A study of the ability of the deformation of titanium sheet by hot single point incremental forming technology

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***Abstract* — Hot Single Point Incremental Forming (HOT SPIF) is a new technology of forming a metal sheet at high temperatures, especially for hard, high strength materials that are difficult to perform at normal temperatures such as Titanium and other materials. The paper presents the application of simulation method to determine the ability of the deformation of Titanium sheet through the angle of deformation α_{max} of the lateral profile of the model under the influence of tool diameter D (mm), step in the direction z of the tool V_Z (mm), the velocity of the tool Vxy (mm/min), the temperature T(^{0}C). The content of this paper consists of the analyzing the influence of these 4 above parameters by building a finite element analyzing (FEA) model to determine the ability of deformation or the maximum lateral angle of forming and to compare the accuracy of FEM model to the one of Computer-aided design (CAD) model. The paper studies the influences of the 4 parameters to the ability to form of Titanium sheet by HOT SPIF.**

Index Terms - HOT SPIF, deformation, Titanium sheet, ability of deformation, FEA, CAD model

1 INTRODUCTION

In small or single batch productions of forming metal sheet products, SPIF technology is selected in forming new products than other traditional methods of forming sheet by deformation because of its flexibility. In SPIF, the application of a circular end tool (spherical end pestle with no cutting edge) in a special SPIF machine or in a conventional CNC milling machine. Controlled by a digital program, the noncutting circular end tool moves in following a predefined trajectory to deform the workpiece sheet metal that is clamped on a special feature to format desired shape [1]. Especially in the manufacture of artificial joints and cranes for each personal patient in medicine, these products have to be made of Titanium for elimination of corrosion and deterioration. Although deformability of Titanium was performed by experimentation [2], simulation comparison of experimental results is necessary to verify the results and to build a simulation model for the product before manufacturing.

2 THE SIMULATION OF DEFORMATION OF TITANIUM SHEET

2.1 *CAD model for simulation*

The mechanical properties of commercial Titanium can be referred in [3]. The deformability of the method forming SPIF is determined by the maximum angle of deformation α_{max}. The largest shaping angle is the most important parameter,

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which represents the limited deformability of the material. The deformation angle is the maximum angle at which the material is not destroyed when formed by pestle [4].

$$\alpha = arccos\left(\frac{x}{R}\right) \qquad (1)$$

Wherein: $\boldsymbol{x} = \boldsymbol{z}_0 - \boldsymbol{z}_{\boldsymbol{M}_1}$

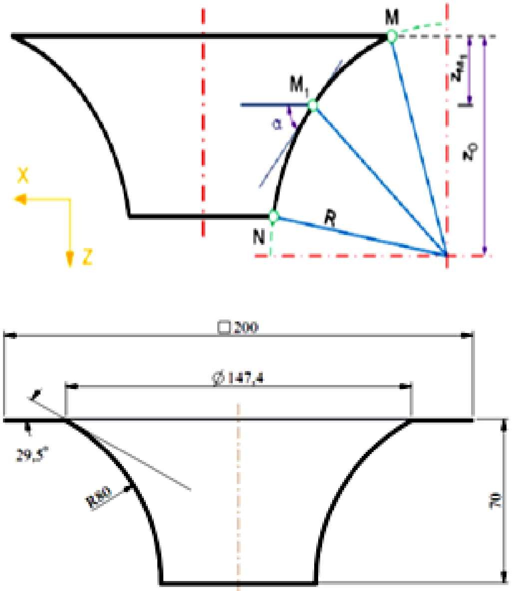


Figure 1: Selected lateral geometric of SPIF model and its real size

2.2 *Selection of the influence parameters in simulation of Titanium sheet by HOT SPIF*

As mentioned above, the four influence parameters and their limited values are represented in table 1 [5]

Table 1: Levels value of 4 influent parameters

NO	**Influent parameters (Input parameter)**	**Sign**	**Unit**	**Level**	
				Low level	**High level**
1	The temperature of titanium sheet	T	ºC	400	700
2	Step in the direction z of the tool	Δz	mm	0.3	0.6
3	The velocity of the tool	V_{xy}	mm/min	500	1500
4	Tool diameter	D	mm	6	12

With the above selected parameters, the study applies the Full Design of Experiment (DOE) 2 levels, the numbers of the experimental model are: $2^4 = 16$.

