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Numerical and Experimental Investigation of the Effect of Open-Die Hot Deep Drawing Process Parameters on the Formability of Commercially Pure Titanium

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ABSTRACT

In the present study, the finite element analysis of the hot deep drawing process of commercially pure (CP) titanium has been performed without the blank holder in order to investigate the influence of temperature (T), die radius (R_d) and blank diameter (D) on the maximum punch force (F_p) and minimum thickness of the blank (t). Tensile tests were first conducted to extract the mechanical properties of CP titanium sheets at various temperatures to simulate the hot deep drawing process. The results of the numerical simulation were used to perform the experimental tests at the optimal condition of the parameters. The experimental results of the process at the optimal condition of the parameters indicated that there is good agreement between the numerical and experimental investigations. The results indicated that the hemisphere of titanium without any wrinkling, tearing, and without any oxidation can be obtained by a blank diameter of 580 mm and forming temperature of 400˚C.

1. Introduction

Titanium is a well-known lightweight metal that exhibits characteristics, such as high strength-to-weight ratios and good corrosion resistance for application in many industries like aerospace, petrochemical, transportation, and biomedical [1-5]. The mechanical properties and formability of titanium and its alloys vary widely. Titanium grade 2 is usually selected for its excellent corrosion resistance, especially in applications in which high strength is not required [6].

Deep drawing process is one of the main and most significant processes to form sheet metals. Due to the hexagonal close-packed (HCP) structure of CP titanium, it usually indicates limited ductility at room temperature [6-7]. In addition, in all forming operations, titanium and its alloys are susceptible to the Bauschinger effect, which is a drop in compressive yield strength subsequent to tensile straining. Increasing the temperature reduces the Bauschinger effect as well as the influence of spring back variation and so full thermal stress relieving removes it completely. Hence the hot deep drawing of titanium alloys is widely performed in aerospace and automobile industries [6].

An investigation of the previous researches revealed that authors have studied the interesting subjects, in the references [1, 7-9], of the behavior of pure titanium in the stretch-drawing process, the improvement of titanium alloy sheets' formability in the hot forming process, the formability of commercially pure titanium sheets at various temperatures, the reduction of spring

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back at the elevated forming temperature, the failure and formability of titanium Ti–6Al–4V alloy in the hot deep drawing process, the effect of process parameters on the deep drawing of Ti-6Al-4V alloy using finite element analysis, and finite element simulations of warm deep drawing for Ti-6Al-4V alloy.

To avoid uncertainty and tentativeness during the design and production stages, numerical simulation with experimental verification can improve the manufacturing efficiency and product reliability. Hence, in the present study, finite element (FE) analysis was applied by the Abaqus®6.14 software to enhance the forming productivity. The mechanical properties of CP titanium sheets at various temperatures ranging from 400 to 600˚C were attained from the experimental results. Next, the simulation of the hot deep drawing process was performed at different temperatures to explore the optimal condition of the parameters. Finally, some confirmation tests were carried out at the optimal condition of the parameters to indicate the reliability of FE analysis.

2. Materials and Methods

2.1. Experimental

The composition of the employed titanium grade 2 is given in Table 1. Material properties were calculated using the uniaxial tensile test performed at 400˚C, 500˚C and 600˚C by constant velocity of 2.5 mm/s. The tensile test specimens were prepared according to the ASTM E8/E8M-15a by a sheet thickness of 10 mm. The specimens were cut along the rolling direction (0°), and at angles of 45° and 90° to the rolling direction. The tensile specimens were wire cut to reduce burrs along the edge.

Table 1. Chemical composition of commercially pure titanium

Element	Ti	Fe	O	N
%W	Base	0.15	0.25	0.018

The tensile tests were conducted using an Autograph Shimadzu AG25TC test machine. For tests carried out at elevated temperatures, a heating furnace was mounted on the Autograph Shimadzu AG25TC test machine. The engineering stress–strain relations were first obtained from the experimental data and then were converted into the true stress–strain relations, according to $\sigma = \sigma0\,(1+e)$ and $\varepsilon = \ln(1+e)$, where σ and ε were true stress and true strain, σ0 and e were engineering stress, and engineering strain, respectively. The true stress–strain relations for CP titanium sheets at different temperatures were obtained from the specimens cut in three different orientations, as given in Fig. 1.

