BỘ GIÁO DỤC VÀ ĐÀO TẠO

TRƯỜNG ĐẠI HỌC SƯ PHẠM KỸ THUẬT

THÀNH PHỐ HỒ CHÍ MINH

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MA VĂN VIỆT

“NGHIÊN CỨU TẠO HÌNH KIM LOẠI TẤM BẰNG CÔNG NGHỆ BIẾN DẠNG GIA TĂNG ĐA ĐIỂM

(TPIF – Two Point Incremental Forming)”

DANH MỤC CÁC CÔNG TRÌNH ĐÃ CÔNG BỐ

NGÀNH: KỸ THUẬT CƠ KHÍ

TP. HCM, tháng 06 năm 2022

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1. **Ma Van Viet**, Nguyen Truong Thinh, Le Van Sy, and Svetlin Antonov "Study on the formability by tpif technology for aluminum sheet at room temperature", E3S Web of Conferences 207, 05005 (2020) PEPM'2020, https://doi.org/10.1051/e3sconf/202020705005
2. **Ma Van Viet**, Nguyen Truong Thinh, Le Van Sy, "Finite element simulation of the formability by tpif technology for aluminum sheet at room temperature", MMMS 2020, CHAPTER 3. Sustainable Machine Design: Metratronics, CAD/CAM/CAE, Maritime Engineering, Pages 192-198, November 12-15, 2020 Nha Trang, Vietnam.
3. **Ma Van Viet**, Nguyen Truong Thinh, Le Van Sy, "Influence of machining parameters on the TPIF formability for aluminum sheet at room temperature", Springer Cham, Pages 238-245, 27 March 2021, https://doi.org/10.1007/978-3-030-69610-8_33
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Study on the formability by TPIF technology for aluminium sheet at room temperature

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Abstract. Two Point Incremental Forming technology (TPIF) is one forming method of incremental sheet forming technology (ISF) which is an innovation sheet forming process with potential advantages such as simplicity, less-time consumption, and high flexibility. This technology using a hemispherical-end tool under CNC movement deforms a metal sheet which is fixed on simple frame. The sheet metal clamped between movable plate and clamp plate, under the metal sheet has a support die which is fixed on bottom plate. The lower plate is firmly positioned on the CNC machine table in while upper plate (included sheet material, movable plate and clamp plate) is able to move easily up and down along guide bars. The sheet material is plastically deformed layer by layer until final-shape product by CNC tool path. This technology is very suit for the rapid prototyping process and the low batch production. In this research, formability of the TPIF process due to operating parameters was investigated with aluminum sheet at room temperature. Four operating parameters such as depth step, feed rate, tool diameter, and spindle speed, was considered their effects on the formability of TPIF process through DOE strategy. The forming results showed that TPIF process for metal sheet material at room temperature has potential applicability in the metal sheet-product manufacturing.

1 INTRODUCTION

Incremental sheet forming, an invention of Leszak in 1967, sheet material (metal and polymer sheet), has been researched the focus of many studies. This process uses a forming tool fixed on a 3-axis CNC milling machine, is controlled by a toolpath. A material is fixed on a simple frame by bolts, is deformed layer by layer by a head of forming tool. The toolpath is exported from the complete geometry of the product through a traditional CAM software. The ISF method is two kinds of Single Point Incremental Forming (SPIF) and Two Point Incremental Forming (TPIF). TPIF and SPIF jig structure differents are a sheet metal of TPIF can move up and down along guide bars, under sheet metal of TPIF has got a support which is fixed died on base plate (fig.1). TPIF is an innovation sheet forming process with potential advantages such as simplicity, less-time consumption, and high

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flexibility. This technology using a hemispherical-end tool under CNC movement deforms a metal sheet which is fixed on simple frame (movable plate). The sheet metal clamped between movable plate and clamp plate, under the metal sheet has a support die which is fixed on base plate which is firmly positioned on the CNC machine table in while upper plate (included sheet material, movable plate and clamp plate) is able to move easily up and down along guide bars. The sheet material is plastically deformed layer by layer until final-shape product by CNC toolpath. This technology is very suit for the rapid prototyping process and the low batch production. A review of TPIF researches such as some topics.

H. Meier et al [8] used two industrial robots for TPIF, compared to other incremental sheet metal forming machines, this system offers a high geometrical form flexibility without the need of any workpiece dependent tools. This way, the surface quality improved highly.

J. Jeswiet et al [13] compare forces in SPIF and TPIF, The forces measured in forming cones and truncated pyramids from 3003-0 Aluminum sheet, 1.21 mm thick, the forces for SPIF and TPIF are the same magnitude. A. Attanasio et al [14] do experiments on a car door handle cavity for evaluating geometrical and dimensional errors, and surface finishing, between TPIF and SPIF with the same working parameters. TPIF assures the achievement of a better dimensional accuracy and surface finishing. Isabel Bagudanch et al [7] investegate a truncated pyramid frustum and a circular generatrix with parameters (step down, tool diameter, feed rate and spindle speed), PVC and PC sheet material between TPIF and SPIF. TPIF is geometrical accuracy and reduce the effect of the springback. So, TPIF technology is better geometrical accuracy and surface quality than SPIF.

Seyed Ali Asghar Asghari et al [9]. were optimate by grey relational analysis with response factors (Min thickness, Springback, Surface roughness) optimize parameters were 15 mm tool nose diameter, 63° wall angle, 800 r/min spindle speed and 0.2 mm deep step with cone shape, analyze formability of aluminum 1050 in TPIF. M. Safari [15] investigated a complicated shape with positive and negative truncated cones, aluminum alloy 3105, 1mm thickness by TPIF with step depth, rotational speed. An optimum parameter combination (Negative/Positive, step depth 0.2 mm and rotational speed 1000 rpm) is obtained to get both maximum achievable outer and inner heights using signal to noise ratio analysis. Hani Mostafanezhad et al [16] studied experimental study based on response surface methodology (RSM) was carried out to analyze effect of wall angle, tool nose diameter, initial sheet thickness and step down on thinning ratio and forming force during TPIF of AA1050 truncated cone. A series of experiments was carried out based on Box-Bhenken experimental design and mathematical models of responses are developed by means of RSM and nalysis of variances. Response surface methodology optimal parameter setting regarding minimum thinning ratio and forming force.

Numerical simulation, Chenhao Wang et al [17] study The enhanced Lemaitre damage model accounting for the micro-crack closure effect is adopted to predict the fracture in TPIF by using Abaqus/Explicit subroutine VUMAT. The material constants in the damage model are calibrated throughout tensile tests by minimizing the force error using Newton approach. The TPIF with a hemispherical shape using the enhanced Lemaitre CDM damage model in FEM shows a good agreement of the thickness distribution, fracture depth and the forming force trend compared with the corresponding experimental results. It is concluded that the enhanced CDM-based Lemaitre model can be used for ductile fracture of AA 7075 aluminium alloy in TPIF with a hemispherical shape. R. Perez-Santiago et al [18] investigate force is a more rigorous process parameter for validation of FEM models qualitative trends like thickness distribution and higher forces obtained at higher $\Delta\theta$ are correctly reproduced. Adil Shbeeb Jaber et al [19] study forming mechanism and multi stages incremental forming.step size and forming tool radius, on the thickness distribution and strain analyses for three stages in multi, with vertical angle.2-D model of cone shaped part with right forming angle with a wall angle of 60°, thickness (1mm) of the aluminum alloy (AA1070). ANSYS 11 software is used to carry out the numerical simulation of the multistage. The results show that, when considering multi-stage incremental sheet forming, the task is even more difficult because the strain and thickness distribution resulting from the first stage will influence the subsequent results. Decreasing in the forming tool radius will increase in the thinning of the wall product due to excessive stretch will occurs, while the incremental step size is not significant effect on the numerical results (thickness, strain) distribution of the product. Finally, the goal to attain a vertical wall angle and equally maintain wall thickness and strain over the wall part is pursued. Mechanical tests, computer programming, geometry and design were required. The simulation results including the thickness and strain distributions over the product walls throughout three stages were concluded. Haibo Lu et al [20] study Part accuracy improvement in two point incremental forming with a partial die using a model predictive control algorithm, a non-axisymmetric shape, which contains both flat and curved walls, The wall angle was 40°, 35mm depth, aluminium (AA 7075-O), 1.6 mm thickness, 20 mm tool diameter, feed rate 4000 mm/min. The control algorithm toolpath correction in the horizontal and vertical directions through optimising two toolpath parameters (Δu_r and Δu_z) in two separate control modules. Compared with the typical, TPIF process that has no toolpath correction, fairly good improvement in geometric accuracy was achieved with the use of the toolpath correction strategy in TPIF with a partial die while the geometric accuracy in the partial fillet areas requires further improvement. This work provides a helpful approach to achieve in-process toolpath control/correction in TPIF.

Xiaoqiang LI et al [21] study experimental and numerical investigation on surface quality for two-point incremental sheet. Forming with interpolator, the influences of process variables (i.e. tool diameter, step size and thickness of interpolators) on the forming process (e.g. surface roughness, forming force and geometric error) are investigated through a systematic experimental approach of central composite design (CCD) in two-point incremental sheet forming (TPIF). The increase in thickness of interpolators decreases the surface roughness in direction vertical to the tool path while increases the surface roughness in direction horizontal to the tool path. The combined influence between thickness of interpolators and process parameters (tool diameter and step size) is limited. The placement of interpolator has little influence on the effective forming force of blank. The geometric error enlarges with the increase of step size and thickness of interpolator while decreases firstly and then increase with an increase in tool diameter. The influencing mechanism of the interpolator method on surface quality can be attributed to the decrease of the contact pressure due to the increase of contact area with the unchanged contact force.

Although the research teams have studied improve surface quality, compare between SPIF and TPIF, geometrical accuracy, response surface methodology optimal parameter setting regarding minimum thinning ratio and forming force, numerical simulation, etc. on TPIF, the formability of sheet material has not been investigated clearly. Therefore, this paper will focus on the formability of sheet material such as aluminum sheet A 1050 H14. The formability of sheet material is investigated by experiment with results towards investigation of maximum wall angle of aluminum sheet A 1050 H14, thickness of 1.5 mm. In this research, a step frustum cone shape with 1° for every step (investigated angle from 65° - 85°) is used to investigate formability of the TPIF process due to operating parameters was investigated with aluminum sheet at room temperature. This investigated shape is a new model in study on the formability by TPIF technology. It has never been used the last researches. Four operating parameters such as spindle speed, depth step, feed rate, tool diameter were considered their effects on the formability of TPIF process through DOE strategy. The forming results showed that TPIF process for metal sheet material at room temperature has potential applicability in the metal sheet-product manufacturing.

2 EXPERIMENTAL EQUIPMENTS

In this study, the jig/fixture for TPIF process is designed to form aluminum sheet at room temperature. The jig/fixture system consists of four guide bars which fix die on a base plate. A support die is fixed on a base plate by four bolts. Four Linear Bushings are fixed die on a movable plate; the group (linear bushing, movable plate) fix on guide bars with linear bushing and can move up and down along guide bars. Between a movable plate and a clamp plate, there is a sheet material is clamped by eight bolts (figure 1). Dimensions of the metal sheet are 400 x 400 mm^2 and 1.5 thickness. The jig/fixture is clamped on the CNC milling machine table (Figure 2). The forming tool has a hemispherical-end shape with diameter equal to 6 mm, 12 mm, 18 mm which is always pressed into the metal sheet surface to create a locally plastic deformation. In this system, the forming tool is designed with enough length to form complete product. It is made from steel round bar and steel ball was welded on the top of the bar to ensure good hardness and wear resistance (Figure 3). The forming tool is checked inversion (figure 4). Mixed lubrication is solid graphite powder and Lithium grease with scale 1:1 and lubrication oil (multi 20W-50) to create linked mixed lubrication, it is used in the experiments to reduce the contact friction between the forming tool and the metal sheet surface.

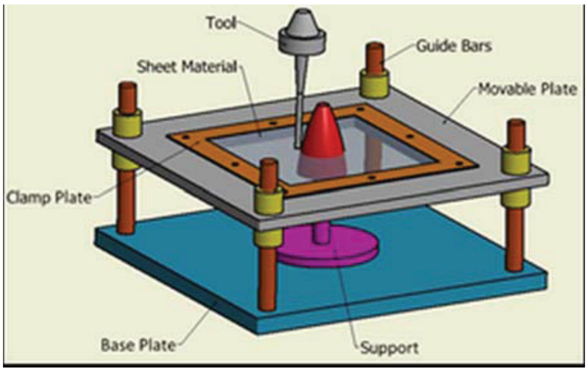

Fig. 1. CAD model of Jig and fixture system for fixture system for TPISF process.

Fig.2 Practical model of Jig and TPIF process.

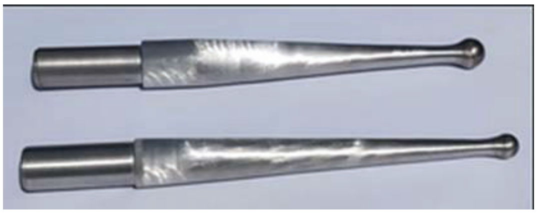

Fig.3 Forming tool in the experimental work.

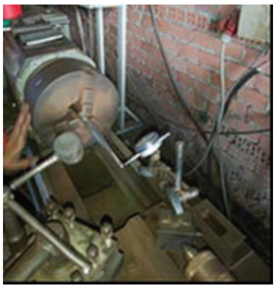

Fig.4 The forming tool is checked inversion

3 EXPERIMENTAL DESIGN

The experiments are performed with a step frustum cone shaped product (Figure 5), which has a step frustum cone to realize the influence of the processing parameters on the formability of aluminum sheet A 1050 H14 at room temperature. The product profile with a step frustum cone shaped enables the investigation of all the from 65^o to 85^o (Fig. 6). The slope of the profile increases with its height, the analyzed region is limited to an angle less than 85^o. An experimental strategy is planned based on the DOE approach to determine the influence of the processing parameters on the formability of aluminum sheet at room temperature.

Fig.5 CAD model

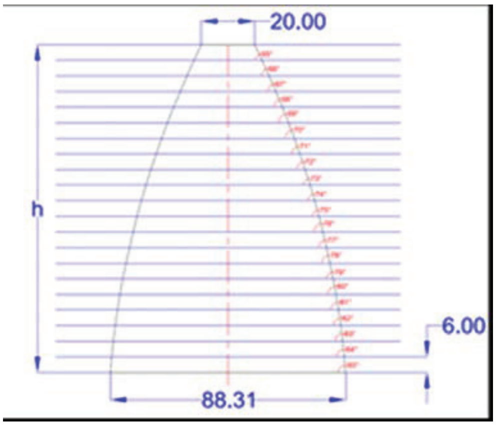

Fig.6 Profile of a shape cone model.

The forming parameters such as depth step (Δz), feed rate (V-xy), tool diameter (D), and spindle speed (n) are chosen to investigate formability of metal sheets based on previous studies [7]. The Box-Behnken, 5 center points design was applied. Minitab 19 software was used based on the selected factors and values in Table 1. A design matrix with 29 experimental runs was generated. Response parameter is maximum wall angles.

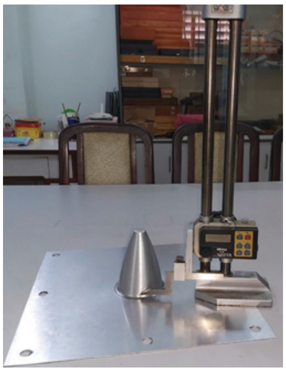

Fig.7 Measurement of mechanical failure height.

Table 1. Processing parameters for experimental design.

