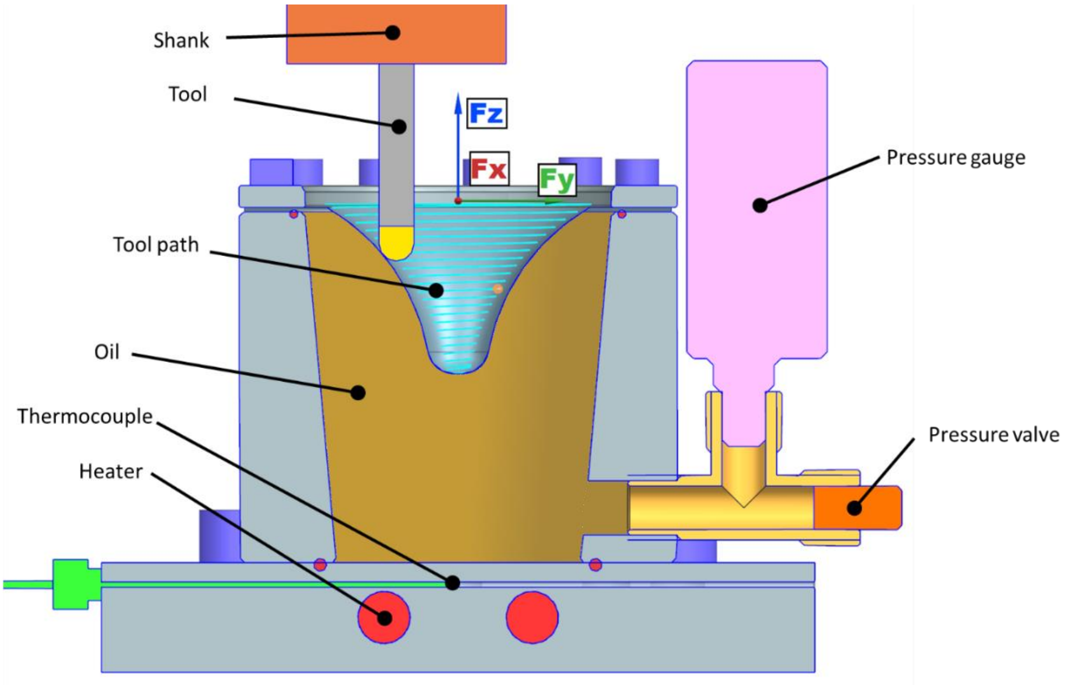

Fig. 1. Heat assisted incremental forming device.

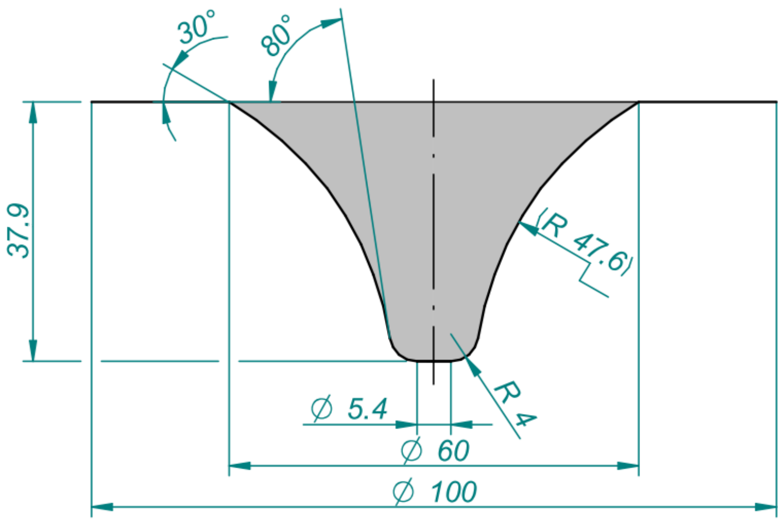

Fig. 2. Desired drawpice shape with varying wall angle from 30° to 80°.

A high-precision piezoelectric dynamometer from Kistler Holding AG in Winterthur, Switzerland, was used to measure the axial force (F_z) and the horizontal components of the forming force (F_x and F_y). This dynamometer has a maximum sampling rate of 200 kHz per channel.

The value of the COF was determined using the following equation (Decultot, 2011; Saidi et al., 2015):

$$\mu = \frac{\sqrt{{F_x}^2 + {F_y}^2}}{\sqrt{{F_z}^2}} \tag{1}$$

Equation (1) is a commonly used method for predicting the COF by considering the axial and horizontal forces experienced during the ISF process. This equation has been widely used by many researchers in this field. Shin (2021) in his thesis, carried out a finite element analysis (FEA) and found that the coefficient of friction had a minimal effect (less than 10%) on the axial force. However, higher COF values were associated with increased horizontal forces. Durante et al. (2009) also used this equation to determine the COF in sliding tests between an ISF tool and 20 mm wide specimens. Hamilton (2010) used the same equation in his thesis, which was subsequently validated by FEM analysis by Li et al. (2014).