2.3 *Building an analysis model in Abaqus software Meshing and boundary conditions*

The element type of C3D6T are used to model with the initial selection of Titanium sheet that is selected as a deformation type with the size of 200x200x1mm and tool and feature are considered as analytical rigid. The Origin of coordinates is the sheet center [6]. Finite Element (FE) calculation considers 4 integration points in the thickness and is performed with ABAQUS/explicit. The meshing is shown in figure 3

The boundary conditions include a tool displacement, which is considered as a rigid body, and a clamping of all the external nodes. The value of the coefficient of friction is chosen equal to 0.1 according to stamping value found in the literature.

A typical explicit time step is presented in figure 2. The innovative part of this method concerns the way that the contact forces are taken into account. First, they are ignored when solving the equilibrium equation. Then, the error in the contact with the tool is computed geometrically. This depends only on the position $\underline{x_1}$ and velocity $\underline{\dot{x}_1}$ of the nodes close to the tool at the end of the time step. Finally, the nodal acceleration $\ddot{x}_0$ at the beginning of the time step can be corrected in order to meet the required contact conditions at the end of the time step. The correction on the acceleration, multiplied by the nodal mass, is equivalent to the contact forces.

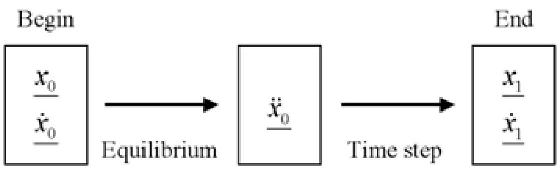


Figure 2: Dynamic explicit time step

In a first approach, elasto-plastic model is used. It includes a Von Mises yield criterion and an isotropic hardening law as presented in equations (2) and (3).

$$f = \underline{\underline{\sigma}}_{eq} - R - R_0 \qquad (2)$$

$$R = Q(1 - e^{-b\lambda}) \quad (3)$$

With:

R: Isotropic hardening law

R_0 : Yield strength

σ_{eq} : Von Mises equivalent stress

Q, b: Materials parameters

The plastic multiplier, λ is calculated from the consistency condition $f = \dot{f} = 0$. Thus, it is deduced from the relation $\frac{\partial f}{\partial \underline{\underline{\sigma}}} : \dot{\underline{\underline{\sigma}}} + \frac{\partial f}{\partial R}\dot{R} = 0$

$$\lambda = H(f)\frac{1}{j}\left\langle \frac{\partial f}{\partial \underline{\underline{\sigma}}} : \dot{\underline{\underline{\sigma}}} \right\rangle \text{ Wherein h=b(Q-R)}$$

In order to simulate the process of deforming Titanium we have to follow strictly the following module steps in Abacus software:

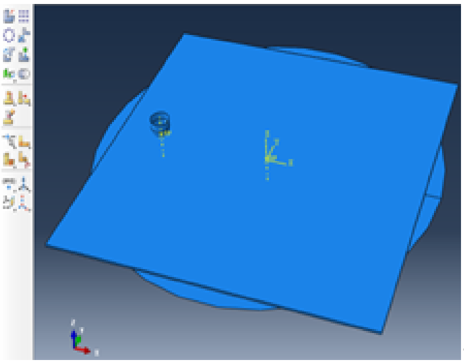
- Property module: to create the material and define its properties.
- Material properties:
- Condition of contact (module interaction)
- Boundary condition of base plate

The base plate is fixed in space (limited to 6 degrees of freedom). Selecting Symmetry/ Antisymmetric/Encastre

Boundary condition of sheet: 4 sides of the square sheet are fixed

Symmetry/Antisymmetric/Encastre type

The boundary condition of the tool: Tools allow to move in the direction x, y, z in the tool trajectory.