No	Experimental parameters	Symboy	Unit	Range of values		
				Low level	Midium level	High level
1	Depth step	Δz	mm	0.1	0.8	1.5
2	Feed rate	Vxy	mm/minute	300	900	1500
3	Tool diameter	D	mm	6	12	18
4	Spindle speed	n	rpm	300	1050	1800

4 RESULTS AND DISCUSSION

The deformation ability of sheet material is measured by wall angle (▯). The higher wall angle is, the greater formability of sheet metal is. The wall angle is measured continuously through the height (h) of the mechanical failures from head of a step frustum cone to mechanical failures on the product (Figure 7). This values are converted into maximum wall angles and insert into the design matrix. According to the experiment results, the roughness of the surface in direct contact with the forming tool is smaller than the other surface. Due to many different factors such as lubrication conditions, contacting condition, machine parameters, etc. Therefore, these parameters are controlled to increase surface quality.

Using the Minitab 19 software and the experimental data, we have the ANOVA for response as Table 2. The p-value is less than 0.05, model is suitable statistically significant. The analysis of variance (ANOVA) shows that the percent influence of parameters and the interaction parameters to the effects on formability of sheet metal. Percent contribution of total variance such as depth step (A) 22.46%, feed rate (B) 18.59%, tool diameter (C) 26.77%, spindle speed (D) 0.19%, AA 22.63%, AC 5.02%, BC 0.56%. The coefficient of determination for regression analysis (R-squared (R2)) is 0.9625 is the goodness-of-fit of the model to the experimental data. It is very close to 1, and obtain 96.25% of the total variance.

Table 2. The Analysis of Variance (ANOVA)

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**%**
Model	8	43.1462	5.3933	64.15	0.000	96.25
z	1	10.0833	10.0833	119.94	0.000	22.46
V-xy	1	8.3333	8.3333	99.13	0.000	18.59
n	1	0.0833	0.0833	0.99	0.331	0.19
D	1	12.0000	12.0000	142.74	0.000	26.77
z*z	1	10.1462	10.1462	120.69	0.000	22.63
z*D	1	2.2500	2.2500	26.76	0.000	5.02
Error	20	1.6814	0.0841	-	-	3.75
Total	28	44.8276	-	-	-	-

Fig. 8 The Products by TPIF Technology.

S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**
0.289946	96.25%	94.75%	88.96%

Regression models for most significant parameters on responses presenting a relationship among processing parameters and their interactions are shown below

$\alpha =$ 79.170 + 7.374 z + 0.000556 V-xy + 0.000111 n - 0.0863 D - 2.451 z*z + 0.000000 z*V-xy- 0.1786 z*D + 0.000069 V-xy*D

According to correlation equation, it shows that tool diameter (D) is inversely proportional to the wall angle. The wall angle is proportional to depth step (Δz) and feed rate (V-xy).

The result of numerical optimization with maximum wall angle is 84.3625 degree.

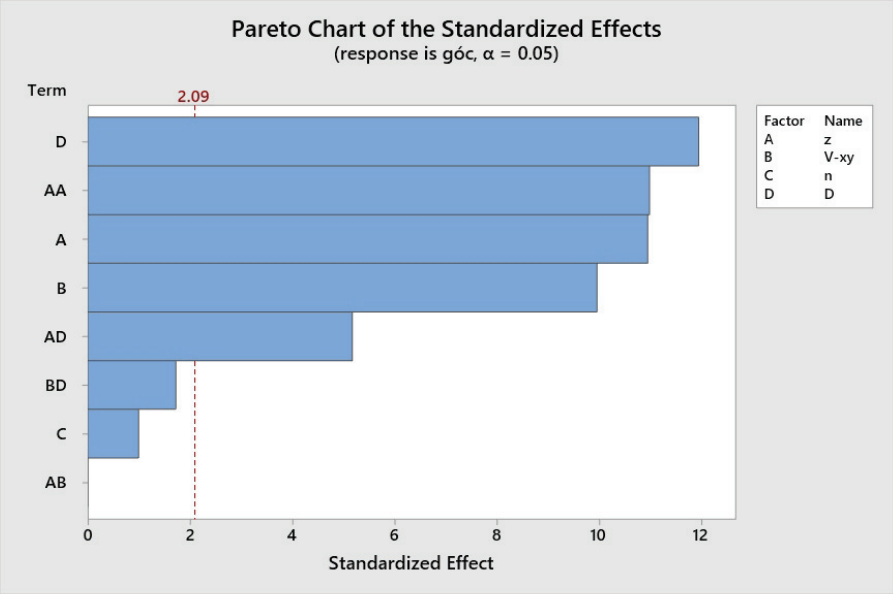

Fig. 9 Pareto Chart for wall angle.

According to Pareto chart for wall angle (Figure 9), it shows that important factors in descending order as tool diameter (D), depth step interactive to depth step (z*z), depth step (z), and feed rate (Vxy).

5 CONCLUSIONS

The Jig and fixture system for TPISF process is designed to fix aluminum sheet A 1050 H14, 1.5 mm thickness for investigating the influences of processing parameters on formability, surface quality at room temperature.

The maximum wall angle (84^o) achieved in TPIF with aluminum sheet A 1050 H14, 1.5 mm thickness at room temperature.

According to the response wall angle analysis, the predicted result of the model is reasonable alignment with the observations taken from the experiments. Thus, the established model can be utilized to estimate the wall angle in TPIF process with 96.25 % confidence within the range of investigated machining conditions.

Optimized maximum wall angle is 84.3625 degree.

The percentage error between the experimental and predicted values of the minimum wall angle is 3.75%, and is found to be insignificant.

Reduce friction between the tool and the sheet metal by good lubrication to have the surface quality. The roughness of the surface in direct contact with the forming tool is smaller than the other surface.

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Finite Element Simulation of The Formability by TPIF Technology for Aluminum Sheet at Room Temperature

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Abstract. TPIF (Two point incremental forming) technology is a flexible forming technology in production, It is suitable in small batches with high economic efficiency (cheap, low production time, hight quality, and etc.). This study shows a simulation method to determine the deformability of aluminum sheet A 1050 H14, 1.5 mm thickness at room temperature by TPIF technology with influence of machining parameters such as depth step, feedrate, tool diameter, and spindle speed. Abaqus software is used to carry out the numerical simulation of building finite element modeling, analyzing model in TPIF process. The result shows that maximum forming angle was achieved in this process. According to simulation results, we can predict deformability of aluminum sheet and put it into practice production.

Keywords: TPIF, finite element method, formability, wall angle, abaqus software.

1. Introduction

TPIF is one of incremental sheet forming technology. It is very flexible to change size, shape, and model product. This process uses a forming tool to deform layer by layer of sheet metal until final-shape product through CNC tool path. The sheet metal is clamped on Jig and fixture system and move down along guide bars with the forming tool (Fig.1). A review of numerical simulation studys for TPIF process such as.

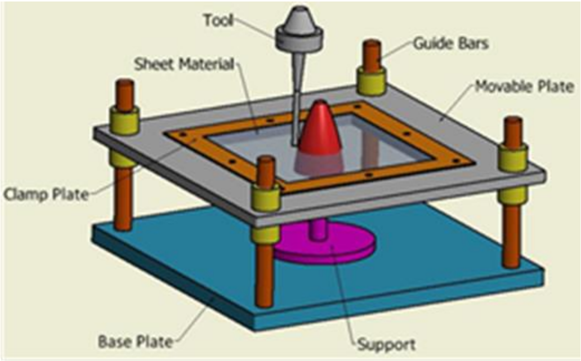


Fig.1. CAD model of Jig and fixture system for TPIF process

R. Perez-Santiago et al. [1] investigate force is a more rigorous process parameter for validation of FEM models qualitative trends like thickness distribution and higher forces obtained at higher $\Delta\theta$ are correctly reproduced. Adil Shbeeb Jaber et al [2] study forming mechanism and multi stages incremental forming. Step size and forming tool radius, on the thickness distribution and strain analyses for three stages in multi, with vertical angle. 2-D model of cone shaped part with right forming angle with a wall angle of 60°, thickness (1 mm) of the aluminum alloy (AA1070). ANSYS 11 software is used to carry out the numerical simulation of the multi stage. The results show that, when considering multi-stage incremental sheet forming, the task is even more difficult because the strain and thickness distribution resulting from the first stage will influence the subsequent results. Decreasing in the forming tool radius will increase in the thinning of the wall product due to excessive stretch will occurs, while the incremental step size is not significant effect on the numerical results (thickness, strain) distribution of the product. Finally, the goal to attain a vertical wall angle and equally maintain wall thickness and strain over the wall part is pursued. Mechanical tests, computer programming, geometry and design were required. The simulation results including the thickness and strain distributions over the product walls throughout three stages were concluded.

Although there are a lot of numerical simulation studys for TPIF process, numerical simulation for the formability of sheet material in TPIF process has not been studied clearly. Therefore, this paper focuses to simulate on the formability of aluminum sheet A 1050 H14, thickness of 1.5 mm. A step frustum cone shape with 1° for every step (investigated angle from 65°-85°) is used to investigate formability of the TPIF process. This investigated shape is a new model in study on the formability by TPIF technology. It has never been used the last researches. Spindle speed, depth step, feedrate, and tool diameter are main operating parameters which effect on the formability of TPIF process. The formability of aluminum in TPIF process was predicted by Abaqus software. This result has potential applicability in the metal sheet-product manufacturing. The present study aims at fracture prediction in a TPIF process throught Abaqus software.

2. Mechanical properties of aluminum sheet A 1050 H14

In this study, sheet material is aluminum sheet A 1050 H14, 1.5 mm thickness with physical properties as Table. 1; True stress-strain curves as Fig.2.

Table 1. Physical properties of aluminum sheet A 1050 H14

Density	2.71 g/cm^3
Thermal Expansion	24×10^{-6} K^{-1}
Thermal conductivity, room temperature	222 W/mK
Electrical resistivity, room temperature	0.0282×10^{-6} Ω.m
Poisson's ratio	0.33
Tensile strength	131.74 MPa
Proof Stress	85 Min MPa
Elongation (ε)	16 %
Elastic Modulus	68.916 Mpa

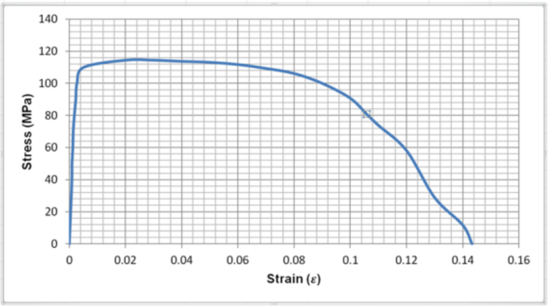


Fig.2. True stress-strain curves of aluminum sheet A 1050 H14 [4]

3. CAD model for deformability investigate

The deformability of aluminum sheet is determined by the maximum wall angle (α_{max}) which the product begins to happen mechanical failures. Maximum wall angle is measured by measuring minimum height from head of product to any mechanical failure and convert to wall angle. A step frustum cone shaped (Fig.4) is built to investigate forming angle from 65° to 85° to reduce simulation run time. CAD model is designed on Creo 6.0 software with dimensions as Fig.3. The size of aluminum sheet A 1050 H14 is 300×300×1.5 mm.

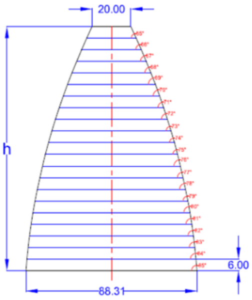


Fig.3. The size of the CAD model

Fig.4. The 3D- CAD model

4. Finite element model of TPIF process

4.1. Select the influence parameters

Arcooding to previous studies, the forming parameters is chosen to investigate formability of metal sheets as depth step (Δz), feed rate (V_{xy}), tool diameter (D), and spindle speed (n) with level as table 2. The study focused on simulation of four parameters affecting the deformability by TPIF technology.

4.2. Building analysis model in Abaqus software

Create and assemble the model (module part and module assembly)

A material Sheet element is created in a 3D environment, deformation type with size 300×300×1.5 mm (Fig.6a). Forming tool (Fig.6c) and support element (Fig.6b) are defined as analytical rigid.

Origin of coordinates is created on the material sheet center. The point of the tool is on the coordinates (0; -15.12; 0). The bottom of the material sheet is contact with the support and the top of the material sheet is contact with the end of forming tool. Created model shows Fig.5.

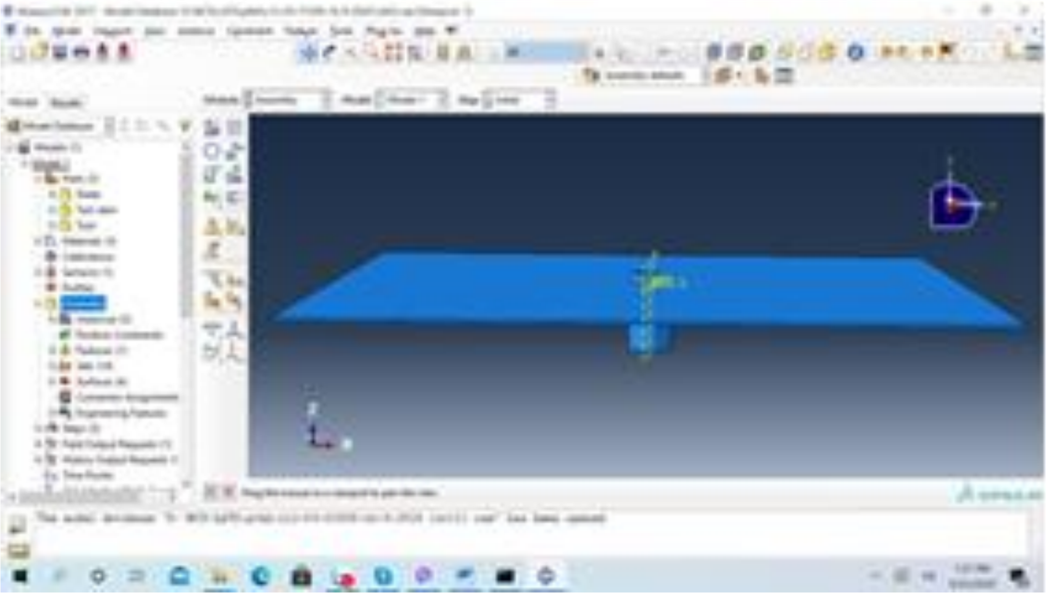
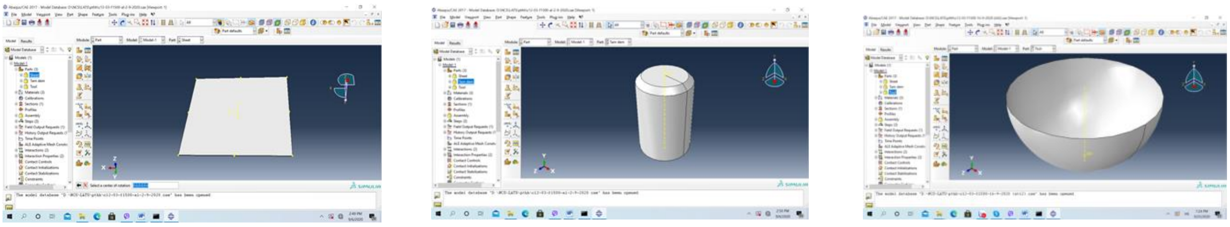


Fig.5. Simulation model



a *b* *c*

Fig.6. a. Sheet material; b. Support; c. The end of forming tool

Create simulation material of aluminum sheet

The Property module is used to create the material and define its properties. The material properties are selected in the general, mechanical, thermal and other tabs. The other hand, the material density parameters, elastic modulus, Poisson's ratio, thermal expansion, plastic, ductile damage, specific heat, and etc. are added.

Condition of contact (module interaction)

Interaction property between material sheet and the support is tangential behavior. In the experimental models, mixed lubricant is used to reduce friction. So, the coefficient of friction between the material sheet and the end of forming tool was chosen to be 0.1 [3].