The experiment used a split-plot design with a I-optimal criterion. There were 25 runs, carefully selected to optimise the design and efficiently capture relevant information. The factors in the experiment were coded to facilitate analysis. The low level of each factor was coded as −1, while the high level was coded as +1. The factors and their respective units were as shown in Table 3. The range of input factors was selected by initial tests while cavity pressure was limited by valve and gauge restrictions.

Table 3. The input factors range with equivalent coded values.

Factor	Name	Units	Min.	Max.	Coded Low	Coded High	Mean	Standard deviation
a	cavity pressure	bar	1	4	−1 ↔ 1	+1 ↔ 4	2.40	1.04
B	tool rotational speed	rpm	100	1000	−1 ↔ 100	+1 ↔ 1000	550.17	363.50
C	feed rate	mm/min	500	2000	−1 ↔ 500	+1 ↔ 2000	1274	619.85
D	step size	mm	0.1	0.5	−1 ↔ 0.1	+1 ↔ 0.5	0.3031	0.1632

3. Results and Discussion

In this experiment, a total of 25 consecutive runs were performed, allowing the researchers to obtain the COF for each run. The COF response was measured as the output variable of interest. Table 4 shows the input factors for each run along with the corresponding COF response.

Table 4. Plan of the experiment with input factors and COF response.

Run	Factor 1 (a: cavity pressure, bar)	Factor 2 (B: tool rotational speed, rpm)	Factor 3 (C: feed rate, mm/min)	Factor 4 (D: step size, mm)	Response (COF)
1	2	1000	1475	0.10	0.12
2	2	100	2000	0.10	0.17
3	2	514	1370	0.31	0.11
4	2	1000	500	0.10	0.1
5	2	590	1175	0.35	0.12
6	2	100	2000	0.50	0.14
7	2	100	500	0.50	0.12
8	2	122	1108	0.10	0.09
9	2	1000	1145	0.33	0.14
10	2	559	2000	0.26	0.11
11	4	100	2000	0.30	0.22
12	4	595	620	0.50	0.2
13	4	100	883	0.14	0.14
14	4	757	1550	0.10	0.13
15	4	1000	2000	0.37	0.18
16	1	581	538	0.50	0.11
17	1	550	500	0.10	0.08
18	1	1000	2000	0.50	0.07
19	1	100	1423	0.32	0.15
20	1	762	2000	0.12	0.11
21	3	1000	2000	0.50	0.1
22	3	100	500	0.27	0.1
23	3	680	500	0.20	0.12
24	3	1000	500	0.50	0.2
25	3	343	1565	0.50	0.13

The coefficient of friction was estimated by calculating the mean value from the stabilised region of the forming process (Fig. 3). This approach ensured that the COF measurement captured the representative behaviour of the system by focusing on a consistent and reliable part of the forming process. By considering the stabilised region, any transient or initial variations were minimised, providing a more accurate estimate of the COF for each run.

For the purposes of the experiment a level of significance α = 0.05 has been selected. The summary (Table 5) provides an overview of the sequential p-values, adjusted R^2 and predicted R^2 for different types of model terms. In your case, the quadratic model was selected and a backward elimination algorithm was applied to remove model terms with p-values greater than 0.05, following the model hierarchy. Based on the p-values and the model hierarchy, the quadratic model was selected as the most appropriate model type. The backward elimination algorithm was then used to remove model terms with p-values greater than 0.05, resulting in a refined model.

Analysis of the experimental data revealed important findings (Table 6). The model used in the study showed a significant fit, as indicated by the low p-value (less than 0.0001) and the high F-value (39.47), with a sum of squares of 0.034. This suggests that the model effectively captures the relationship between the factors and the response variable.

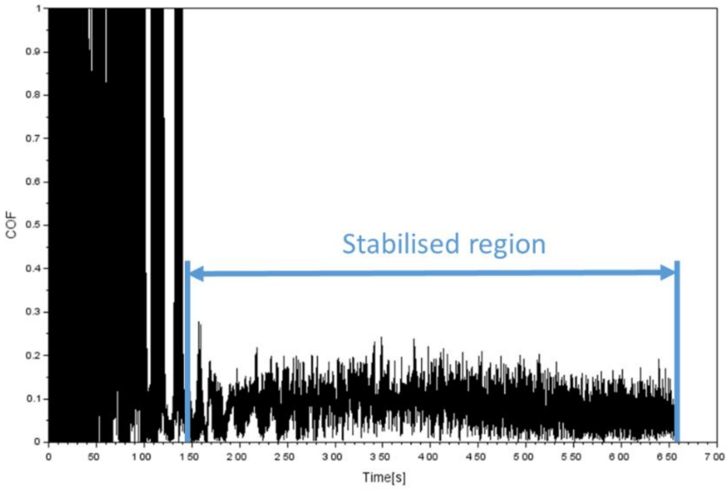

Fig. 3. Stabilised range of the COF selected for analysis.