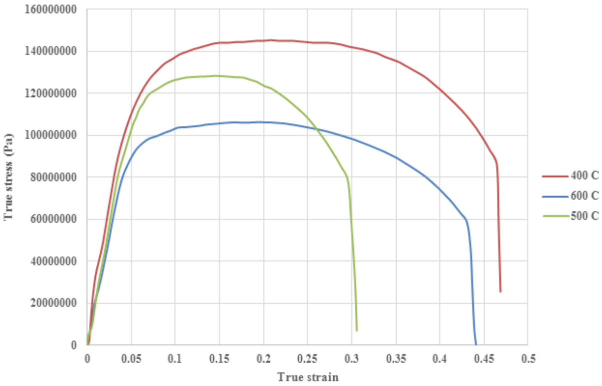

Fig. 1. Results of the tensile test for CP titanium for different temperatures at an orientation of 0°.

The anisotropy of CP titanium sheet is measured from the tensile specimens at different temperatures. Index of anisotropy is the plastic strain ratio, i.e. r-value, which is defined as the ratio of plastic strain in the transverse direction to that of the thickness direction in a uniaxial tensile test. In the present study, the r-value has been obtained from the tensile tests for specimens of 0°, 45°, and 90° directions at different temperatures. The r-values measured from specimens stretching to 20% are given in Table 2. Since a higher r-value indicates better drawability, it shows that CP titanium sheets display a better deep drawing quality in the rolling direction than the other two directions.

Table 2. R-values of CP titanium at different temperatures

Temperature (˚C)	R_0	R_{45}	R_{90}
400	1.9289	1.3952	1.4573
500	1.4264	1.1930	1.2969
600	1.2705	1.0585	1.2102

2.2. Finite element analysis

The finite element analysis was performed using a commercially software package Abaqus®6.14 to predict the maximum punch force (F_p) and minimum thickness of the blank (t) in the hot deep drawing process. The finite element analysis significantly decreased the running time and costly die tryouts. However, the efficiency of the numerical simulations depends on the defined models and the accuracy of the input data. In order to enhance the accuracy of the simulation results, the material properties of CP titanium, obtained from the uniaxial tensile test, were applied as the input data. Hill's quadratic yield criterion for an isotropic material was chosen as a material model in the simulation. The evaluated material properties used in the simulations are given in Table 3. The dynamic explicit method was applied in the hot deep drawing process. The tooling geometry was defined as a rigid shell model, including the die and the punch. In addition, the blank geometry was modeled by elements of both shell and solid. For the sake of symmetry, the quarter-size of the blank and that of the tooling were discretized.

Table 3. Material properties of CP titanium at different temperatures

Density (g/cm^3)	Young's modulus (GPa)	Poisson's ratio	Conductivity (W/m.K)	Expansion coefficient (1/°C)	Specific heat (J/kg.°C)
4510	105	0.37	16.4	0.0000086	520

After a generation of surfaces, fine meshing was done in those regions of the tool components where severe plastic deformation had occurred. The blank and the tool components were meshed using S4R shell elements as it exhibited wrinkling and tearing in the blank. Adaptive meshing was used on the blank to achieve precise results. The friction coefficient between the blank and the die was set to be 0.3. The punch speed varied based on the adjustable speeds of the press instrument. Selective mass scaling was used for finite element (FE) simulations.

The clearance (C) between the die and punch is measured based on the equations obtained from the experimental methods. The clearance equations are related to the thickness of the blank and it can be calculated using the equation $C = 0.2\sqrt{10\,t}$ [13] for high temperature materials. In this paper, the clearance (C) between the die and punch was measured to be 2 mm.

3. Results and Discussion

The simulation of the hot deep drawing process was performed by changing the parameters of temperature (T), blank diameter (D) and die radius (R_d). These parameters were changed in the process to reduce the punch force and to improve the thickness distribution of the blank without wrinkling and tearing. Due to the high thickness of the blank (10 mm), the deep drawing process was performed without the blank holder. In order to reduce the probability of wrinkling, the blank diameter (D) should be decreased and the die radius (R_d) should be increased. However, there is an optimum value for the blank diameter (D) and the die radius (R_d).