Boundary condition of the support element

The support element is fixed in space (limited to 6 degrees of freedom). We select Symmetry/Antisymmetry/Encastre.

Boundary condition of material sheet

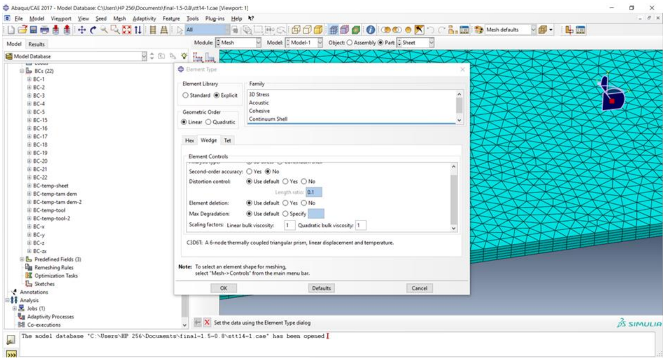
Four sides of the material sheet are fixed on a movable plate by a clamped plate and bolts, it can move up and down along guide bars. It also are selected the Symmetry/Antisymmetry/Encastre type.

Boundary condition of tool

A forming tool allows to move in the direction x, y, z in tool trajectory (acoording to helical run tool data) in time step t. Using module Amplitudes to enter coordinates in three directions x, y, z and time step t.

Meshing (module mesh)

The deformation elements are meshed. The rigid elements are not meshed in Abaqus software. Select the mesh type in tab Element type. Type C3D6T is selected (Fig.7) (C3D6T:A 6-node thermally coupled triangular prism, linear displacement and temperature).



Module: Mesh Model: Model-1 Object: ○ Assembly ● Part: Sheet

Element Type

Element Library: ○ Standard ● Explicit

Geometric Order: ● Linear ○ Quadratic

Family: 3D Stress / Acoustic / Cohesive / Continuum Shell

Hex Wedge Tet

Element Controls

Second-order accuracy: ○ Yes ● No

Distortion control: ● Use default ○ Yes ○ No

Length ratio: 0.1

Element deletion: ● Use default ○ Yes ○ No

Max Degradation: ● Use default ○ Specify

Scaling factors: Linear bulk viscosity: 1 Quadratic bulk viscosity: 1

C3D6T: A 6-node thermally coupled triangular prism, linear displacement and temperature.

Note: To select an element shape for meshing, select "Mesh->Controls" from the main menu bar.

Set the data using the Element Type dialog

```
The model database "C:\Users\HP 256\Documents\final-1.5-0.8\stt14-1.cae" has been opened
```

Fig.7. The mesh model

Analytical step (module Step)

Selecting type step is Dynamic, Temp-disp, Explicit to see the effects of temperature. Pay particular attention to time period parameters. That is the total running time of the forming tool is equal to the time of the last step. This is not the time the computer processes but the total time of the steps.

$$t_{total} = \frac{\text{Length of trajectory}}{\text{The velocity of the tool}}$$
$$= \frac{\sum_0^N\left(\sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2 + (z_{i+1} - z_i)^2}\right)}{V_{xy}}$$

Create a job analysis and analysis (module job)

Analytical work done in job module includes analysis and view the analysis process. The analysis process is managed and monitored in the job monitor dialog box.

Total time and step time coincide with the time step in amplitude. The CPU time is the real time that the computer takes to calculate.

5. Results and discussion

TPIF process was simulated with obtained results as follows.

The value of simulation with the parameters as Table 2. The results show Fig.8.

Table 2. The influent parameters

No.	Influent parameters (Input parameter)	Sign	Unit	Value	α (°)
1	Depth step	Δz	mm	0.8	82°
2	Feedrate	V_{xy}	mm/min	900	
3	Tool diameter	D	mm	18	
4	Spindle speed	n	rpm	1800	

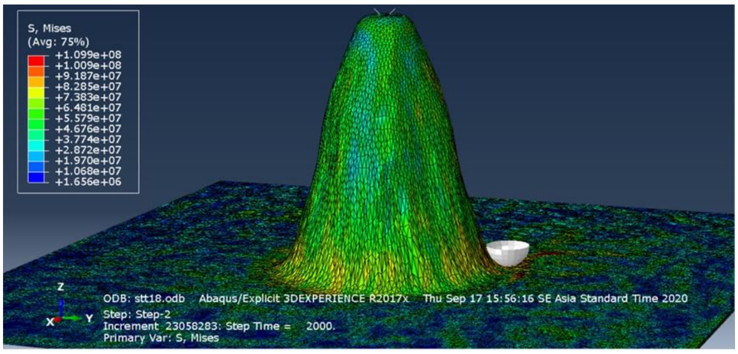


Fig.8. The product after simulated forming

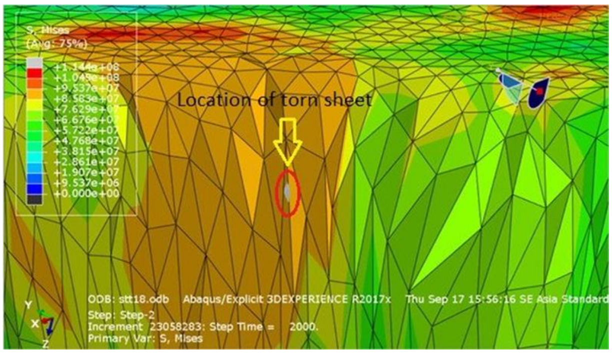


Fig.9. Location of torn sheet

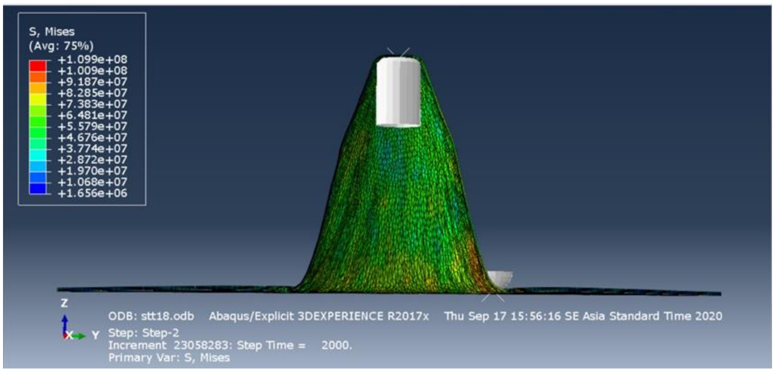


Fig.10. The section of the broken sheet

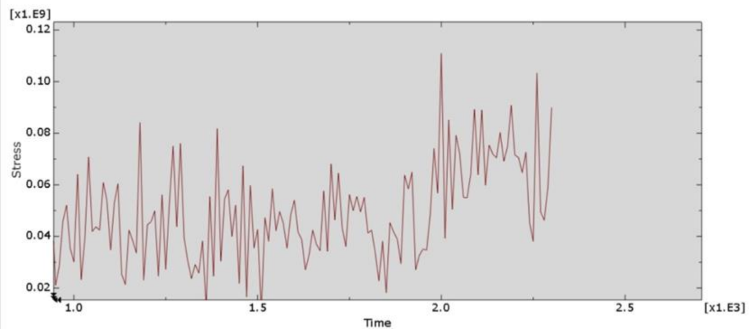
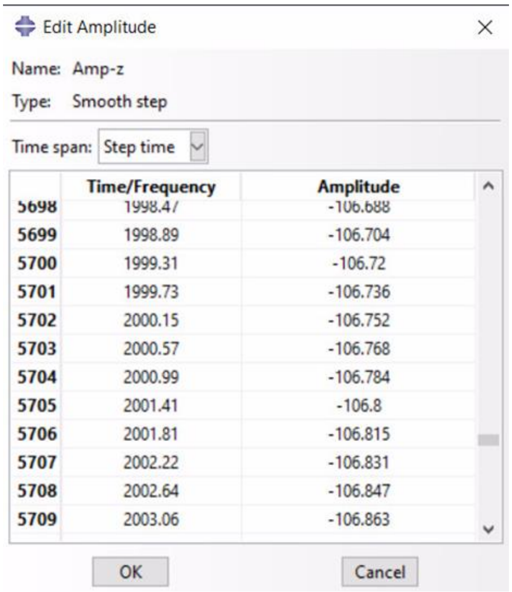


Fig.11. Stress at the torn sheet position

According to the stress diagram (Fig.11) of the case being analyzed, the stress exceeds 114.439 Mpa at time t = 2000. The corresponding heighth of position is -106.752 mm (Fig.12). We convert the forming angle 82^o.



Name: Amp-z

Type: Smooth step

Time span: Step time

	Time/Frequency	Amplitude
5698	1998.47	-106.688
5699	1998.89	-106.704
5700	1999.31	-106.72
5701	1999.73	-106.736
5702	2000.15	-106.752
5703	2000.57	-106.768
5704	2000.99	-106.784
5705	2001.41	-106.8
5706	2001.81	-106.815
5707	2002.22	-106.831
5708	2002.64	-106.847
5709	2003.06	-106.863

Fig.12. Heighth of torn sheet position is -106.752 mm

6. Conclusion

The step frustum cone profile was successfull simulated in TPIF. The nodal displacement values obtained was according to the tool path defined. The wall thickness prediction and the thickness distribution of simulation agrees very well with the sine law. The simulation results showed the forming angle. The simulated profile is the same CAD profile. We can possible to perform TPIF process simulation before putting it into practice, it helps save the testing and machining cost, time, and etc.

Acknowledgments

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Influence of Machining Parameters on the TPIF Formability for Aluminum Sheet at Room Temperature

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Abstract. Two Point Incremental Forming (TPIF) technology is very flexible forming technology, cost-effective, and potential advantages (high flexibility, simplicity, less-time consumption). This technology uses a hemispherical-end tool controlled by CNC milling machine to deform a metal sheet which is fixed on the jig/fixture. The jig/fixture is firmly positioned on the CNC milling machine table which includes clamped plate, movable plate base plate and semi-support. The metal sheet material is clamped between movable plate and clamp plate by 8 bolts and can move down along 4 guide bars. The sheet material is deformed layer by layer by the hemispherical-end tool following CNC tool path. This paper aims influence of machining parameters on the formability of aluminum sheet at room temperature which is deformed by TPIF technology. The investigated parameters are depth step, feed rate, tool diameter, and spindle speed through Design of Experiment (DOE). The formability has been known the ability of metal sheet to deform until happen failure through the achieved forming angle.

Keywords: Incremental sheet forming · TPIF · Formability · Maximum forming angle · Metal sheet material · Design of Experiment

1 Introduction

Incremental sheet forming technology is invented by Leszak in 1967 [1]. After that, it is researched by many studying groups. ISF technology uses a head forming tool deform a sheet material layer by layer to complete product. The forming tool is controlled by a toolpath which is exported from Creo 6.0 software. A sheet material is fixed on a simple frame which is fixed on the table of 3-axis CNC milling machine. The ISF has got two sorts of Single Point Incremetal Forming (SPIF) and TPIF. The TPIF technology is moldless machining technology with many advantages (high flexibility, simplicity, less-time consumption, and etc.). It uses more and more in the other countries. A review of TPIF studies such as.

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Attanasio [4] do experiments on a car door handle cavity for evaluating geometrical and dimensional errors, and surface finishing, between TPIF and SPIF with the same working parameters. TPIF assures the achievement of a better dimensional accuracy and surface finishing.

Hani Mostafanezhad [2] studied experimental study based on response surface methodology (RSM) was carried out to analyze effect of wall angle, tool nose diameter, initial sheet thickness and step down on thinning ratio and forming force during TPIF of AA1050 truncated cone. A series of experiments was carried out based on Box-Bhenken experimental design and mathematical models of responses are developed by means of RSM and analysis of variances. Response surface methodology, optimal parameter setting regarding minimum thinning ratio and forming force. Asghari [3] were optimate by grey relational analysis with response factors (min thickness, springback, surface roughness) optimize parameters were 15 mm tool nose diameter, 63° wall angle, 800 r/min spindle speed and 0.2 mm deep step with cone shape, analyze formability of aluminum 1050 in TPIF.

Although there are a lot of teams study geometrical accuracy, surface quality, compare forces in SPIF and TPIF, and etc. on TPIF, the studys of sheet material formability have not been investigated clearly. This research uses a step frustum cone shape (every step with 1°) (Fig. 3) to investigate influence of machining parameters on formability of aluminum sheet at room temperature by TPIF technology. Survey limited angle is from 65°–85°. This investigated model is a new model in study influence of machining parameters on the formability by TPIF technology which it has never been used the last researches. The machining parameters are considered their effects on the formability (depth step, feedrate, tool diameter, and spindle speed) through DOE strategy. The achieved results show that it can put into practice in production.

2 Experimental Equipment

In this equipment, a sheet material with dimension of 400 × 400 mm^2, 1.5 mm in thickness is fixed between movable plate and clamp plate by 8 bolts and can move down along 4 guide bars on the jig/fixture. The jig/fixture (Fig. 1) is firmly positioned on the CNC milling machine table. The sheet material is deformed layer by layer by the hemispherical-end tool with 6 mm, 12 mm, 18 mm diameter following CNC tool path. The end of a round steel bar and a steel ball (good hardness and wear resistance) are welded with each other to create the forming tool (Fig. 3). The forming tool is checked inversion. Solid graphite powder and lithium grease with scale 1:1 and lubrication oil (multi 20W-50) are mixed each other to create a mixed lubrication (Fig. 2).

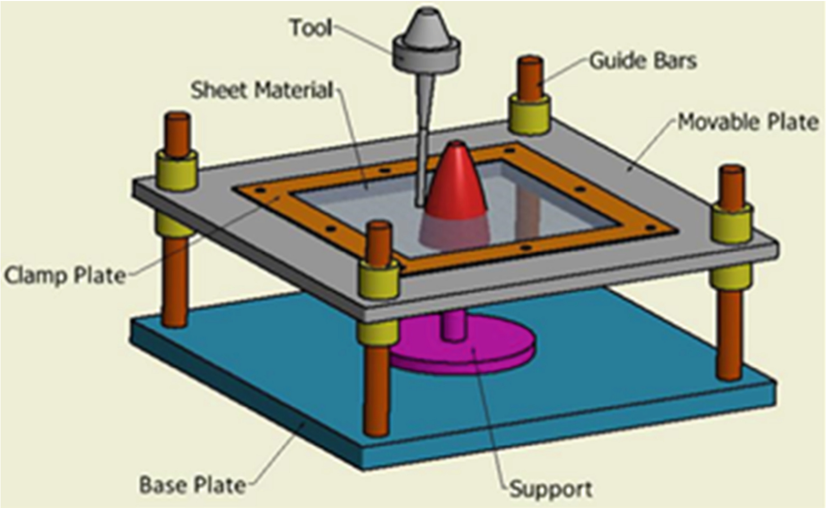

Fig. 1. Jig and fixture system

Fig. 2. Experiment system for TPISF process

Fig. 3. Forming too

3 Experimental Design

A step frustum cone shaped (Fig. 4) is built to investigate forming angle from 65° to 85°. Formed product is investigated about maximum wall angle through DOE to determine the influence of the machining parameters on the TPIF formability for aluminum sheet at room temperature. The Box-Behnken experiment mode is used 4 factors, 5 center points, 29 base runs (Table 2), with factor level (Table 1). Response parameter of DOE is the maximum wall angle in the experiments. The formed products are measured height from head of product to any mechanical failure (Fig. 6). Every height value is converted into a wall angle and inserted into the design matrix (Fig. 5).