Table 5. Criteria of model selection.

Source	Sequential p-value	Adjusted R^2	Predicted R^2	Decision
Linear	0.0252	0.2947	0.0282	Rejected
2FI	0.0048	0.6919	0.3119	Rejected
Quadratic	0.0006	0.9299	0.7922	Selected

Table 6. Analysis of variance (ANOVA) table for the reduced quadratic model.

Source	Sum of Squares	Degrees of freedom	Mean Square	F-value	p-value	
Model	0.0339	10	0.0034	39.47	< 0.0001	significant
a - cavity pressure	0.0083	1	0.0083	97.06	< 0.0001	
B - tool rotational speed	8.823E-07	1	8.823E-07	0.0103	0.9207	
C – feed rate	0.0002	1	0.0002	2.61	0.1283	
D - step size	0.0026	1	0.0026	30.52	< 0.0001	
aD	0.0017	1	0.0017	19.35	0.0006	
BC	0.0082	1	0.0082	95.12	< 0.0001	
CD	0.0054	1	0.0054	62.70	< 0.0001	
a^2	0.0029	1	0.0029	33.45	< 0.0001	
B^2	0.0026	1	0.0026	30.68	< 0.0001	
D^2	0.0015	1	0.0015	17.20	0.0010	
Residual	0.0012	14	0.0001			
Correlation Total	0.0351	24				
					R^2	0.9657
Standard deviation	0.0093				**Adjusted R^2**	0.9413
Mean	0.1304				**Predicted R^2**	0.8872
C.V. %	7.11				**Adeq Precision**	25.3212

Among the individual factors, a - cavity pressure had a highly significant effect on the response variable, with a large sum of squares (0.0083) and a high F-value (97.06). This means that variations in cavity pressure have a significant effect on the COF response. On the other hand, the tool rotational speed (B) had a negligible effect on the response, with a very small sum of squares ($8.823 \cdot 10^{-7}$) and a low F-value (0.0103). The p-value of 0.9207 further confirms that changes in tool speed do not significantly affect the response variable. Similarly, the feed rate (C) had little effect on the response as indicated by its relatively low sum of squares (0.0002) and F-value (2.61). The p-value of 0.1283 suggests that changes in feed rate have a relatively small effect on the response. In contrast, the step size (D) had a significant effect on the response, with a substantial sum of squares (0.0026) and a high F-value (30.52). The low p-value (less than 0.0001) further supports the importance of this factor in influencing the response variable. The interactions between the factors were also examined. The interactions aD, BC and CD showed significant effects on the response, as evidenced by their large sum of squares and high F-values. These results highlight the importance of considering the combined influence of multiple factors rather than analysing them individually. In addition, the quadratic terms a^2, B^2 and D^2 also showed a significant influence on the response, with substantial sums of squares and high F-values. This suggests that the relationship between these factors and the response variable is nonlinear. The overall fit of the model was evaluated using the R^2 value, which measures the proportion of variability in the response that is explained by the model. In this case, the R^2 value was determined to be 0.9657, indicating that the model explains approximately 96.57% of the variation in the response variable.