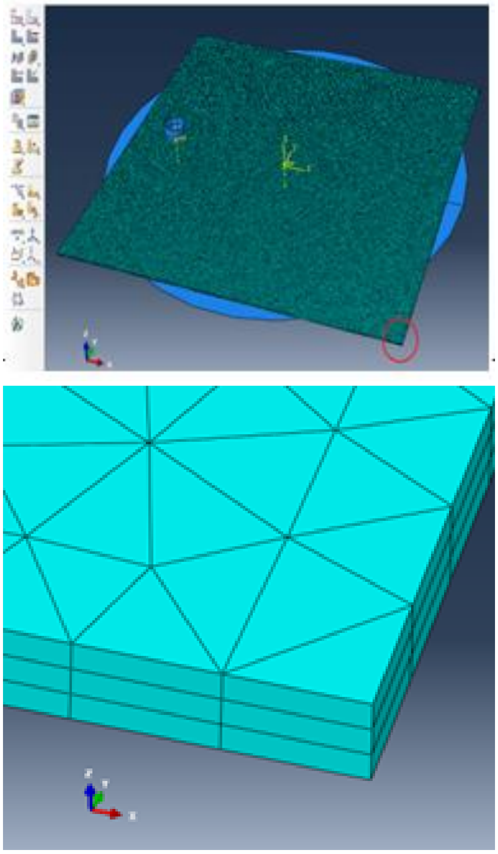


Figure 3: Initial simulation model and mesh model (with thickness)

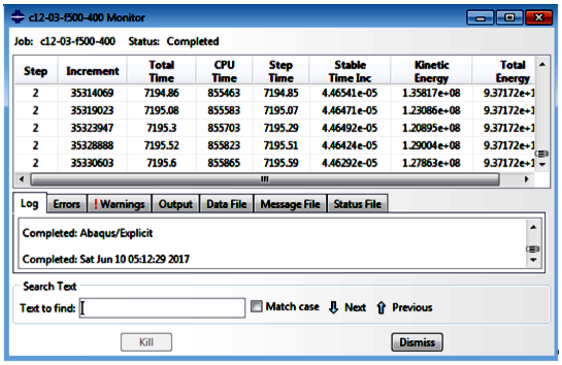
2.4 *Analytical step (module Step)*

Selected type step is Dynamic, Temp-disp, and Explicit to see the effects of temperature. The time period parameters are interested with the reason of the total running time of the tool is equal to the time of the last step that is not the time of 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



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Job:  c12-03-f500-400    Status:  Completed

Step  Increment  Total    CPU     Step     Stable       Kinetic       Total
                 Time     Time    Time     Time Inc     Energy        Energy
 2    35314069   7194.86  855463  7194.85  4.46541e-05  1.35817e+08   9.37172e+1
 2    35319023   7195.08  855583  7195.07  4.46471e-05  1.23086e+08   9.37172e+1
 2    35323947   7195.3   855703  7195.29  4.46492e-05  1.20895e+08   9.37172e+1
 2    35328888   7195.52  855823  7195.51  4.46424e-05  1.29004e+08   9.37172e+1
 2    35330603   7195.6   855865  7195.59  4.46292e-05  1.27863e+08   9.37172e+1

Completed: Abaqus/Explicit

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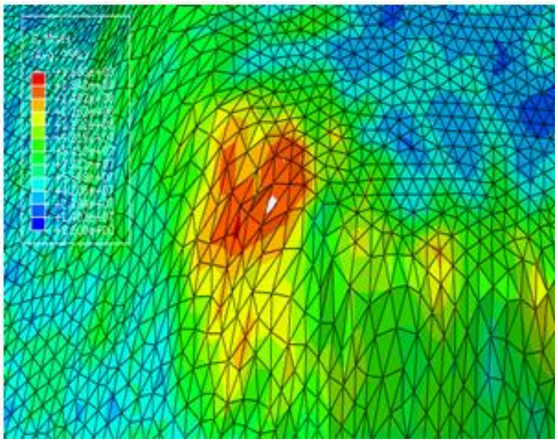
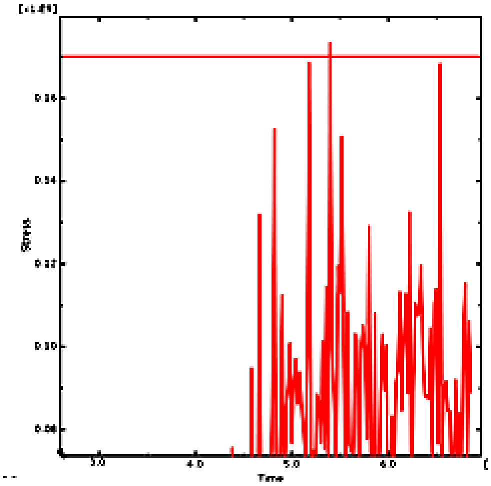
Figure 4: Managing the analytical process