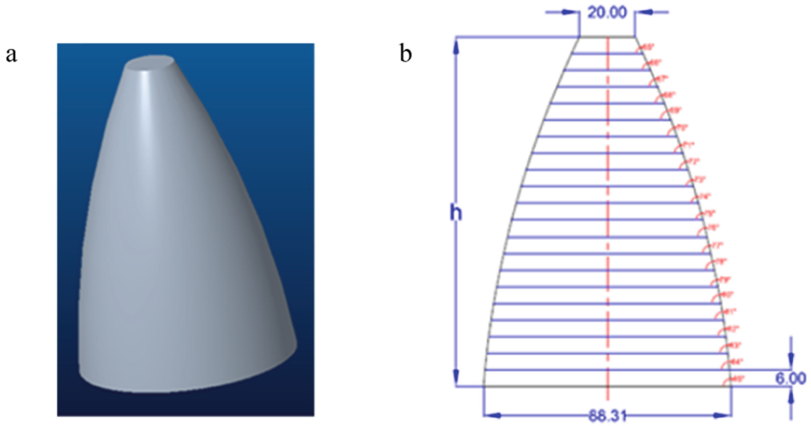

Fig. 4. A (a) CAD model of forming product, (b) Geometric profile of forming product.

Table 1. Machining parameters for experimental design

No	Machining parameters	Unit	Range of values	
			Low level	High level
1	Depth step (z)	mm	0,1	1.5
2	Feed rate (V_{xy})	mm/minute	300	1500
3	Tool diameter (D)	mm	6	18
4	Spindle speed (n)	rpm	300	1800

Fig. 5. The formed products

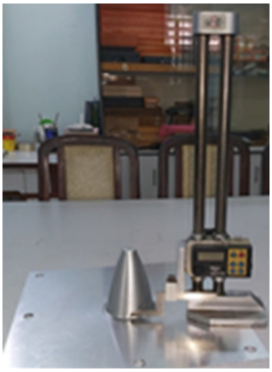

Fig. 6. Measuring the forming height

Table 2. Design of experiments and results for forming angle

Run	z	V_{xy}	n	D	Wall angle (degree) α
1	0.8	900	1050	12	82
2	0.8	1500	300	12	83
3	0.8	900	1800	18	81
4	1.5	900	300	12	82
5	0.1	900	300	12	80
6	0.8	300	1050	18	80
7	0.8	900	1050	12	82
8	0.8	900	1050	12	82
9	0.8	900	1050	12	82
10	1.5	300	1050	12	81
11	0.8	900	1050	12	82
12	0.8	300	300	12	81
13	0.8	1500	1800	12	83
14	0.1	900	1050	18	80
15	0.8	300	1050	6	83
16	0.8	900	300	6	83
17	0.8	1500	1050	6	84
18	0.8	900	300	18	81
19	1.5	900	1050	18	80
20	1.5	1500	1050	12	83
21	0.8	900	1800	6	83
22	0.8	300	1800	12	82
23	0.1	1500	1050	12	81
24	0.1	900	1800	12	80
25	1.5	900	1050	6	83
26	0.8	1500	1050	18	82
27	0.1	900	1050	6	80
28	0.1	300	1050	12	79
29	1.5	900	1800	12	82

4 Results and Discussion

The model summary (Table 3), the experiments model is 96.25% obtain statistically significant data. According to Table 3, we can analyze the effect of machining parameters on formability of aluminum sheet at room temperature. A relationship among machining parameters and response.

$\alpha = 79.17 + 7.374z + 0.000556\, V_{xy} + 0.000111n - 0.0863D - 2.451\, z^2 - 0.1786zD + 0.000069\, V_{xy}\, D$.

A relationship among processing parameters and response, it shows that the formability is proportional to feed rate (V_{xy}), spindle speed (n), and inverse proportion to tool diameter (D).

These machining parameters are effect on formability and product quality. So we can optimizing to have good results. In this experiment, optimized machining parameters are depth step 1.29 (mm), feed rate 1500 (mm/minute), tool diameter 6 (mm), spindle speed 1800 (rpm).

According to the analysis of variance (ANOVA) result (Table 3), we can see the percent influence of parameters and the interaction parameters such as depth step (z) 22.49%, feed rate (V_{xy}) 18.59%, tool diameter (D) 26.77%, spindle speed (n) 0.19%, interaction parameter z * z 22.63%, interaction parameter zD 5.02%, interaction parameter V_{xy} D 0.56% (Fig. 7).

Table 3. Analysis of variance (ANOVA)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	8	43.1462	5.3933	64.15	0.000
Z	1	10.0833	10.0833	119.94	0.000
V_{xy}	1	8.3333	8.3333	99.13	0.000
n	1	0.0833	0.0833	0.99	0.331
D	1	12.0000	12.0000	142.74	0.000
z*z	1	10.1462	10.1462	120.69	0.000
z*D	1	2.2500	2.2500	26.76	0.000
Error	20	1.6814	0.0841		
Total	28	44.8276			
S	R-sq	R-sq(adj)	R-sq(pred)		
0.289946	96.25%	94.75%	88.96%		

Fig. 7. Main effects

Through residual analysis (Fig. 8) carried out a model adequacy examination. Experimental data are the same with the predicted results of the constructed model. Figure 9 shows all residual plots for formability. Figure 8 (normal probability plot) shows the residuals concentrate in a straight line approximately. So, the error distribution is normal, the observed results are the same predicted results. The plot of the residual versus fitted values show Fig. 8 (versus fits), a confidence interval with 95% for all values. In Fig. 8 (histogram), the histogram of residuals is distributed normally. In Fig. 8 (versus order), the residuals are independent. According to the analysis of residuals, the constructed model is suitable for predicting formability, and all residuals are falling within control limits.

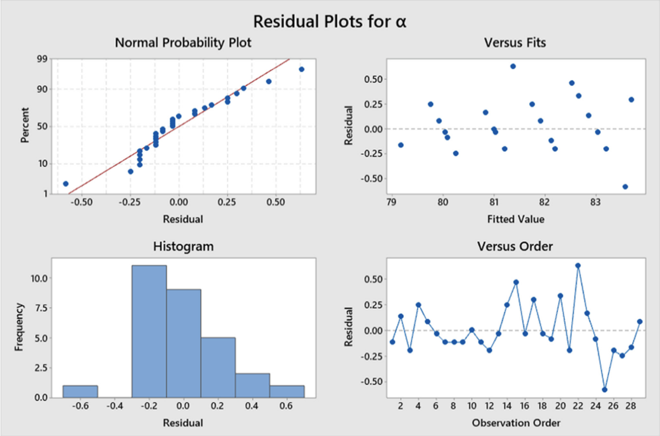

Fig. 8. Residual Plots for α

The interactive influences of independent parameters on formability show the 3D surface plot of formability (Fig. 9). It base on a relationship among machining parameters and responses. These graphs show change of two factors. The roughness of the surface exposed to the forming tool is smaller than the other surface, due to many different reasons such as contact conditions, lubrication and machine parameters. Therefore, we can control the best surface quality.

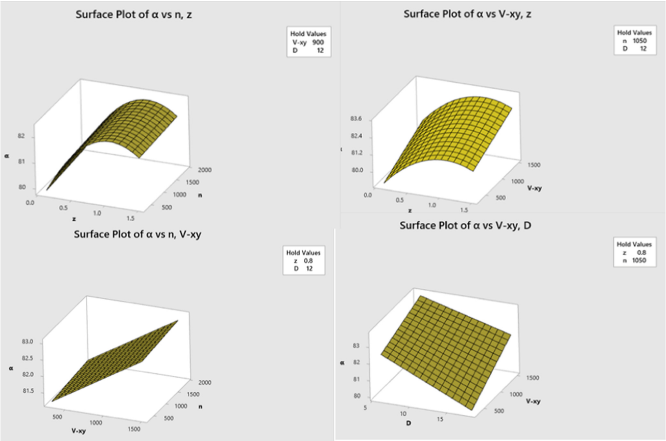

Fig. 9. Surface Plot of α vs n, z; α vs Vxy,z; α vs n, Vxy; α vs Vxy, D

5 Conclusion

In order to have good results, the jig and fixture system for TPIF process is important to reach good results. It is designed very stable to create some results as follows.

According to the analysis results, the experiments model is 96.25% with investigated machining conditions.

The percent influence of parameters and the interaction parameters such as depth step (z) 22.49%, feed rate (V_{xy}) 18.59%, tool diameter (D) 26.77%, spindle speed (n) 0.19%, interaction parameter zz 22.63%, interaction parameter zD 5.02%, interaction parameter $V_{xy}D$ 0.56%.

The formability is proportional to feedrate (V_{xy}), spindle speed (n), and inverse proportion to tool diameter (D).

Optimized machining parameters are depth step 1.29 (mm), feed rate 1500 (mm/minute), tool diameter 6 (mm), spindle speed 1800 (rpm) to obtain maximum formability $\alpha = 84.36°$ by TPIF technology for aluminum sheet A1050 H14, 1.5 mm thickness at room temperature.

Lubrication is an important factor to obtain high quality of product surface. The surface roughness exposed to the forming tool is smaller than the other surface.

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Effect of Lubrication on Deforming the Aluminum Sheet with Two Points Incremental Forming Technology

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Abstract. Facing a complex competition on a global manufacturing market, the companies always change the sharp and size of the products and reducing the designing and development of the products. The manufacturers have been looking for new technologies which are able to response the best customer exigency. These technologies must flexible, simple, inexpensive process, specially, not much time for product design and development. The incremental sheet forming technology has emerged as the best choice for those requirements. Particularly, Two Point Incremental Forming process (TPIF) is method of incremental sheet forming, which was shown the higher geometric accuracy and deformation. This technology is flexible, low cost, economic efficiency which uses the movement of CNC machine tool to form sheet material by layer to layer to the final product shape. The sheet material is clamped firmly on the jig/fixture which can move down along guide bars. The jig/fixture is fixed on the CNC milling machine table. During TPIF processing, the ball end of forming tool always contacts with the metal sheet to deform it following the CNC tool path. The product surface quality will be affected by this contact between metal sheet and tool surface through deformed process. It is also the main cause of wearing the top of forming tool which results on the inaccuracy of a geometric product shape and poor surface quality. This paper focuses on using the kind of lubricants and the lubricating way for TPIF process by investigating the four lubricants such as solid graphite powder, lubrication oil (Gear VG 150 EP), lithium grease, and mixed lubrication. The mixed lubrication is included such as solid graphite powder, lubrication oil, lithium grease with different percentages which helps reducing the contacting friction and improving the surface quality. The influents of machining parameters and their mechanism on the surface quality are analyzed in this study through investigations with TPIF technology for aluminum sheet at room temperature.

Keywords: Lubrication · Two Point Incremental Forming · Roughness surface · deformed profile

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1 Introduction

Beside forming parameters, machine, toolpath strategy and geometry influence final surface quality of product. Suitable lubricant is also an important factor. It helps improve surface quality of product, reduces forming forces and prevents wear of the end forming tool. Thus, we can overview some studies following.

Diabb et al. [1] study vegetable oil nano lubricants and wear in SPIF process. Sunflower and cornoils, added with 0.0125, 0.025, 0.05 and 0.1 wt% of SiO_2 nanoparticles was used to lubricate 6061 aluminum sheet alloys in SPIF process. The 6061 aluminum sheet surface wears asignificant and reduces when 0.025 wt% of SiO_2 nanoparticles areadded into the vegetable oils. Sornsuwit et al. [2] study lubricants and material properties on formability in SPIF process. Surface roughness of SUS 304 and SUS 316L is low with air blowing as lubricant. Surface roughness of $TiGr_2$ is low with MoS_2 lubricant. Jawale et al. [3] study lubrication study for SPIF of copper. This study result, the mineral oil is used to lubricate. It is an economical and optimal choice for incremental forming of copper and having a significant and positive effect on surface finish. It can also be concluded that the lubrication conditions, in the case of copper, do not affect the formability. Shisode et al. [4] study mixed lubrication for forming of sheet metal. A mixed lubrication was used to determine friction coefficient. It based on local contact conditions and resulting tribological system. The boundary friction direct affects to the measured tool and workpiece surface. The Reynolds equation was used to account the roughness effects. On the other hand, FE software was used to simulate the coupled friction model (boundary friction and the hydrodynamic friction model). Simulation results is clearly showed.

Generally, all studies focused on lubricants suitable for SPIF. In this study, solid graphite powder, lubrication oil (Gear VG 150 EP), lithium grease, and mixed lubrication were studied with lubricating way forming tool submergedinthe, effect of lubrication on deforming the aluminum sheet with two points incremental forming techonology. We will chose lubricants suitable from four lubrications for aluminum sheet with two points incremental forming techonology to obtain the best product surface quality through investigations a frustum cone shaped with TPIF technology for aluminum sheet at room temperature.

2 Experimental Equipment

Experimental equipments incluse a 3 axis CNC milling machine, a Jig and fixture system for TPISF process (Fig. 2), a forming tool (Fig. 1) a ball ended forming tool with 12 mm of diameter and etc. A sheet material is a Aluminum sheet A1050 H14 with 400 × 400 mm^2 dimension, 1.5 mm thickness. A sheet material is clamped between movable plate and clamp plate by bolts and move along guide bars. The Jig and fixture system is clamped on the CNC milling machine table (Fig. 3).

Fig.1. Forming tool

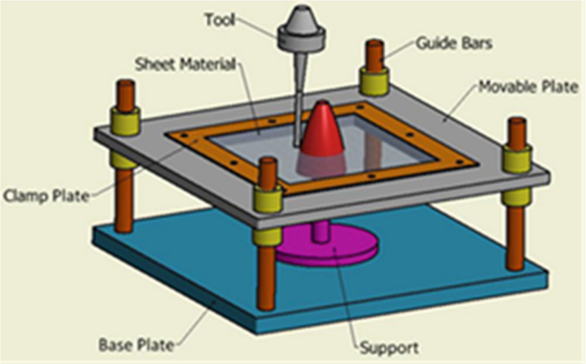


Fig. 2. CAD model of Jig and fixture system for TPISF process

Fig. 3. Practical model of Jig and fixture system for TPISF process

3 Experimental Design

A frustum cone shaped (Fig. 4) is built for experiments. Formed products are investigated about surface roughness and profile through experiments to determine the influence of lubrication on surface roughness and profile with the TPIF for aluminum sheet at room temperature. Experimental parameters, lubricant and lubricating way were chosen as Table 1 (Fig. 5).

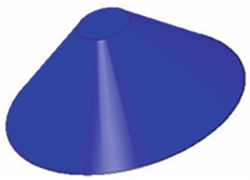


Fig. 4. Mode CAD of a cone shaped

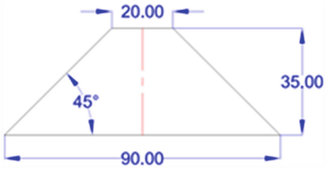


Fig. 5. Profile of frustum cone shape

4 Results and Discussion

4.1 Surface Roughness

Surface quality is characterized by surface roughness. From the measured results, the roughness of the surface exposed to the forming tool is smaller than the other surface, due to many different reasons such as contact conditions, lubrication and machine parameters. Therefore, we can control the best surface quality (Figs. 6, 7 and 8).

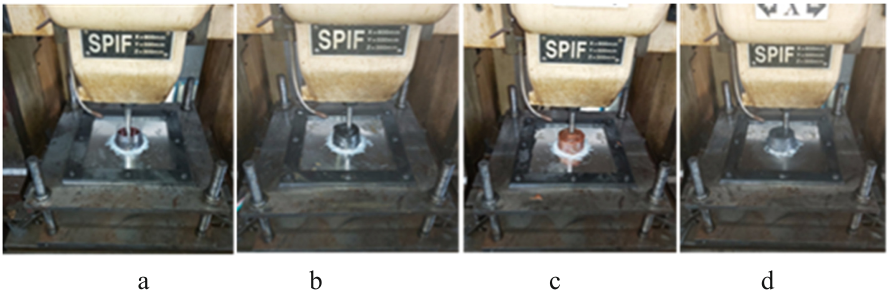


Fig. 6. Lubrication for TPIF by oil (a), mixed lubrication (b), lithium grease (c), and solid graphite powder solid graphite powder (d)

Table 1. Machining parameters for experimental design, lubricant, and application method.