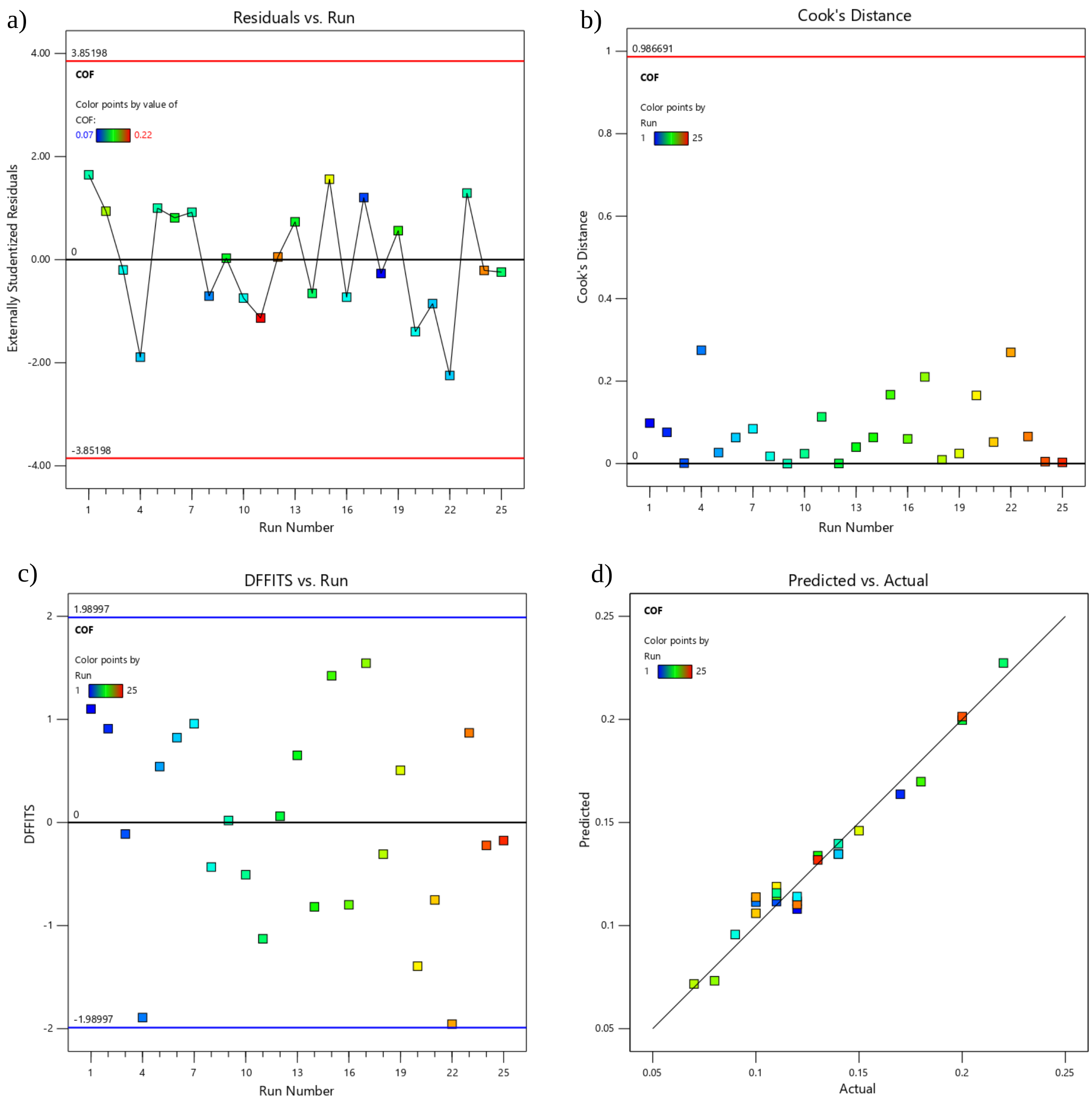

Fig. 4. Diagnostic plots: a) residuals vs. run, b) Cook's distance, c) DFFITS vs. run, d) predicted vs. actual.

The plot of the externally studentized residuals versus the order of the trials (Fig. 4a) is used to identify any lurking variables that may have influenced the response during the current trials. In this graph, a random scatter pattern is desirable, indicating that there are no systematic influences or time-related variables affecting the response. Cook's distance is a measure of the influence of each data point in a regression model. It takes into account both the leverage (how extreme the predictor variables are) and the residual (the difference between the observed and predicted values) of each observation. Cook's distance provides a summary of how much the regression model would change if a particular observation were removed from the data set (Fig. 4b). The difference in fit(s) (DFFITS) statistic measures the influence of each observation on the predicted values of the regression model. Quantifies the change in the predicted value if the i-th observation is removed from the analysis. A larger value of DFFITS indicates that the observation has a greater influence on the predicted values within its neighbourhood in the design space (Fig. 4c). The predicted vs. actual graph compares the predicted response values from the regression model with the actual response values obtained during the experiment. This graph helps to assess the accuracy of the model by examining how closely the predicted values match the actual values. It can reveal any discrepancies or patterns that may indicate areas where the model's predictions differ from the observed data (Fig. 4d). The diagnostic plots contain no outliers and they are in line with expectations for the chosen model.