Based on the mechanical properties of CP titanium, obtained from the tensile tests at high temperatures, the simulation of the hot deep drawing process was performed at different temperatures of 400, 500 and 600°C. In addition, the blank diameter (D) and the die radius (R_d) varied in the simulation of the process to extract the optimum value of these parameters. The results of the simulation revealed that the process at a temperature of 400°C can attain the accurate shape of a hemisphere. By simulating the hot deep drawing process at a temperature of 500°C, tearing occurred in the blank, as shown in Fig. 2. This can be due to the lower formability of CP titanium at a temperature of 500°C than that at a temperature of 400°C, as can be observed from the results of the tensile test in Fig. 1.

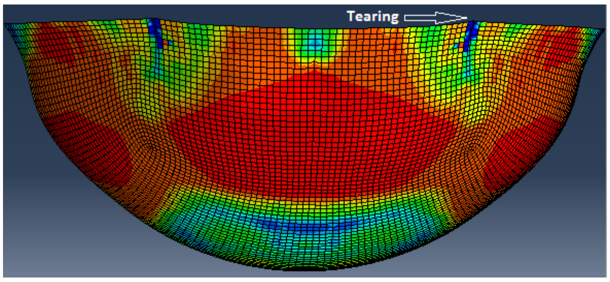

Fig. 2. Tearing in the blank at a temperature of 500°C.

Furthermore, by increasing the temperature up to 600°C, the blank was detached from the punch and thus the hemispherical shape of the blank was not formed completely (Fig. 3). This occurrence is due to the low flow stress of the blank at 600°C as well as its small diameter which provoked the fast entrance of the blank into the die. It was observed from the simulation results that the maximum punch forces during the process were

54.5, 45.2 and 38.4 ton at the temperature values of 400, 500 and 600˚C, respectively. In addition, the minimum thickness of the blank was measured to be 8.65, 8.59 and 8.48 mm at the temperature values of 400, 500 and 600˚C, respectively. However, a more uniform thickness was observed at higher temperatures because of lower mean flow stress and a slightly larger work hardening exponent. As can be deduced from the results, the punch force is minimized at a temperature of 600˚C, and the blank thickness is maximized at a temperature of 400˚C. Therefore, with regard to the detachment of the blank from the punch at a temperature of 600˚C, a temperature of 400˚C is better than 500 and 600˚C.

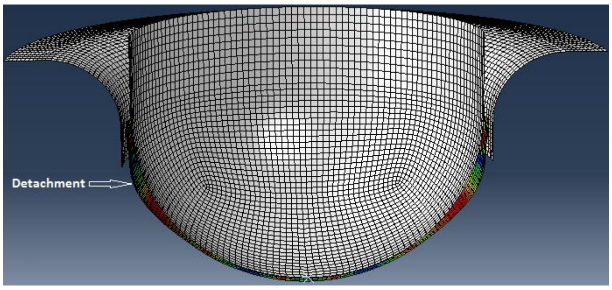

Fig. 3. Detachment of the blank from the punch at a temperature of 600˚C.

The blank diameter has also been varied to detect its optimum value. When the process was conducted by a large blank diameter, the wrinkling could be observed in the blank (Fig. 4), while by using a small blank diameter, the blank began falling into the die during the process. The simulation results indicated that the optimum blank diameter to prevent these problems is 580 mm. The other parameter that was changed in the simulation of the process was the die radius. At a low die radius, tearing occurred in the blank, and by increasing the die radius, the wrinkling occurred in the blank. The results indicated that the optimum die radius for preventing wrinkling and tearing is 80 mm. Thus by changing these parameters, temperature (T), die radius (R_d) and blank diameter (D), it was observed that their optimum values for the simultaneous minimization of the punch force and distribution of the blank thickness are T= 400˚C, R_d= 80 mm and D= 580 mm.

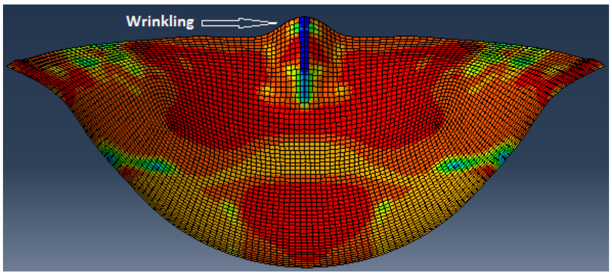

Fig. 4. Wrinkling of the blank at a temperature of 400˚C and diameter of 600 mm.