No	Lubrication		Experimental parameters				Outer surface roughness (μm)
	Lubricant	Application method	Depth step (Δz) mm	Feed rate (Vxy) mm/minute	Tool diameter (D) mm	Spindle speed (n) rpm	
1	Solid graphite powder	Tool submerged in the lubricant	0.2	800	12	1000	3.82
2	Lubrication oil (Gear VG 150 EP)	Tool submerged in the lubricant	0.2	800	12	1000	0.95
3	Lithium grease	Tool submerged in the lubricant	0.2	800	12	1000	1.94
4	Mixed lubrication	Tool submerged in the lubricant	0.2	800	12	1000	0.94

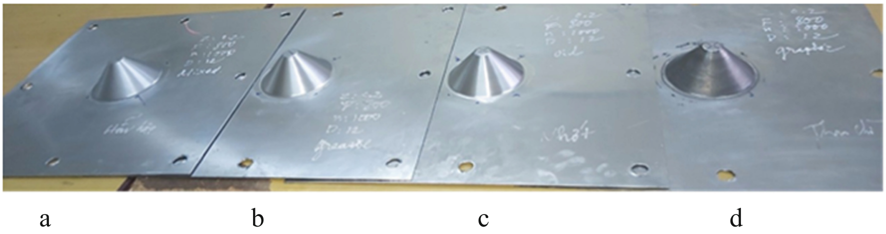


Fig. 7. Products by TPIF. (a: mixed lubrication, b: lithium grease, c: oil lubrication, d: solid graphite powder solid graphite powder)

Fig. 8. Measuring outer surface roughness of a frustum cone product by surface roughness measuring machine

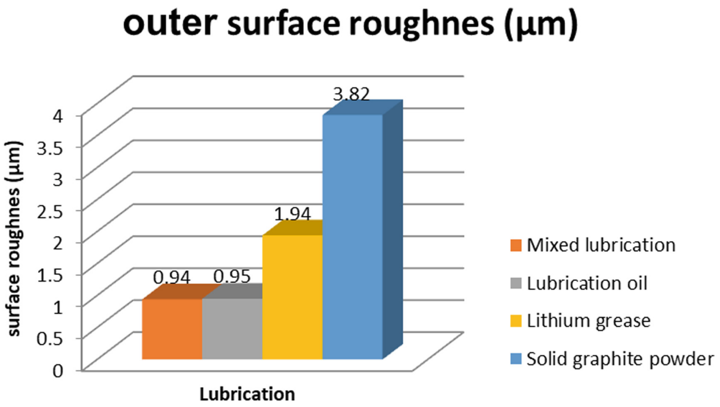


Fig. 9. Outer surface roughnes (µm) with four lubrications

Table 1 shows the product surface roughness of four lubricats with the same lubricating way and experimental parameters. Lubrication help reduces surface roughness. However, product surface roughness is different, it is up to very lubrication. The graph (Fig. 9) shows that lubrication with mixed lubrication is the lowest surface roughness conditions and lubrication with solid graphite powder is the highest surface roughness. Oil lubrication and mixed lubrication are the same the product surface roughness. On the other hand, heating exchange of oil lubrication is very good due to the liquid, so product surface is very smooth and bright (Fig. 10b). Solid graphite powder lubrication, the first, product surface roughness is smooth; after that product surface roughness increases roughened up due to friction and heat increases (Fig. 10 a). Solid graphite powder lubrication is solid condition, so heating exchange of it is very bad.

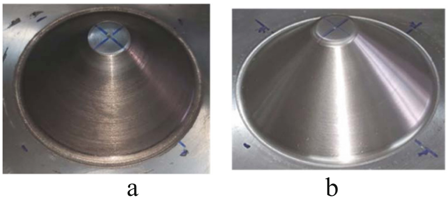


Fig. 10. a. Solid graphite powder lubrication product, b. oil lubrication product.

4.2 Profile deviation

The products are measured by coordinate measuring machine (CMM) with an accuracy of 2 μm and a probe diameter of 3 mm (Fig. 11). A conical cone profile are rebuilt by the profile measured data. The profiles is presented on the same graph (Figs. 12 and 13).

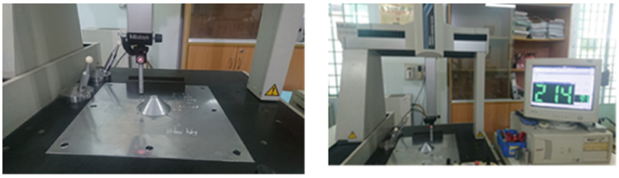


Fig. 11. Coordinate measuring machine

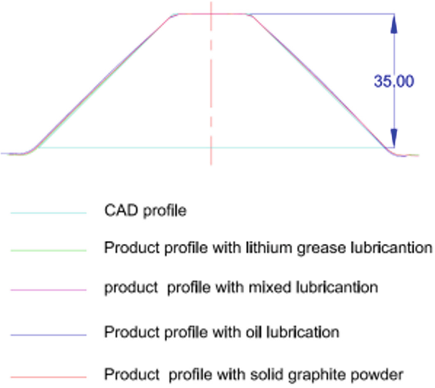


Fig. 12. Compare CAD and product profile.

Table 2. The thickness distribution

No	Thickness (mm)
1	0.512
2	0.505
3	0.51
4	0.511
5	0.507
Average	**0.509**

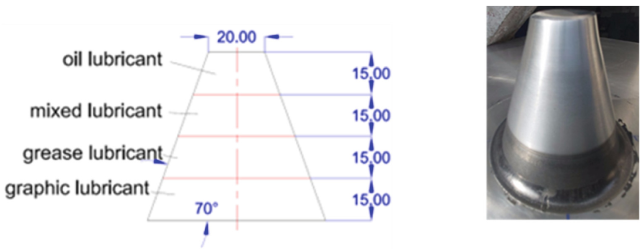


Fig. 13. Integrated lubricants on a frustum cone product

According to graph (Fig. 12). It shows that CAD profile and the experimental profiles obtained from several lubrications is near the same. We said that lubricats is near no significant effect on product profiles.

4.3 Thickness distribution.

A frustum cone mode was chosen with tilt angle 70° (Fig. 14 b) to investigate thickness distribution. The thickness distribution is measured by micrometer with accuracy ± 0.001 mm (Fig. 14 c). Measurement times are five times with average value as (Table 2).

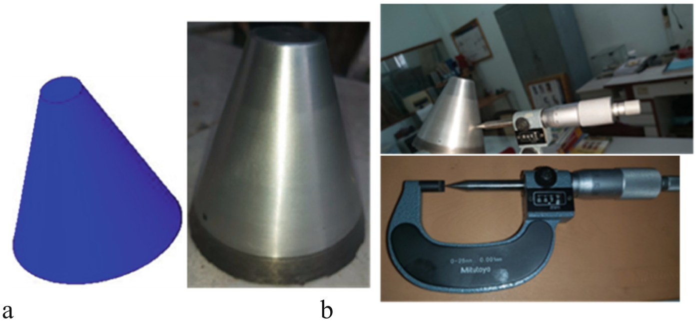
The wall thickness prediction is calculated by the sine law [5].

$t_1 = t_o\mathrm{Sin}(90-\alpha) = t_o\mathrm{Cos}\alpha = t_o\mathrm{Cos}70^o = 1.5*0.342602 = 0.51$ mm,
$t_1 = 0.51$ mm.

Percent of error between the wall thickness prediction and the thickness distribution is Δt.

$$\Delta t = (t_0 - t_1) * 100/t_0 = (0.51 - 0.509) * 100/0.51 = 0.196\%$$

According t_o the calculation and measerment results. The wall thickness prediction and the thickness distribution agrees very well with the sine law.



a b c

Fig. 14. a. Frustum cone CAD mode with tilt angle 70°. b. Integrated lubricants on a frustum cone product. c. Measuring thickness of a frustum cone product by micrometer.

5 Conclusion

In order to have good results, the Jig and fixture system is important to investigate the influences of processing parameters on formability. It is designed very stable to creat some results as follows.

The product surface quality and geometric accuracy are formed by The TPIF process, are very good.

The wall thickness prediction and the thickness distribution agrees very well with the sine law.

Lubication is a important factor to achive products with hight quality of surface. Thus, We can chose suitable lubricants and lubricating way. Mixed lubrication is the best lubricant in four lubricants such as solid graphite powder, lubrication oil, lithium grease, and mixed lubrication.

Lubricats is near no significant effect on product profiles.

Oil lubrication and mixed lubrication are the same the product surface roughness.

Oil lubrication is very good heat exchange due to the liquid. Thus, product surface is very smooth and bright. Solid graphite powder lubrication is solid so it is very bad heat exchange, product surface is bad.

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ORIGINAL ARTICLE

Influence of lubricants and lubricating methods on surface roughness in the two-point incremental sheet forming process

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Abstract

The selection of lubricants depends on the deformation mechanism of each process which significantly affects the surface roughness. In the incremental sheet forming process, there has been little attention on this aspect. This study investigates the influence of lubricants and lubricating methods on the surface quality and geometric accuracy during the two-point incremental forming process (TPIF). By using five different lubricants and two lubricating methods, the experiments were conducted to deform the 45°-cone parts with an aluminum sheet. Then, the formed parts were analyzed in terms of surface roughness and geometric accuracy. The morphology of the formed surfaces was also observed by using the scanning electronic microscope (SEM). The experimental results showed that the mixed lubricant (graphite powder + MSo2 + machine oil) greatly improved the surface quality and geometric accuracy. Using vegetable oil as an alternative lubricant for the TPIF process induced low cost and environmental effects but provided the surface quality similar to machine oil.

Keywords Lubricant · Lubricating method · Surface roughness · Geometric accuracy · TPIF · Incremental forming

1 Introduction

Incremental sheet forming (ISF) is an innovative and flexible process to produce asymmetrical and symmetrical products from both polymeric and metal sheets. It has been recognized as a potential process which is suitable for radical prototype changes of design and development with low and medium series or customized products. There are two approaches to form products from the ISF process identified by the existence or absence of a support or die used in the forming process. They are called as single-point incremental forming (SPIF) and two-point incremental forming (TPIF). Both approaches use the movement of a hemi-spherical end-forming tool generated for CNC machines or robots. The blank clamped firmly on the simple frame is deformed progressively layer by layer to the final product. The SPIF has not used any support or die during the forming process while the TPIF has required a partial or full die to overcome their disadvantages in geometric accuracy.

In the literature, many researchers have been focusing on the improvement of geometric accuracy or surface quality to mature the ISF process with industrial requirements. It has been noted that the dimensional accuracy of formed parts from the SPIF process may still not satisfy some applications in automotive and aviation industries which require geometric tolerances to be less than ± 1 mm over the whole deformed part dimensions (or less than ± 0.2 mm for some large parts) [1]. Therefore, most researchers have performed studies to overcome inaccuracy of formed parts with the SPIF process by (i) selecting optimal forming parameters [2, 3]; (ii) forming tool and sheet materials [4]; (iii) forming tool and toolpath strategies [5]; (iv) using multistage strategies [6]; (iv) heating the forming sheet [7]; (v) using TPIF [8]. The dimensional accuracy of the deformed part is mainly caused by spring-back, sheet thinning, pillow, sheet bending effects (regions of unwanted plastic deformation). The authors showed that those approaches effectively improved the geometric accuracy with different levels [9]. However, to satisfy the needs from further application industries for ISF, deep research efforts are still required [10].

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The quality of the formed surface is also an interesting aspect which was needed to satisfy the application industries. It is identified that the surface roughness in the ISF process is higher than one in conventional processes such as deep drawing, stamping, spinning, etc. Lubrication for metal sheets is an important task in the convenience process because it affects the quality of the formed surface and wearing of the forming tools. The selection of lubricants depends on the deformation mechanism of the forming process, but it seems not to be caused by the decrease in formability [11, 12]. However, there were few researchers devoting to effects of lubricants and lubricating methods on the surface roughness in the ISF process. Most studies focused on the improvement of the forming surface quality by optimizing machining parameters [13]. It was concluded that the depth step has great influence on the formed surface in the SPIF process [14, 15]. Hussain et al. [16] investigated the suitable tool and lubricant in the deformation of titanium sheets. The authors made various combinations of tools and lubricants to study the influence of each combination on the formed surface quality. Then, the surface roughness of formed surfaces was measured and the surface quality was examined by a scanning electron microscope (SEM). The authors concluded that the proper surface coating of the metal sheet is essential to achieve better quality of the forming surface. The use of HSS tool material with the combination of molybdenum disulfide and petroleum jelly also achieved good surface quality. Jawale et al. [17] investigated the influence of lubrication on the deformation of copper sheets. The authors compared SEM analysis of different lubrication states and concluded that lubrication has a positive effect on the formed surface; however, the formability was not influenced by the lubricants. Azevedo et al. [11] studied the effects of lubricant types during the deformation of aluminum and DP780 steel sheets on the quality of the forming surface. The authors performed the SPIF process with a range of distinct lubricants. They found that good surface quality was achieved on the aluminum sheet, but worse surface formed on the steel sheet. For warm ISF processes, Zhang et al. [18] studied the effects of suitable lubricants and lubricating methods for deforming the magnesium alloy sheet (AZ31). The authors used pulsed anodic oxidation method (PAO) for the lubricants K2Ti4O9 whisker and solid graphite or MoS2 powder-coated porous ceramic to coat the sheet surface before forming the sheet by the SPIF process. The formed surfaces were analyzed by the SEM and the surface coated by PAO method was found to have good surface quality.

In this study, the effects of lubricants and lubricating methods are investigated on aluminum sheets with the two-point incremental forming process (TPIF). The tests were performed with four lubricants, including AS40 grease/paste, graphite powder, VG150 machine oil, and vegetable oil. The lubricants had been provided for contact between the forming tool and the metal sheet by spraying, coating, and submerging methods before the TIPF was started. The original surface and forming surface were analyzed by the SEM to understand the effects of the lubricants and lubricating methods on the surface roughness. Moreover, the profiles of the forming parts were also measured by coordinate-measuring machine (CMM) and compared to CAD profile to evaluate the geometric accuracy.

2 Experimental equipment and process

2.1 Experimental equipment

The fixture and jig used for all experiments in this study were designed for the TPIF process to reduce the geometric inaccuracy of the formed part. This system uses four sliding ball bushings allowed to move axially relative to four guide bars with high-precision motion. The sliding ball bushings are fixed with moveable clamping plates and slide smoothly in axial direction of the guide bars. The supports are designed depending on the experimental purposes and can replace various product models. The whole system is placed on the fixed plate and is clamped firmly on the machine table by six bolts as shown in Fig. 1a. The forming tool is made by welding a

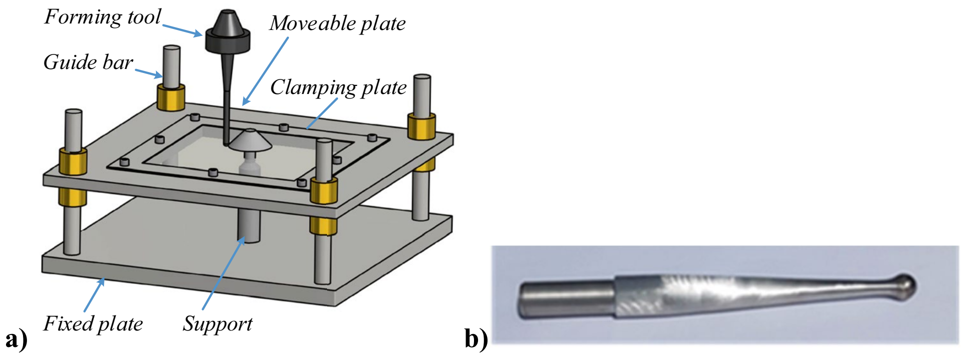


Fig. 1 The experiment system of TPIF (**a**) and the forming tool (**b**)

Table 1 The lubricants and physical properties

Lubricant	State	Viscosity (mm^2/s)	Density (kg/m^3)
Graphite powder	Solid	-	1800
AS40 grease	Paste	-	1760
VG 150 EP oil	Liquid	150	872
Vegetable oil (sunflower oil)	Liquid	48.6	920
Mixing lubricant	Paste	-	-

chrome steel ball on the top of the tool with high hardness of about 64 HRC to reduce the friction and wearing in the forming process (Fig. 1b). The lubricants are necessary for the contact zone between the forming tool and the metal sheet, lengthening the longevity of the forming tool, improving heat distribution, removing chips, and improving the quality of the forming surface. Additionally, to eliminate sliding friction, the forming tool must roll without sliding over the metal sheet surface when it is moving. It is required that the traveling distance along the metal sheet must be equal to the average circumference of the tool in the contact zone multiplied by the spindle speed (ω) via the following equation:

$$\omega = \frac{v}{\pi r\sqrt{\frac{1}{2}(1-\cos 2\alpha)}}$$

where v, r, α is the feed rate, forming tool radius, and wall angle of the deforming part, respectively. The set of optimized machining parameters used in this experimental campaign is the results of our previous studies which give excellent forming surface quality [19, 20]. Therefore, this study uses different lubricants and lubricating methods based on optimized machining parameters, which brings better understanding of their effects on the geometric accuracy and surface roughness.