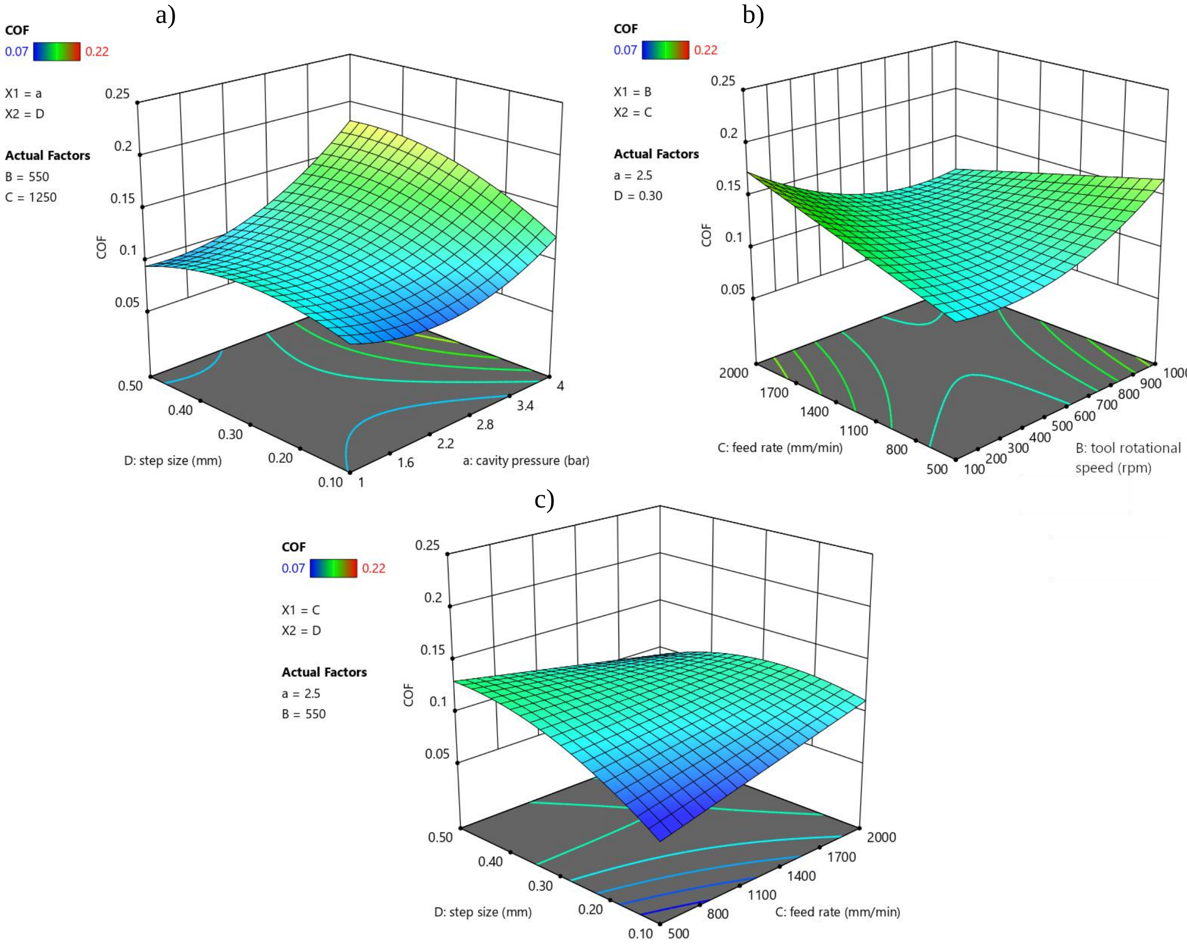

Fig. 5. Response surfaces characterise COF values for the obtained model by the inputs: a) cavity pressure and step size, b) feed rate and tool rotational speed, c) step size and feed rate.

Response surfaces provide valuable information on the relationship between the input factors and coefficient of friction. By analysing these surfaces, we can observe the effect of different input factors on the COF. One notable finding is that higher cavity pressure has a positive effect on COF, indicating that increased pressure leads to higher friction levels. This suggests that careful control and optimisation of cavity pressure are critical in managing friction during the forming process. Furthermore, the response surfaces show that the combination of the correct tool speed and feed rate can effectively reduce friction. This highlights the importance of selecting appropriate tool speeds and feed rates to minimise frictional forces and improve overall system performance. To further illustrate the influence of step size and feed rate on COF, a graphical representation is shown in Fig. 5. This figure provides a visual understanding of how variations in step size and feed rate affect the COF. By examining the trends and patterns in Fig. 5, valuable information can be gained about the optimal values of step size and feed rate that will result in the desired COF levels. Overall, response surface analysis provides valuable information about the relationship between input factors and COF, allowing engineers and researchers to make informed decisions and optimise the forming process to achieve the desired friction characteristics.

4. Conclusions

In this research article, the influence of input parameters on the COF during the ISF process of a grade 5 titanium alloy sheet was investigated. The goal was to gain insight into the frictional conditions which allows for better understanding of contact conditions between tool and workpiece. Results obtained in this research are helpful for process modelling with finite element method. The main findings and conclusions of this study are summarised as follows:

- ANOVA was performed to determine the significance of each input parameter and their interactions on the COF. It was found that all four input parameters contributed significantly to the variation in COF. Furthermore, interactions between these parameters also have a significant effect on the COF.
- The input parameters, including cavity pressure, tool rotational speed, feed rate and step size, have a significant influence on the COF during the ISF process. These parameters play a crucial role in determining the frictional conditions.
- A reduced quadratic model was chosen to represent the relationship between the input parameters and the COF. This model accurately captures the nonlinear behaviour and interactions between the input factors. The obtained model, incorporating the input parameters, exhibited a high coefficient of determination R^2 (0.9657), indicating that approximately 96.57% of the variability in the coefficient of friction was explained, with further validation through adjusted R^2 (0.9413) and predicted R^2 (0.8872) values. The coefficients of the model can be used to predict the COF within the investigated parameter range.
- Cavity pressure has a significant effect on COF. Higher cavity pressure values tend to increase the COF, indicating a higher friction between the tool and the titanium alloy sheet. This finding suggests that controlling the cavity pressure can help to optimise frictional conditions and improve overall process performance.
- The tool rotational speed is another critical factor that affects COF. Higher tool speeds result in higher COF values, indicating increased friction during the forming process. This means that the adjustment of the tool speed can be used to control frictional conditions and achieve the desired surface quality and formability.
- Feed rate has a marked effect on COF. Higher feed rates tend to reduce the COF, indicating a lesser friction between the tool and the sheet. This suggests that adjusting the feed rate can help to optimise the frictional conditions and improve the overall performance of the ISF process.
- The step size plays an important role in determining the COF. Larger step sizes are associated with higher COF values, indicating increased friction during the forming process. Therefore, controlling the step size can be a critical parameter in achieving the desired frictional conditions and improving the formability and surface finish of the formed components.