There are 16 cases of the simulation model, here only shows the first case result image in table 2. The results of other cases are summarized in table 3.

Table 2: The value of simulation for case 1

NO	Influent parameter	Sign	Unit	Value	α (^{0})
1	The temperature of titanium sheet	T	^{o}C	400	72.224^0
2	Step depth Vz of tool	Δz	mm	0,3	
3	The velocity of	V_{xy}	mm/ minute	500	
4	Tool diameter	D	mm	12	





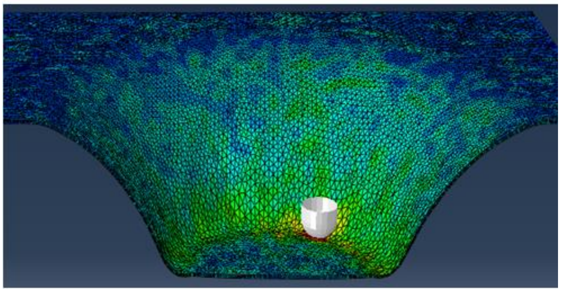


Figure 5: Left and middle: Location of torn sheet case 1 Right: Stress at the torn sheet position of case 1

According to the stress diagram (figure 5, Right) of the case being analyzed, the stress exceeds the tensile strength of 170 MPa at step time of t = 5400 at the corresponding depth of -45.576. Based on the formula (1) with z_0 = 70mm, R = 80 mm we could calculate the distortion angle of 72.224^0

3 EXPERIMENTAL PROCESS OF FORMING TITANIUM SHEET BY HOT SPIF

The experimental process is performed in SPIF machine in CAD-CAM workshop of National Key Laboratory of Digital Control and System Engineering (DCSELAB) with a designed feature for HOT SPIF. The experimental processes are performed with the same parameters of the simulation processes with the number of iteration is 3 for 16 experimental model. A total number of experimental models is 16x3 = 48 models.

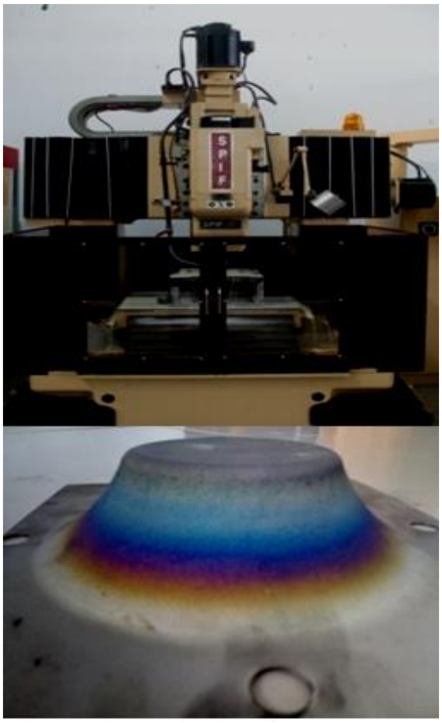


Figure 6 Specialist SPIF machine with special feature for HOT SPIF and a hot Titanium Sheet model

Figure 7 Measure the bottom of the experimental models after releasing of the feature to define the depth at breakage for deducing the angle α by formula (1). The results are summarized in Table 3

4 COMPARISON OF SIMULATED AND EXPERIMENTAL RESULTS

Table 3 displays the comparisons of experiment results and simulation results.