2.2 Experimental setup

All the experiments were conducted on the aluminum sheet A-1050 H14 with the thickness of 1.5 mm. The choice of lubricants for this study were based on two important characteristics—viscosity and phase (e.g., liquid, solid, gel/pastes, etc.) which can be used for many application industries with the TPIF process. The study tried to cover as many distinct lubricant types as possible as shown in Table 1.

The aluminum sheet was deformed in 45°-cone shape (see Fig. 2a) using each of the above lubricants and three lubricating methods (spraying, coating, and submerging), depending on their phases. The mixing lubricant is a mixture including graphite powder, AS40 grease, and machine oil to reduce dust particles spreading over the environment and increase the lubricating capacity of graphite powder. The TPIF was run with helical tooth path and stopped when it had any mechanical failures. The experimental system and deforming model are shown in Fig. 2a.

2.3 Experimental campaign

A conventional CNC machine was customized for the ISF process as shown in Fig. 2a. The aluminum sheet was clamped firmly on the moveable plate while the forming tool was moving on the outer surface of the 45°-cone model from its center to edge. The main parameters for the TPIF process are depth step of 0.2 mm/s, tool diameter of 12 mm, feed rate of 800 mm/min, and spindle speed of 1000 rpm which make the forming tool roll without sliding on the sheet surface. This set of machining parameters was optimized for the best quality of the formed surface in the previous studies [19, 20]. All aluminum sheets were measured with respect to surface roughness and microstructure by SEM images before being deformed by the TPIF process.

Depending on the lubricating method, each experiment was prepared with a lubricant on the forming sheet. Graphite powder was spread on the whole upper sheet surface with thickness to be equal to the tip-tool diameter (12 mm) and was bonded with the surface by a very thin grease film. Paste/grease lubricants were coated a layer with the height of 12 mm while liquid lubricants were locked up in the bonded tank on the upper sheet surface to ensure the forming tool immersed in the lubricants. Graphite powder can

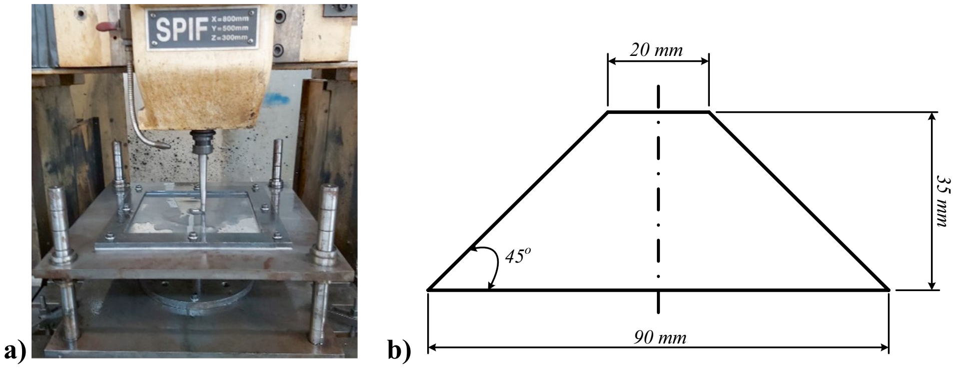


Fig. 2 The experiment system (**a**) and the forming model (**b**)

Table 2 Lubricants and lubricating methods

Lubricant	Spraying	Coating	Submerging
Graphite powder	-	No. 10	No. 2
AS40 grease	-	No. 4	
Lubrication oil (Gear VG 150 EP)	No. 6	-	No. 3
Vegetable oil (sunflower oil)	No. 8		No. 7
Mixing lubricant	-	No. 9	No. 1

be dangerous in some forming applications because it produces dust in the environment. Thus, it was also mixed with grease and machine oils (accounting for 50% of the mix) to be coated on the sheet surface. The liquid lubricants were sprayed directly on the forming tool tip by an existing circulatory cooling/lubrication system of the CNC machine. The lubricating methods for experiments of the TPIF process with different lubricants are shown in Table 2.

3 Results and discussion

In all experiments, the lubricants and lubricating method shown in Table 2 had been directly applied on the upper surface of the metal sheet before the TPIF process was started. The lubricants were always ensured to fully fill up the contact area between the forming tool and metal surfaces. The forming process would be stopped when the cone achieved the height of 350 mm or any mechanical failure occurred. The final formed parts were unclamped and underwent roughness tests and profile measurement. The profile of each formed part was measured at each quarter for both upper and lower surfaces by using a CMM (Fig. 3b).

3.1 The geometric accuracy and thickness distribution

The profiles were extracted from the CMM machine in the coordinate formatted file. The outer and inner profiles were compared to the CAD profiles as shown in Fig. 4a. The profile can be divided into three regions: top, wall, and bottom of the cone shape. In general, the wall regions showed to best fit with CAD profiles for all lubricants with the maximum error of about 0.1 mm. While, the top and bottom regions had a lower accuracy with the maximum error of 0.2 mm. However, these results present a higher accuracy in comparison with the SPIF process (maximum error in ± 1.5–2 mm) with the same material and machining parameters [5, 10, 19, 21, 22].

The lubricants submerged completely in the forming tool tip showed an excellent accuracy of the TPIF process with the maximum error of about 0.08 mm (the specimens were numbered in nos. 1, 2, 3, 4, and 7 in Figs. 4b and 5). The lubricant filled the contact area between the surface of the forming tool and the metal sheet. From experimental observations, the forming tool moving on the metal sheet creates a local valley where the lubricant agglomerates around the tool tip. Thus, this way can keep continuous lubrication between the tool tip and the sheet surface and make the friction decrease significantly. Otherwise, the spraying and coating methods showed less geometric accuracy due to a discontinuous and non-uniform lubrication in the contact zone when the forming tool moved on the sheet, resulting in high direct friction of the tool tip with the sheet surface.

A good geometric accuracy was found for both pure graphite powder and mixed lubricants with the error of 0.02 mm in the wall region. This result is very important because graphite is a cheap solid lubricant which is appropriate for metal forming in practice and cost. Using the mixed lubricant (50% graphite) avoided the spread of graphite dust to the environment. The grease and machine oils in the mixed lubricant helped the graphite particle stick and fill up small valleys on the metal surface. Thus, the efficiency of lubrication is better than pure graphite powder. The geometric accuracy of the mixed lubricant is about 0.02 mm. In addition, the machine oil (Gear VG 150 EP) also resulted in good geometric accuracy.

Thickness distribution of the formed part with different lubricants and lubricating methods is shown in Fig. 4b. The

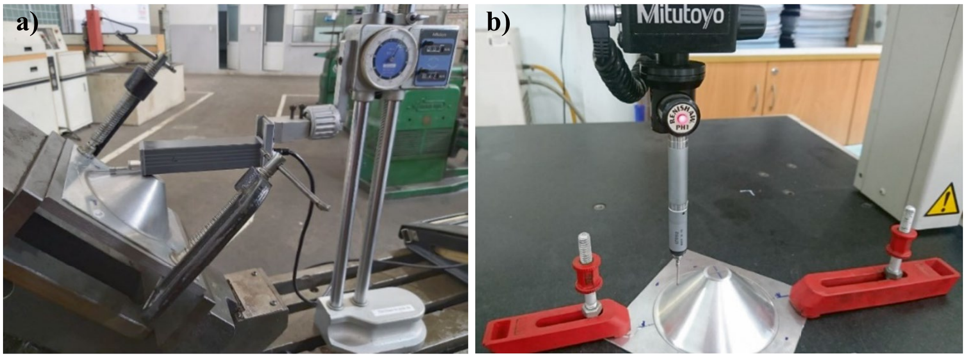


Fig. 3 **a** Measuring the surface roughness; **b** measuring the profile of the formed part

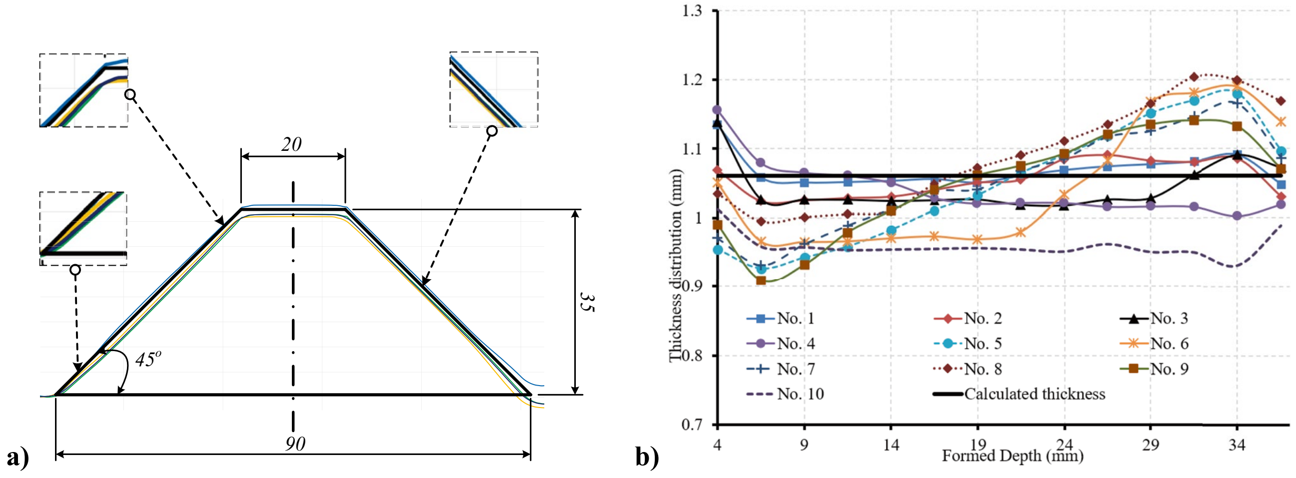


Fig. 4 **a** CAD and measured profiles; **b** thickness distribution of the formed part

thickness of formed part was calculated through a sine law formula of $t = t_o \sin\alpha$ (where t is the thickness of final part, t_o is the thickness of a blank sheet, and α is the half-apex of part) [21]. The result of calculated thickness was drawn as a line in Fig. 4b. The measured thickness from CMM machine at different distances from the clamped position to the supported position is distributed in adjacent areas of this line (Fig. 4b). The samples coated or sprayed lubricants (nos. 4, 6, 8, 9, and 10) showed that the thickness distribution of the formed part has a high deviation from the line. Specially, the sample of no. 10 is the furthest from the line about 0.15 mm. The cause of this deviation is from the contact condition between forming tool and the aluminum sheet which the graphite layer exists in this contact. This phenomenon decreased the deviation with sample of nos. 1, 2, 3, and 7, where the forming tool was submerged into the lubricants. The use of mixed lubricant and submerged method also has the smallest deviation from the line.

3.2 The surface roughness measurement

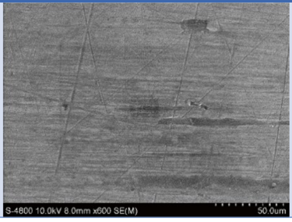
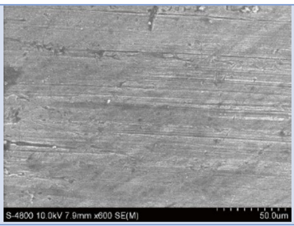
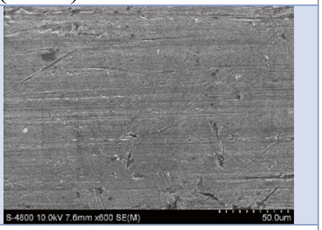
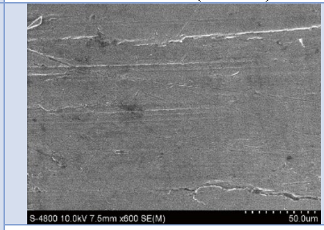
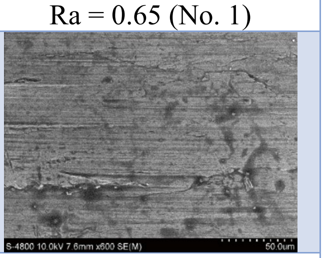
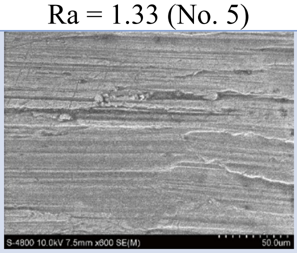
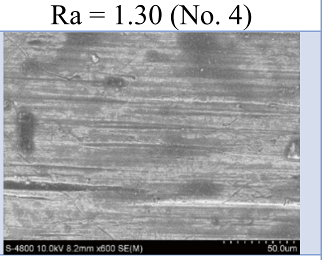
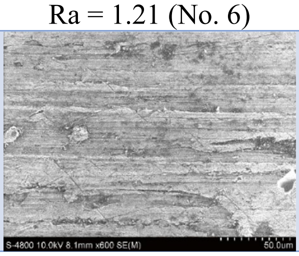
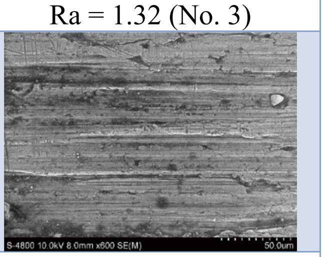
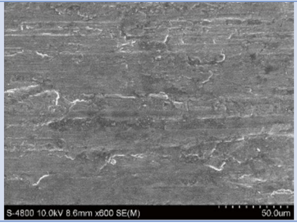
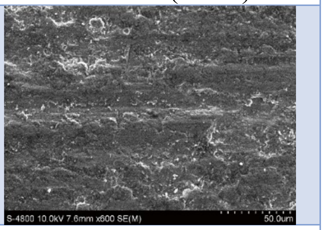
For measurement of surface roughness, the formed part for each lubricant and lubricating method was fixed on a rotating vise inclined 45° with respect to the horizontal plane (Fig. 3a). A Mitutoyo machine was used to measure the roughness parameters of two cone surfaces according to ISO 1302 with the arithmetic mean roughness (Ra) (Fig. 3b). The results are shown in Fig. 5 with the outer surface contacting with the forming tool. Observations showed that graphite powder was not a good lubricant for two lubricating methods in the TPIF process. Although graphite powder is a good lubricant in industrial applications, the lubricating efficiency depends on the size of the graphite particle. A large particle is difficult to fill in the contacting surface between the forming tool and the metal sheet in the TPIF process. In addition, this lubricant spreads a large amount of dust to the surrounding environment. Thus, this lubricant is not suitable for the TPIF process with high values of Ra (Ra = 4.32 for the discontinuous lubricating method and Ra = 2.6 for the continuous lubricating method). The SEM images (Fig. 5) also showed that the submerging method gave the better surface than the coating method due to the discontinuous graphite powder coated on the metal sheet.