The results of this study provide information on the frictional behaviour of the grade 5 titanium alloy sheet during ISF. Understanding the COF can help to optimise process parameters to improve formability limits, surface quality and overall process performance. Although this study investigated the influence of input parameters on the COF, more research is needed to investigate the effects of other factors, such as lubricant type and tool geometry, on frictional conditions during ISF. In addition, investigating the relationship between COF and other performance indicators, such as surface roughness and forming forces, would contribute to a comprehensive understanding of the ISF process.

References

Ajay, C.V. (2020). Parameter optimization in incremental forming of titanium alloy material. *Transactions of the Indian Institute of Metals*, 73(9), 2403–2413. https://doi.org/10.1007/s12666-020-02044-1

Ambrogio, G., Palumbo, G., Sgambitterra, E., Guglielmi, P., Piccininni, A., Napoli, L.D., Villa, T., & Fragomeni, G. (2018). Experimental investigation of the mechanical performances of titanium cranial prostheses manufactured by super plastic forming and single-point incremental forming. *The International Journal of Advanced Manufacturing Technology, 98*, 1489–1503. https://doi.org/10.1007/s00170-018-2338-6

Bautista-Monsalve, F., García-Sevilla, F., Miguel, V., Naranjo, J., & Manjabacas, M.C. (2021). A novel machine-learning-based procedure to determine the surface finish quality of titanium alloy parts obtained by heat assisted single point incremental forming. *Metals*, *11*(8),1287. https://doi.org/10.3390/met11081287

Cheng, Z., Li, Y., Xu, C., Liu, Y., Ghafoor, S., & Li, F. (2020). Incremental sheet forming towards biomedical implants: A review. *Journal of Materials Research and Technology*, *9*(4), 7225–7251. https://doi.org/10.1016/j.jmrt.2020.04.096

Decultot, N. (2011). *Formage incrémental de tôle d'aluminium: Étude du procédé à l'aide de la mesure de champs et identification de modèles de comportement.* Universite de Toulouse.

Duflou, J.R., Habraken, A.M., Cao, J., Malhotra, R., Bambach, M., Adams, D., Vanhove, H., Mohammadi, A., & Jeswiet, J. (2017). Single point incremental forming: state-of-the-art and prospects. *International Journal of Material Forming, 11*, 743–773. https://doi.org/10.1007/s12289-017-1387-y

Durante, M., Formisano, A., Langella, A., & Minutolo, F. (2009). The influence of tool rotation on an incremental forming process. *Journal of Materials Processing Technology, 209*, 4621–4626. https://doi.org/10.1016/j.jmatprotec.2008.11.028

Hamilton, K.A.S. (2010). *Friction and External Surface Roughness in Single Point Incremental Forming: A study of surface friction, contact area and the 'orange peel' effect*. Master of Applied Sciences Thesis, Queen's University, Kingston, Ontario, Canada. Retrieved from https://qspace.library.queensu.ca/handle/1974/5425 (accessed on 19 May 2023).

Harfoush, A., Haapala, K.R., & Tabei, A. (2021). Application of artificial intelligence in incremental sheet metal forming: A review. *Procedia Manufacturing*, *53*, 606–617. https://doi.org/10.1016/j.promfg.2021.06.061

Harhash, M., & Palkowski, H. (2021). Incremental sheet forming of steel/polymer/steel sandwich composites. *Journal of Materials Research and Technology*, *13*, 417–430. https://doi.org/10.1016/j.jmrt.2021.04.088

Hussain, G., Gao, L., & Zhang, Z. Y. (2008). Formability evaluation of a pure titanium sheet in the cold incremental forming process. *The International Journal of Advanced Manufacturing Technology*, *37*(9), 920–926. https://doi.org/10.1007/s00170-007-1043-7

Jadhav, S., Goebel, R., Homberg, W., & Kleiner, M. (2003). Process optimization and control for incremental forming sheet metal forming. *Proceedings of the Conference of the International Deep Drawing Research Group*, Bled, Slovenia, 11-15 May 2003, pp. 165–171.