Table 3: Experiment and simulation results of HOT SPIF forming angles

NO	D (mm)	Δz (mm)	V_{xy} (mm/min)	T (^{0}C)	α (^{0}) simulation	α (^{0}) experiment	Deviation %
1	12	0.3	500	400	72.224	71.1	1.568474
2	12	0.6	500	400	70.935	72.4	2.044162
3	12	0.6	500	700	72.421	70.5	2.688198
4	12	0.3	500	700	73.069	72.4	0.919784
5	12	0.6	1500	700	71.119	71.7	0.813617
6	12	0.3	1500	400	71.109	71	0.153403
7	12	0.3	1500	700	71.386	71.3	0.120544
8	12	0.6	1500	400	70.567	71	0.611724
9	6	0.6	500	700	70.262	73.2	4.095858
10	6	0.3	1500	400	69.994	70	0.008572
11	6	0.6	500	400	69.915	69	1.317352
12	6	0.3	500	400	69.907	70.4	0.702745
13	6	0.6	1500	400	68.716	72	4.667557
14	6	0.3	500	700	70.771	73.1	3.237623
15	6	0.6	1500	700	69.228	70	1.108972
16	6	0.3	1500	700	70.251	71.1	1.201265

The difference between Simulation and Experiment results is shown in the diagram in figure 7.

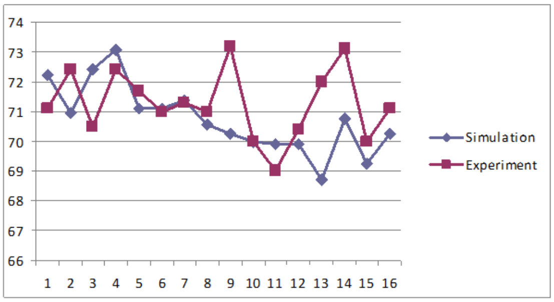


Figure 8 Comparison of simulation and experiment of angle of deformation (vertical axis) through the number of models (horizontal axis)

CONSIDERATION:

Simulation values with a 12mm tool diameter are greater than or equal to the experiment, simulation values with a diameter of 6mm are smaller than the experimental ones.

All deviations are less than 5%. This tolerance is acceptable for simulations close to experiment.

5 POST SIMULATION: STATISTICS RESULT OF TITANIUM HOT SPIF

Regressive equation

The regressive equation of deformation ability of Titanium under the influence of 4 input parameters by Design Expert software:

$$\begin{aligned}\alpha = {} & 70,732+0,875D-0,337\Delta z-0,436V_{xy}\\ & +0,335T-0,010D\Delta z-0,126DV_{xy}\\ & +0,064DT-0,052\Delta zV_{xy}+0,027\Delta zT\\ & -0,135V_{xy}T+0,197D\Delta zV_{xy}+0,084D\Delta zT\\ & +0,056DV_{xy}T+0,039\Delta zV_{xy}T-0,081D\Delta zV_{xy}T\end{aligned} \qquad (4)$$

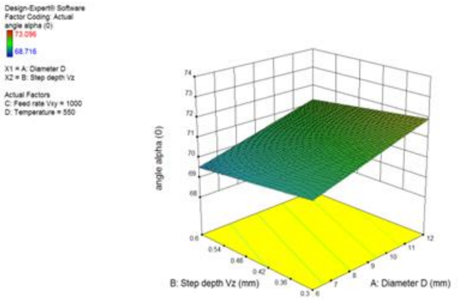
The Design-Expert software help to analyses the mutual influences of 2 in 4 parameters to the formability (angle α). Figure 8 illustrates the mutual influences of deformation angle α to 2 in 4 influenced parameters. Consideration the results:

- The forming angle α is a positive correlation to the tool diameter.

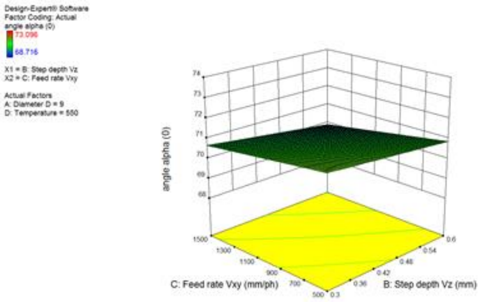
- The forming angle α is a negative correlation between the feed rate V_{xy} and step depth V_z of the tool.