The graphite powder mixed with a proper amount of grease and machine oils brought high lubricating efficiency in the TPIF process. The grease and machine oils acted as the adhesive and filled the graphite particles in concaves on the metal surface. This mixture also prevented the spread of graphite powder. The SEM images also showed that there were few concaves on the formed surface. The submerging lubricating method showed a smoother surface than the coating method. With this lubricant, the surface quality can achieve Ra = 0.65 which is useful for many industrial applications.

The AS40 and machine oil (Gear VG 150) which are two popular lubricants used in the machine industry showed a relatively good surface quality in the TPIF process. There was no difference in applying the lubricating method with AS40 grease. However, there was a significant difference between the two lubricating methods of the machine oil. The submerging lubricating method for the machine oil was more preeminent than the spraying method. It is necessary to use a circulatory pump system to provide machine oil for the TPIF deformation process. On the other hand, using vegetable oil in the TPIF process with the submerging method also produces a good level of surface quality as in the case of machine oil. It is a potential substitute for mineral oil to decrease cost and environmental effects.

Finally, it is worth mentioning the submerging lubricating method is best suitable for the TPIF process where the

Fig. 5 SEM images of the sample with different lubricants and lubricating methods

Lubricants	Spraying/Coating method	Submerging method
Original aluminum sheet	 Ra = 0.52 (No. 0)	
Mixed Lubricant	 Ra = 1.46 (No. 9)	 Ra = 0.65 (No. 1)
AS40 grease	 Ra = 1.33 (No. 5)	 Ra = 1.30 (No. 4)
Gear VG 150 oil	 Ra = 1.21 (No. 6)	 Ra = 1.32 (No. 3)
Vegetable oil	 Ra = 1.85 (No. 8)	 Ra = 1.35 (No. 7)
Graphite Powder	 Ra = 4.32 (No. 10)	 Ra = 2.6 (No. 2)

lubricating film can be filled easily out the contact zone between the forming tool and the metal surface. The mixed lubricant brings potential advantages to achieve good surface quality in the TPIF process. Vegetable oils with lower viscosity values still provide a cheaper way to apply for the TPIF process which obtain surface quality quite similar to machine oil.

4 Conclusion

This study investigated the effects of lubricants and lubricating methods during the TPIF process. The 45°-degree cone part was formed with different lubricants and lubricating methods. The machining parameters and toolpath strategy were kept the same for all experiments. Then the formed part was analyzed in terms of both geometric accuracy and surface quality. By selecting the same toolpath and the optimal machining parameters like the previous studies, it shows that using a suitable lubricant and lubricating method may significantly improve the geometric accuracy and the surface quality of the formed parts in the TPIF process. The following conclusions can be extracted from this study:

- The lubricants and lubricating methods had significant effects on both the geometric accuracy and the surface quality of the formed parts in the two-point incremental forming process. The continuous lubricating method (immersing method) greatly affected the surface roughness; thus, it is important to ensure enough lubrication in the contacting zone during the TPIF process.
- The formed profile at the wall region best fitted with CAD profile while other regions had slight differences. However, the geometric error in the TPIF process was much less than one in the SPIF process with the same machining conditions. The excellent geometric accuracy was found for both pure graphite powder and mixed lubricants with the error of 0.02 mm in the wall region. The machine oil also provided a good geometric accuracy.
- The lubricants had significant effects on the surface roughness. The mixed lubricant (graphite powder + MSo2 + machine oil) greatly improved the surface quality and thickness distribution and also prevented the spread of graphite powder to the surrounding environment. This mixture had good adhesion and filled in the concaves in the metal sheet with the role as a lubricating film on the contacting surface between the forming tool and the metal sheet.
- The vegetable oil acted as an alternative lubricant for the TPIF process with low cost, but the obtained surface quality was quite similar to the machine oil. Use of this lubricant can help reduce machining cost and environment impacts.

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Declarations

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Conflict of interest The authors declare no competing interests.

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ẢNH HƯỞNG CỦA NHIỆT ĐỘ TẠO HÌNH TẤM HỢP KIM MAGIE BẰNG PHƯƠNG PHÁP BIẾN DẠNG GIA TĂNG CỤC BỘ

EFFECTS OF FORMING TEMPERATURE ON MAGNESIUM SHEET UNDER SPIF PROCESS

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TÓM TẮT

Công nghệ biến dạng gia tăng đơn điểm (SPIF) cho vật liệu kim loại tấm đang được nghiên cứu rộng rãi tại Việt Nam và trên thế giới. Để tăng khả năng biến dạng cho các loại vật liệu tấm khó biến dạng (hợp kim magie, titan, inox...vv), các tấm vật liệu thường được gia nhiệt bằng nhiều phương pháp khác nhau. Việc xác định nhiệt độ và thông số biến dạng của công nghệ SPIF ở nhiệt độ cao thường là yếu tố rất quan trọng mà ảnh hưởng đến khả năng biến dạng và chất lượng của sản phẩm. Bài báo này sẽ trình bày ứng dụng công nghệ SPIF ở nhiệt độ cao cho vật liệu tấm magie và xem xét đến cơ tính của tấm ở các nhiệt độ khác nhau với khả năng tạo hình trong công nghệ SPIF. Hệ thống gia nhiệt trực tiếp cũng được thiết kế để dùng biến dạng tấm bằng công nghệ SPIF và trong thí nghiệm kéo mẫu ở nhiệt độ và tốc độ kéo khác nhau. Sau đó, các mẫu kéo được phân tích cấu trúc tế vi để xác định các đặc điểm cơ tính của hợp kim magie ứng với thông số biến dạng. Kết quả cho thấy, ở nhiệt độ $250^{\circ}C$, hợp kim magie cho khả năng biến dạng, cơ tính và chất lượng sản phẩm tốt nhất đối với công nghệ tạo hình SPIP.

Từ khóa: *Tạo hình không khuôn; SPIF; Biến dạng ấm; Hợp kim magie; Phân tích cấu trúc tế vi.*

ABSTRACT

Single point incremental forming technology (SPIF) for metal sheet has studied popularly at Vietnam and other countries. To improve formability of SPIF for hard-to-deform sheet materials such as magnesium alloy, titanium, stainless steel...etc, heating process for metal sheets has been carried out for SPIF process. The selection of forming temperation and forming parameters for SPIF process is very important task which effect on the formability and formed product. This paper presents applicability of warm SPIF for magnesium sheet and considers the mechanical properties of magnesium sheet alloy at different temperature and deforming speed. The heating system is designed to be able to carry out SPIF process at warm condition with different forming speed and temperature. Then, the tested specimens taken from mechanical tests were used for microstructure analysies. The results showed that magnesium sheet is well formed at the temperature of $250^{\circ}C$ with high geometric accuracy.

Keywords: *Die-less, SPIF, warm forming, magnesium alloy, microstructure analysis.*

1. GIỚI THIỆU

Công nghệ biến dạng gia tăng đơn điểm (SPIF) đã thu hút sự quan tâm của nhiều nhà khoa học trong thời điểm hiện nay [1]. Một trong những ưu điểm của phương pháp này là không yêu cầu khuôn đắt tiền và thiết bị phức tạp, giảm thời gian chuẩn bị và gá đặt. Công nghệ SPIF sử dụng máy CNC để biến dạng vật liệu tấm với dụng cụ biến dạng đầu chỏm cầu không cạnh cắt. Tấm vật liệu được kẹp chắc trên một khung và gá chắc chắn trên bàn máy CNC. Dụng cụ tạo hình sẽ được lập trình chạy theo biên dạng sản phẩm và biến dạng tấm theo từng lớp vật liệu cho đến khi hoàn chỉnh hình dạng thực của sản phẩm. Khả năng biến dạng của công nghệ này hơn hẳn công nghệ truyền thống (dập, vuốt, chồn, ép, miết...vv) cho nên có thể thực hiện với các mô hình phức tạp và đáp ứng việc tạo mẫu nhanh cho các sản phẩm làm từ vật liệu tấm (kim loại tấm hoặc polymer tấm). Công nghệ này thích hợp cho các loạt sản phẩm vừa và nhỏ, giảm giá thành sản phẩm. Trong thời điểm hiện tại, các nghiên cứu đã tập trung hầu hết các khía cạnh của quá trình gia công như: Máy – thiết bị, dụng cụ tạo hình, các thông số ảnh hưởng đến gia công (đường kính dao, chiều dày tấm, vận tốc quay trục chính, điều kiện tiếp xúc, loại vật liệu ... vv), cơ học biến dạng. Đa số các nghiên cứu thường tập trung vào việc ứng dụng công nghệ SPIF ở nhiệt độ thường cho các loại vật liệu kim loại biến dạng tốt [1]. Đối với vật liệu kim loại như hợp kim magie, titan, inox,...vv, thì rất khó biến dạng bằng công nghệ SPIF ở nhiệt độ thường. Các vật liệu dạng này đòi hỏi dung nhiệt hỗ trợ quá trình biến dạng, đặc biệt hợp kim magie được sử dụng rất nhiều trong công nghiệp ô tô và hàng không vì đặc tính nhẹ và bền [5-9]. Trong thời điểm hiện nay, có nhiều nỗ lực để thực hiện công nghệ này đối với hợp kim magiê được liệt kê sau đây:

Ambrogio [5] thực hiện nghiên cứu đầu tiên về việc áp dụng công nghệ SPIF để biến dạng tấm hợp kim magie. Tác giả đã tập trung vào việc xác định các giới hạn khả năng tạo hình của tấm hợp kim cũng như ảnh hưởng của các thông số công nghệ với khả năng tạo hình. Phạm vi nhiệt độ khảo sát từ 200°C đến 300°C, các thí nghiệm được thực hiện để đánh giá ảnh hưởng của đường kính dụng cụ, chiều sâu xuống dao và nhiệt độ thí nghiệm. Kết quả cho thấy rằng, khả năng tạo hình của tấm hợp kim magie tăng đáng kể. Các ảnh hưởng của nhiệt độ và chiều sâu tiến dao khá quan trọng, trong khi đường kính dụng cụ ảnh hưởng không đáng kể.

Ji [7] khảo sát công nghệ SPIF cho tấm hợp kim magie trong một khoảng nhiệt độ rất rộng từ 20°C đến 250°C. Tác giả đã thực hiện các thí nghiệm kiểm tra cơ tính của vật liệu ở các nhiệt độ khác nhau để đánh giá ảnh hưởng của nhiệt độ đối với biến dạng trong phương ngang và phương đối xứng tại 20°C, 50°C, 100°C, 150°C, 200°C và 250°C. Kết quả cũng cho thấy khả năng tạo hình tăng theo nhiệt độ. Các thí nghiệm và mô phỏng PTHH của công nghệ SPIF được thực hiện, sau đó với mô hình côn với các nhiệt độ khác nhau. Tác giả đề xuất một khái niệm mới để cải thiện khả năng tạo hình mà cho phép vượt quá giới hạn tạo hình của mô hình nón với góc nghiêng lớn hơn.

Zhang [6] khảo sát ảnh hưởng của các phương pháp sản xuất tấm hợp kim magie đối với mức độ bất đẳng hướng trong quá trình biến dạng SPIF. Nghiên cứu này, tập trung vào bốn loại tấm AZ31 được chế tạo bằng phương pháp khác nhau. Các phương pháp chế tạo bao gồm đùn nóng, cán + nóng/ cán nguội, cán dải đúc và cán qua. Các tác giả kết luận rằng, cán nóng/đúc nguội - cán tấm với kích thước hạt của 5-15μm có độ bất đẳng hướng nhỏ. Những dạng còn lại ảnh hưởng đáng kể đến khả năng ☞

tạo hình, nhưng nó giảm bớt ảnh hưởng độ bất đẳng hướng khi tăng nhiệt độ. Các tác giả cũng đề nghị rằng, tấm AZ31 sản xuất bằng phương pháp cán ấm có khả năng tăng hình tốt nhất đối với quá trình SPIF.

Nhìn chung, các nhóm nghiên cứu đã khảo sát ở các dải nhiệt độ khác nhau nằm trong vùng nhiệt độ ấm để tìm ra sự ảnh hưởng của thông số công nghệ với khả năng tạo hình [2-4]. Bản chất về khả năng biến dạng tăng khi gia nhiệt và ảnh hưởng của các thông số biến dạng chỉ mới khảo sát ở mức vĩ mô, chưa làm rõ các yếu tố về cơ tính và cấu trúc kim loại ở các nhiệt độ khác nhau. Trong nghiên cứu này sẽ biến dạng tấm hợp kim magie ở nhiệt độ thích hợp (vùng ấm) với mong muốn tăng khả năng biến dạng vật liệu trong công nghệ SPIF. Việc xác định nhiệt độ phù hợp mà đảm bảo cơ tính vật liệu, chất lượng sản phẩm và quá trình biến dạng tối ưu nhất. Thí nghiệm kéo mẫu cắt từ tấm hợp kim magie được kéo ở tốc độ kéo và nhiệt độ kéo khác nhau nhằm khảo sát các thông số về cơ tính của tấm kim loại. Nhằm hiểu rõ hơn bản chất cơ tính do ảnh hưởng của nhiệt độ và tốc độ kéo, các mẫu sau khi kéo được chụp SEM nhằm thấy rõ cấu trúc tế vi của tấm kim loại. Cuối cùng, việc khảo sát mẫu sản phẩm bằng công nghệ SPIF ở nhiệt độ từ 25°C – 300°C cũng được thực hiện nhằm kiểm nghiệm khả năng biến dạng và chất lượng sản phẩm sau khi biến dạng. Trong nghiên cứu này, hệ thống gia nhiệt thiết kế dựa trên hiệu ứng Joule và điều khiển tự động quá trình gia nhiệt sử dụng để gia nhiệt trong quá trình biến dạng bằng công nghệ SPIF [2]. Các mẫu kéo được gia nhiệt bằng phương pháp gia nhiệt cảm ứng cao tần được điều khiển một cách tự động sẽ cho độ chính xác rất cao.

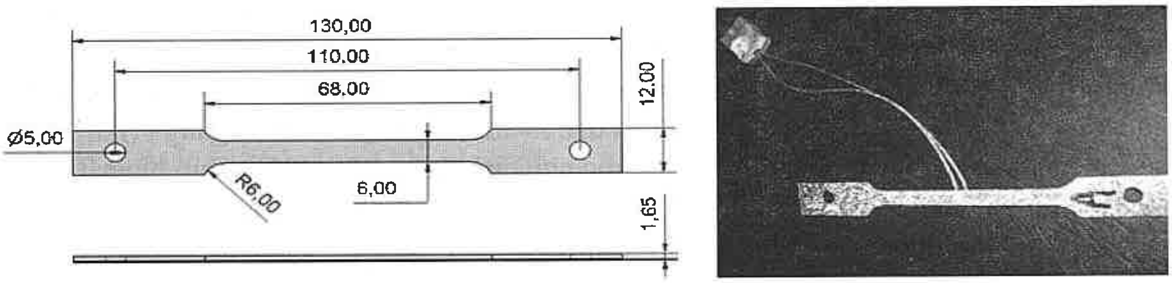
2. THIẾT BỊ THÍ NGHIỆM

Nghiên cứu này sử dụng vật liệu hợp kim magie có tên thương mại là AZ31 với thành phần hóa học và các hệ số cơ lý tính như trình bày trong Bảng 1.