Kim, M., Lee, H., & Park, N. (2022). Evaluation of deformation for titanium alloy sheet in single point incremental forming based on asymmetric yield function. *International Journal of Material Forming*, *15*(5), 66. https://doi.org/10.1007/s12289-022-01712-5

Kumar, R., Kumar, G., & Singh, A. (2020). An assessment of residual stresses and micro-structure during single point incremental forming of commercially pure titanium used in biomedical applications. *Materials Today: Proceedings*, *28*, 1261–1266. https://doi.org/10.1016/j.matpr.2020.04.147

Li, Y., Liu, Z., Daniel, W.J.T. (Bill), & Meehan, P.A. (2014). Simulation and experimental observations of effect of different contact interfaces on the incremental sheet forming process. *Materials and Manufacturing Processes*, 29(2), 121–128. https://doi.org/10.1080/10426914.2013.822977

Li, R., Wang, T., & Li, F. (2023). The formability of perforated TA1 sheet in single point incremental forming. *Materials*, *16*(8), 3176. https://doi.org/10.3390/ma16083176

Martins, P. A.F., Bay, N., Skjoedt, M., & Silva, M.B. (2008). Theory of single point incremental forming. *CIRP Annals*, 57(1), 247–252. https://doi.org/10.1016/j.cirp.2008.03.047

McPhillimy, M., Yakushina, E., & Blackwell, P. (2022). Tailoring titanium sheet metal using laser metal deposition to improve room temperature single-point incremental forming. *Materials*, *15*(17), 5985. https://doi.org/10.3390/ma15175985

Milutinović, M., Lendjel, R., Baloš, S., Zlatanović, D.L., Sevšek, L., & Pepelnjak, T. (2021). Characterisation of geometrical and physical properties of a stainless steel denture framework manufactured by single-point incremental forming. *Journal of Materials Research and Technology*, *10*, 605–623. https://doi.org/10.1016/j.jmrt.2020.12.014

Mishra, S., Yazar, K. U., Kar, A., Lingam, R., Reddy, N. V., Prakash, O., & Suwas, S. (2021). Texture and microstructure evolution during single-point incremental forming of commercially pure titanium. *Metallurgical and Materials Transactions A*, *52*(1), 151–166. https://doi.org/10.1007/s11661-020-06000-y

Najm, S.M., & Paniti, I. (2020). Study on effecting parameters of flat and hemispherical end tools in SPIF of aluminium foils. *Tehnicki Vjesnik - Technical Gazette*, *27*(6), 1844–1849. https://doi.org/10.17559/TV-20190513181910

Najm, S.M., & Paniti, I. (2021). Artificial neural network for modeling and investigating the effects of forming tool characteristics on the accuracy and formability of thin aluminum alloy blanks when using SPIF. *The International Journal of Advanced Manufacturing Technology*, *114*(9), 2591–2615. https://doi.org/10.1007/s00170-021-06712-4

Najm, S.M., Paniti, I., Trzepieciński, T., Nama, S.A., Viharos, Z.J., & Jacso, A. (2021). Parametric effects of single point incremental forming on hardness of AA1100 aluminium alloy sheets. *Materials*, *14*(23), 7263. https://doi.org/10.3390/ma14237263

Naranjo, J., Miguel, V., Martínez, A., Coello, J., Manjabacas, M.C., & Valera, J. (2017). Influence of temperature on alloy Ti6Al4V formability during the warm SPIF process. *Procedia Engineering*, *207*, 866–871. https://doi.org/10.1016/j.proeng.2017.10.843

Oleksik, V., Trzepieciński, T., Szpunar, M., Chodoła, Ł., Ficek, D., & Szczęsny, I. (2021). Single-point incremental forming of titanium and titanium alloy sheets. *Materials*, *14*(21), 6372. https://doi.org/10.3390/ma14216372

Patel, D., & Gandhi, A. (2022). A review article on process parameters affecting Incremental Sheet Forming (ISF). *Materials Today: Proceedings*, *63*, 368–375. https://doi.org/10.1016/j.matpr.2022.03.208

Pepelnjak, T., Sevšek, L., Lužanin, O., & Milutinović, M. (2022). Finite element simplifications and simulation reliability in single point incremental forming. *Materials*, 15(10), 3707. https://doi.org/10.3390/ma15103707

Popp, M., Rusu, G., Racz, S.G., & Oleksik, V. (2021). Common defects of parts manufactured through single point incremental forming. *MATEC Web of Conferences*, *343*, 04007. https://doi.org/10.1051/matecconf/202134304007

Racz, S.G., Breaz, R.E., Tera, M., Gîrjob, C., Biriș, C., Chicea, A.L., & Bologa, O. (2018). Incremental forming of titanium Ti6Al4V alloy for cranioplasty plates—decision-making process and technological approaches. *Metals*, *8*(8), 626. https://doi.org/10.3390/met8080626

Rosca, N., Oleksik, M., & Oleksik, V. (2021). Experimental study regarding PA and PE sheets on single point incremental forming process. *MATEC Web of Conferences*, *343*, 03009. https://doi.org/10.1051/matecconf/202134303009

Saidi, B., Boulila, A., Ayadi, M., & Nasri, R. (2015). *Prediction of the friction coefficient of the incremental sheet forming SPIF*. Proceedings of the 6th International Congress Design and Modelling of Mechanical Systems CMSM'2015, Hammamet, 23-25 March 2015, Tunisia, pp. 1–2.