- The forming angle α is a positive correlation to the temperature T.

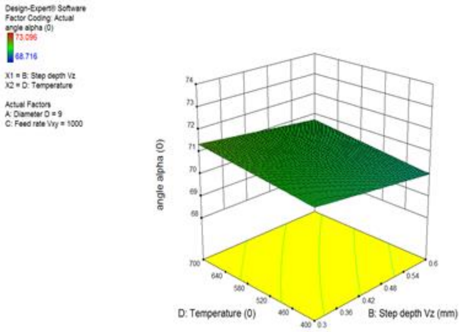
Analyses of the influence of input parameters



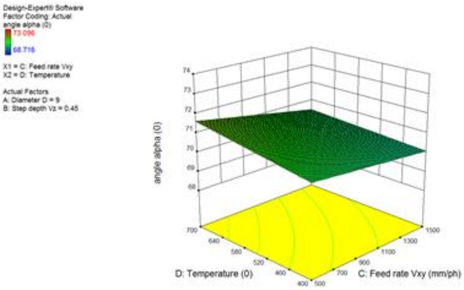
1.Influence of Step depth Vz and diameter D



2.Influence of Feed rate Vxy and Step depth Vz



3.Influence of temperature T and Step depth Vz



4.Influence of temperature T and Feed rate Vxy

Figure 9: Influence of 4 parameters: Step depth Vz, Feed rate Vxy, diameter D and temperature T to the formability angle α

6 CONCLUSIONS

The simulation and experimental results show that the diameter D of the tool and temperature T of the Titanium sheet are a positive correlation to the ability of deformation (angle α) in the meanwhile the Step depth Vz and the Feed rate Vxy of are negative to the angle. In reality, with the purpose of increasing the ability of deformationα, we should use the bigger tool at high temperature but the diameter D of the tool cannot be increased freely because there is also the increase of force of forming and the SPIF technology could not perform the small radius of the product. The increase in the temperature T of the sheet is influenced by the mechanical properties of the tool and it must be limited. The decrease of feed rate and step depth will engender to the decrease of productivity of the process. In the future, it is possible to perform simulations before processing and will save the cost of testing, saving time and cost of machining.

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Nghiên cứu khả năng tạo hình vật liệu titan sử dụng công nghệ tạo hình gia công đơn điểm (HOT SPIF) bằng phương pháp mô phỏng số

Trần Trọng Hỷ, Nguyễn Tấn Hùng, Võ Tuyển, Lê Khánh Điền, Phạm Huy Hoàng,
Nguyễn Thanh Nam, Nguyễn Ngọc Phương

***Tóm tắt*— Phương pháp tạo hình gia công đơn điểm (Hot single point incremental forming HOT SPIF) là công nghệ mới để tạo hình các loại vật liệu tấm ở nhiệt độ cao, đặc biệt là các loại vật liệu có trở lực biến dạng cao mà các phương pháp gia công ở nhiệt độ thường khó thực hiện được, phổ biến hiện nay là Titan. Nghiên cứu này trình bày phương pháp mô phỏng để xác định khả năng biến dạng của vật liệu ở nhiệt độ cao, trong đó ảnh hưởng của các thông số đường kính dụng cụ D(mm), bước tiến theo phương z của dụng cụ Δz(mm), tốc độ chạy dụng cụ Vxy (mm/phút), nhiệt độ T(^{0}C) đến góc tạo hình α_{max} là nội dung chính của bài báo. Quá trình phân tích ảnh hưởng của các thông số công nghệ được tiến hành bằng việc xây dựng mô hình phần tử hữu hạn, phân tích mô hình, xác định góc biến dạng giới hạn và so sánh độ chính xác của mô hình phần tử hữu hạn (FEA) với mô hình bằng phần mềm máy tính (CAD). Kết quả nghiên cứu sẽ cung cấp các chế độ gia công tạo hình cho quá trình HOT SPIF trên tấm titan để đạt được góc tạo hình phù hợp nhất.**

Từ khoá - HOT SPIF, biến dạng, Titan tấm, khả năng biến dạng, mô hình FEA, CAD.