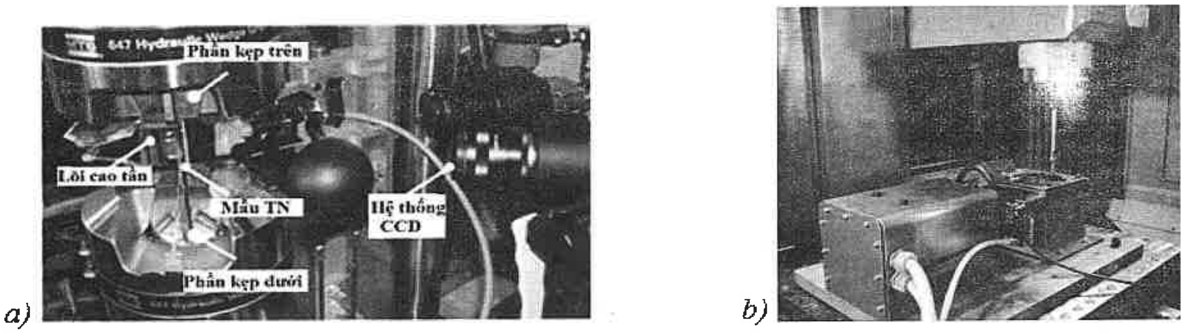
Nguyên tố	Hàm lượng %	Cơ lý tính	Giá trị
Al	2.50 - 3.50 %	Khối lượng riêng	1770 kg/m^3
Ca	<= 0.040 %	Module đàn hồi	45.10^9 N/m^2
Cu	<= 0.050 %	Hệ số Poisson	0.35
Fe	<= 0.0050 %	Module trượt	17.10^9 N/m^2
Mg	97.0 %	Hệ số giãn nở nhiệt	27.10^{-6}m/m-°C (20-200°C)
Mn	>= 0.20 %	Nhiệt dung riêng	1.000 J/kg-°C
Ni	<= 0.0050 %	Hệ số dẫn nhiệt	96.0 J/s-m-K
Si	<= 0.10		
Zn	0.60 - 1.40 %		

Bảng 1. Thành phần hóa học và thông số cơ lý tính của hợp kim magie

Để khảo sát được cơ tính của tấm hợp kim magie, các mẫu thử được cắt theo mẫu chuẩn (UNI EN 10002) có kích thước như Hình 1, theo ba phương khác nhau theo phương cán tấm 0°, 45°, và 90°. Bề mặt mẫu được phun lớp Nitride-Boron (đen trắng) để hệ thống camera CCD dễ dàng nhận diện được hiện tượng biến dạng. Cảm biến nhiệt được hàn cứng ngay ở phần chính giữa của mẫu đảm bảo không bị đứt khi kéo và nối vào hệ thống giám sát nhiệt.



Hình 1. Kích thước mẫu thử và chuẩn bị mẫu



Hình 2. Thiết bị thí nghiệm: a) Thiết bị kéo; b) Thiết bị tạo hình SPIF ở nhiệt độ cao

Các thí nghiệm được thực hiện ở cả nhiệt độ phòng và nhiệt độ cao với các vận tốc kéo khác nhau cho trong Bảng 2. Thiết bị kéo MTS có lực kéo tối đa 5 tấn, các biến dạng được đo bằng hệ thống quang học và phần mềm xử lý ảnh. Các biến dạng dọc trục và biến dạng ngang được đo cẩn thận bằng hệ thống này. Thủ tục thí nghiệm gồm các bước: i) Mẫu được nung nóng đến nhiệt độ biến dạng trong thời gian tối đa 120s và duy trì nhiệt độ trong 120s tiếp theo để đảm bảo có phổ nhiệt đồng nhất trên toàn bộ vùng đo; ii) Nhập các tham số kéo và tiến hành kéo; iii) Làm nguội mẫu bằng không khí sạch; iv) Xử lý kết qủa đo bằng phần mềm chuyên dụng. Mẫu thí nghiệm và hệ thống đo được gá đặt như trình bày trong hình 2. Các mẫu được kéo với vận tốc hằng số và thủ tục kéo tự động ngừng khi mẫu bị đứt. Một phần mẫu (gần vết đứt) được xử lý bề mặt để phân tích cấu trúc tế vi.

Nhiệt độ (°C)	**Vận tốc thí nghiệm**	
	Vận tốc kéo (mm/s)	**Vận tốc biến dạng (s)**
Nhiệt độ phòng	0.02, 0.2, 2	0.1, 0.01, 0.001
200	0.02, 0.2, 2	0.1, 0.01, 0.001
250	0.02, 0.2, 2	0.1, 0.01, 0.001
300	0.02, 0.2, 2	0.1, 0.01, 0.001

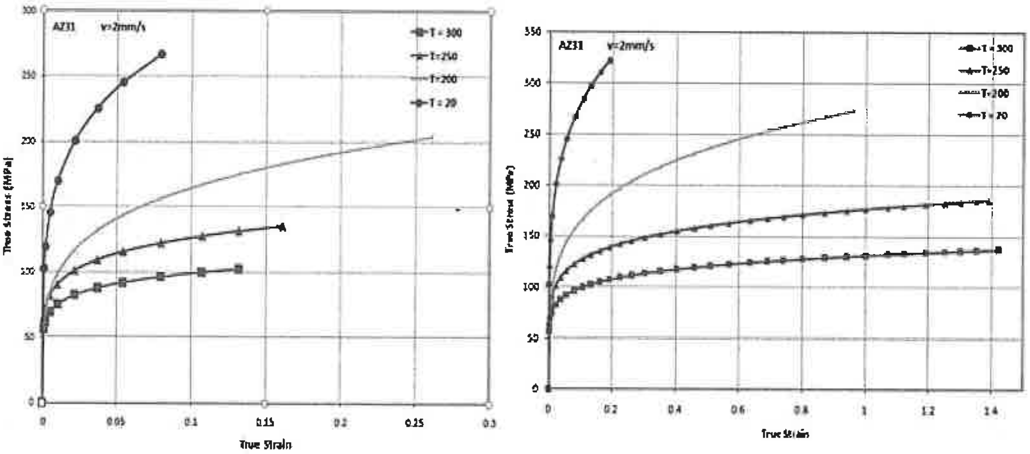
Bảng 2. Thông số kéo mẫu

Hệ thống gia nhiệt được thiết kế để phục vụ cho việc gia nhiệt tấm hợp kim trình bày trong tài liệu [2]. Các tấm được biến dạng theo mô hình côn có góc nghiêng thay đổi theo chiều sâu với các thông số gia công được thiết kế theo ma trận quy hoạch thực nghiệm đáp ứng bề mặt (RSM), bao gồm nhiệt độ tạo hình T(°C), chiều sâu tiến dao Z(mm), tốc độ tiến dao ngang F(mm). Các đáp ứng nhập vào ma trận thực nghiệm, bao gồm góc nghiêng tường côn α, độ nhám bề mặt trong côn Ra. Mỗi mô hình được lặp lại 2 lần để đảm bảo kết quả đo là chính xác. Các mức giá trị của thông số gia công (Bảng 3) được chọn theo kinh nghiệm, đặc tính vật liệu và khả năng của máy sẽ được chạy trong tổng số 16 lần [2].

Bảng 3. Thông số thí nghiệm và mức giá trị

Thông số gia công	**Mức giá trị**	
	Mức thấp	Mức cao
Nhiệt độ (°C)	200	300
Chiều sâu tiến dao (mm)	0.2	1
Tốc độ tiến dao ngang (mm.s^{-1})	1.000	6.000

3. KẾT QUẢ THÍ NGHIỆM

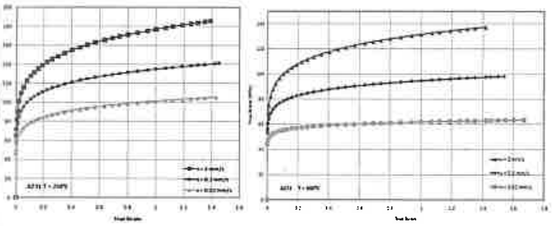


Hình 3. Thí nghiệm kéo khi thay đổi nhiệt độ và tốc độ kéo

Các mẫu hợp kim được kéo lần lượt theo các vận tốc kéo khác nhau ở các nhiệt độ từ 25°C đến 300°C cho đến khi đứt gãy. Kết quả cho thấy, hợp kim magiê có biến dạng rất kém ở nhiệt độ phòng (25°C). Tuy nhiên, khi tăng nhiệt độ thì khả năng biến dạng của nó rất tốt. Đối với mẫu cắt theo phương 90°, kết quả kéo ở cùng vận tốc 2mm/s cho thấy rằng, ở nhiệt độ khoảng 200°C, hợp kim magie có khả năng biến dạng trên 200%, so với nhiệt độ phòng (Hình 3a). Nếu tiếp tục tăng nhiệt độ hơn nữa thì khả năng biến dạng bắt đầu giảm, khi đạt nhiệt độ 300°C tấm hợp kim bắt đầu có hiện tượng trượt chảy. Cho nên, nhiệt độ lớn hơn 300°C sẽ không thích hợp cho việc biến dạng tấm hợp kim magie.

Đối với mẫu cắt theo phương 0°, kết quả kéo ở cùng vận tốc 2mm/s cho thấy, khi tăng nhiệt độ thì khả năng biến dạng tăng theo. Khả năng biến dạng từ 250°C đến 300°C có sự thay đổi rất ít. Mẫu bị chảy trượt khi nhiệt độ đạt giá trị 300°C.

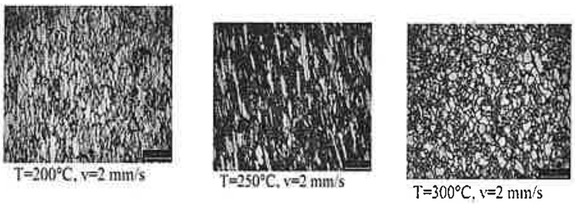
Hình 4a và b sự ảnh hưởng của tốc độ kéo mẫu ở nhiệt độ 250° C và 300° C. Ở 250°C cho thấy ảnh hưởng của tốc độ kéo đối với khả năng biến dạng tương đối thấp. Tốc độ kéo càng cao thì khả năng biến dạng sẽ bị giảm. Tuy nhiên, tốc độ kéo ảnh hưởng rất rõ nét đến khả năng biến dạng ở nhiệt độ 300°C. Tốc độ kéo càng thấp thì khả năng biến dạng của mẫu càng cao.



Hình 4. Kết quả kéo mẫu ở các thông số khác nhau

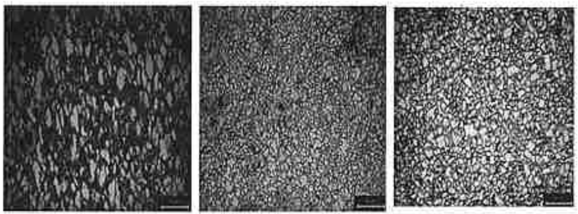
Để hiểu rõ bản chất các hiện tượng trên, ta quan sát cấu trúc tế vi của các mẫu ở các nhiệt độ và tốc độ kéo khác nhau. Hình 5 cho thấy hình ảnh cấu trúc tế vi của các mẫu khi kéo ở vận tốc 2mm/s. Các cấu trúc hạt bị kéo giãn dài theo chiều kéo, khi tăng nhiệt độ, khả năng dịch chuyển của các hạt dễ hơn nên các biên hạt bị kéo rất dài ở nhiệt độ 250°C. Tuy nhiên, hiện tượng kết tinh lại xảy ra ở nhiệt độ 300°C nên biên giới hạt được sắp xếp lại với phương không bị kéo dài theo phương kéo. Hiện tượng bị hạt kim loại bị kéo dài theo phương kéo ở vận tốc cao sẽ làm giảm khả năng biến dạng của kim loại. Ở 250°C, hạt bị kéo dài quá mức nhưng ở 300°C thì các hạt được sắp xếp lại thô hơn nên khả năng biến dạng là tương đối khó. Nó phản ánh khả năng kéo kim loại trên Hình 3.

Khi giảm tốc độ kéo đến 0.02mm/s, hiện tượng biên giới hạt ít bị kéo dài theo phương kéo. Đặc biệt tại nhiệt độ 250°C, hạt có kích thước rất nhỏ (khoảng 5µm) và phân bố đồng đều thì khả năng biến dạng sẽ tăng lên rất đáng kể. Tuy nhiên, ở 300°C xảy ra hiện tượng kết tinh lại cho kết quả hạt có kích thước thô và phân bố không đồng đều. Cho nên, khả năng biến dạng của tấm hợp kim sẽ bị giảm đáng kể.



T=200°C, v=2 mm/s T=250°C, v=2 mm/s T=300°C, v=2 mm/s

Hình 5. Cấu trúc tế vi của mẫu khi kéo ở vận tốc 2mm/s

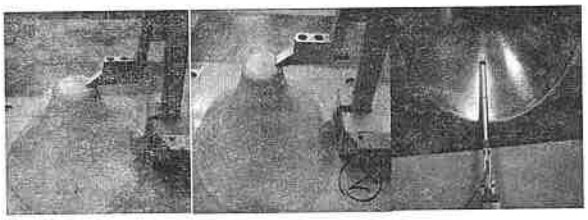


T=200°C, v=0.02 mm/s T=250°C, v=0.02 mm/s T=300°C, v=0.02 mm/s

Hình 6. Cấu trúc tế vi của mẫu ở tốc độ kéo 0.02mm/s

Kết quả khảo sát khả năng tạo hình tấm hợp kim bằng công nghệ SPIF cho thấy khả năng tạo hình lớn nhất tại nhiệt độ 300°C và tốc độ biến dạng thấp. Tuy nhiên, hiện tượng chảy trượt và mềm quá mức đã làm cho hình dạng sản phẩm không đảm bảo độ chính xác hình học [2,3]. Ở nhiệt độ tạo hình 250°C, sản phẩm có độ chính xác hình học rất cao, chất lượng bề mặt tốt nhất và khả năng biến dạng giảm không đáng kể so với khả năng biến dạng ☞

ở 300°C. Vấn đề này đã được nhóm nghiên cứu trình bày chi tiết trong tài liệu [2-4].



Hình 7. Kết quả biến dạng tấm magie bằng công nghệ SPIF ở nhiệt độ cao

4. KẾT LUẬN

Kết quả từ nghiên cứu này đã làm rõ và củng cố thêm các kết luận về khả năng biến dạng, độ chính xác hình học của sản phẩm biến dạng bằng công nghệ SPIF dưới góc độ sâu hơn. Khảo sát cơ tính của tấm hợp kim ở các vận tốc biến dạng và nhiệt độ khác nhau sẽ giúp hiểu rõ hơn ảnh hưởng của chúng đến khả năng tạo hình tấm hợp kim magie. Phân tích cấu trúc tế vi giúp hiểu rõ sự ảnh hưởng của nhiệt độ đến sự phân bố cấu trúc kim loại dưới các nhiệt độ khác nhau mà sẽ ảnh hưởng đến chất lượng của sản phẩm. Ta có thể kết luận rằng, nhiệt độ tạo hình là một trong các yếu tố rất quan trọng để tăng khả năng biến dạng của tấm hợp kim magie bằng công nghệ SPIF. Nhiệt độ biến dạng phải được chọn dưới mức 300°C và giá trị tốt nhất có thể lựa chọn là khoảng 250°C để có thể đảm bảo các yếu tốt khả năng biến dạng và chất lượng của sản phẩm. Ở nhiệt độ 250°C, tốc độ biến dạng phải chọn hợp lý để quá trình biến dạng xảy ra trong điều kiện tốt nhất. Ở 250°C, sự phân bố của hạt tinh thể khá đều và kích thước của chúng rất nhỏ khoảng dưới 5µm mà sẽ cho chất lượng biến dạng tốt nhất. Kết quả phân tích kéo mẫu ở nhiệt độ và tốc độ kéo khác nhau cùng với việc nghiên cứu cấu trúc tế vi của mẫu sau biến dạng đã củng cố vững chắc các kết luận từ nghiên cứu trước đây [2,5].◆

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