Sbayti, M., Bahloul, R., & Belhadjsalah, H. (2020). Efficiency of optimization algorithms on the adjustment of process parameters for geometric accuracy enhancement of denture plate in single point incremental sheet forming. *Neural Computing and Applications*, *32*(13), 8829–8846. https://doi.org/10.1007/s00521-019-04354-y

Sbayti, M., Ghiotti, A., Bahloul, R., BelhadjSalah, H., & Bruschi, S. (2022). Effective strategies of metamodeling and optimization of hot incremental sheet forming process of Ti6Al4Vartificial hip joint component. *Journal of Computational Science*, 60, 101595. https://doi.org/10.1016/j.jocs.2022.101595

Shin, J. (2021). *Investigation of Incremental Sheet Forming (ISF) using Advanced Numerical and Analytical Approaches*. PhD Thesis, University of Michigan, MI, USA. https://doi.org/10.7302/2657

Szewczyk, M., & Szwajka, K. (2023). Assessment of the tribological performance of bio-based lubricants using analysis of variance. *Advances in Mechanical and Materials Engineering*, *40*, 31–38. https://doi.org/10.7862/rm.2023.4

Szpunar, M., Ostrowski, R., Trzepieciński, T., & Kaščák, Ľ. (2021). Central composite design optimisation in single point incremental forming of truncated cones from commercially pure titanium Grade 2 sheet metals. *Materials*, *14*(13), 3634. https://doi.org/10.3390/ma14133634

Titanium. (2023). Titanium Ti-6Al-4V (Grade 5), Annealed. [WWW Document]. Retrieved from: https://www.matweb.com/search/DataSheet.aspx?MatGUID=a0655d261898456b958e5f825ae85390&ckck=1 (accessed on 23 July 2023).

Trzepieciński, T., Szpunar, M., Dzierwa, A., & Żaba, K. (2022a). Investigation of surface roughness in incremental sheet forming of conical drawpieces from pure titanium sheets. *Materials*, *15*(12), 4278. https://doi.org/10.3390/ma15124278

Trzepieciński, T., Szpunar, M., & Ostrowski, R. (2022b). Split-Plot I-Optimal design optimisation of combined oil-based and friction stir rotation-assisted heating in SPIF of Ti-6Al-4V titanium alloy sheet under variable oil pressure. *Metals*, *12*(1), 113. https://doi.org/10.3390/met12010113

Więckowski, W., Adamus, J., Dyner, M., & Motyka, M. (2023). Tribological aspects of sheet titanium forming. *Materials*, *16*(6), 2224. https://doi.org/10.3390/ma16062224

Yoganjaneyulu, G., Vigneshwaran, S., Palanivel, R., Alblawi, A., Rasheed, M. A., & Laubscher, R. F. (2021). Effect of tool rotational speed on the microstructure and associated mechanical properties of incrementally formed commercially pure titanium. *Journal of Materials Engineering and Performance*, *30*(10), 7636–7644. https://doi.org/10.1007/s11665-021-05900-3

Zwolak, M., Szpunar, M., Ostrowski, R., & Trzepieciński, T. (2022). Research on forming parameters optimization of incremental sheet forming process for commercially pure titanium Grade 2 sheets. *Archives of Metallurgy and Materials*, *67*(4), 1411–1418. https://doi.org/10.24425/amm.2022.141068

Wpływ Parametrów Wejściowych na Współczynnik Tarcia podczas Formowania Przyrostowego Blach ze Stopu Tytanu Grade 5

Streszczenie

Niniejszy artykuł badawczy koncentruje się na badaniu wpływu parametrów wejściowych na współczynnik tarcia podczas przyrostowego formowania blach tytanowych grade 5. Stopy tytanu są szeroko stosowane w różnych gałęziach przemysłu ze względu na ich odporność na korozję i korzystny stosunek wytrzymałości do masy. Kształtowanie przyrostowe to elastyczny i opłacalny proces produkcji elementów o złożonych kształtach. Celem tego badania była analiza warunków tarcia podczas kształtowania przyrostowego, które wpływają na formowalność blachy, jakość powierzchni i ogólną wydajność procesu. Eksperymenty przeprowadzono przy użyciu kombinacji smarowania MoS_2 i ogrzewania materiału blachy wspomaganego obrotami narzędzia. Wartość współczynnika tarcia wyznaczono na podstawie składowych siły kształtowania (siły osiowej i sił poziomych), które mierzono za pomocą precyzyjnego dynamometru piezoelektrycznego. Zastosowano plan split-plot i wykonano 25 prób w celu uzyskania wartości współczynnika dla każdej z nich. Wyniki badania dostarczają cennych informacji na temat związku między parametrami wejściowymi a współczynnikiem tarcia, przyczyniając się do zrozumienia warunków tarcia występujących podczas kształtowania przyrostowego.

Słowa kluczowe: ANOVA, współczynnik tarcia, kształtowanie przyrostowe, stopy tytanu