In order to validate the results of the simulation, several experiments were performed in different conditions of the parameters. In order to execute the hot deep drawing process, the collection of the die and the punch was assembled at a hydraulic press of 250 tons, as shown in Fig. 5. Before performing the process, the CP titanium blank was placed in a furnace in order to reach the desired temperature. The mixture of the hydraulic oil and graphite was used as a lubricant of the die and punch. Laser thermocouple was used in order to control the temperature of the blank during the process. By conducting the process at a temperature of 600˚C, it was observed that the blank was detached from the punch and the hemispherical shape of the blank was not formed, as seen from the simulation result. The three dimensional scan of the formed hemisphere was captured to be compared with the result of the simulation, as given in Fig. 6. The results of the simulation and experiment for the maximum punch force (F_p) and minimum thickness of the blank (t) were compared with each other and are given in Table 4. It can be seen from Fig. 6 and Table 4 that the results of the simulation are close to those of the experimental tests.

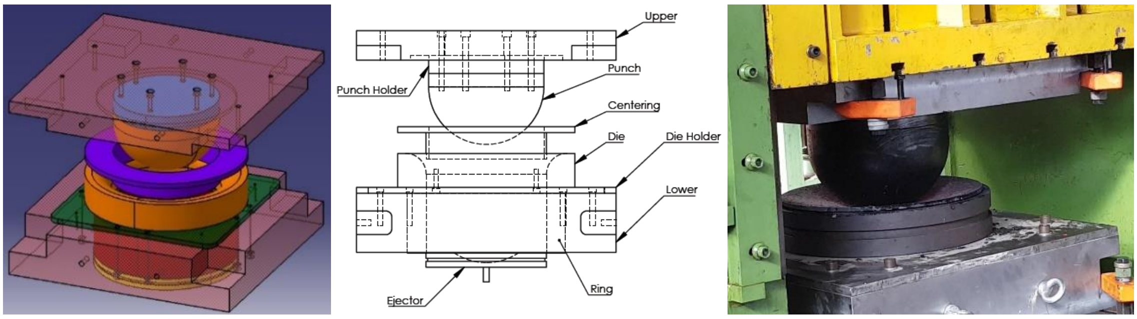

Fig. 5. Assemblage of the die and punch on a hydraulic press.

Fig. 6. Comparison of the result of the simulation and experiment.

Table 4. Comparison of F_P and t, in the simulation and experiment at a temperature of 600˚C

Run	F_P (ton)	T (mm)
Simulation	38.4	8.48
Experiment	35.5	8.92
Error	7.5%	4.9%

An experiment was also conducted at a temperature of 500˚C. After performing the process at a temperature of 500˚C, tearing was observed in the blank. Fig. 7 indicates the location of tearing in the blank by the simulation and experiment. As can be seen from Fig. 7, tearing occurred in the flange region of the blank. This can be due to the large Bauschinger effect in titanium alloys. Heavy compressive hoop stresses and radial tensile stresses occur in the flange region. As the material loses its compressive strength due to the Bauschinger effect, a slight wrinkling tendency will lead to fracture [13].

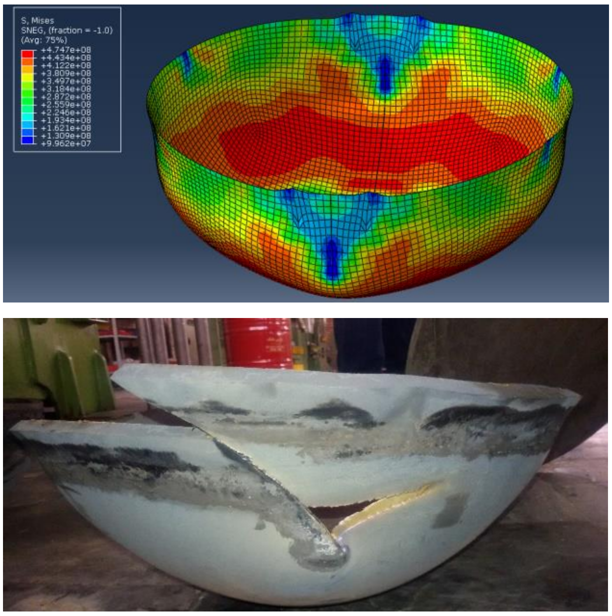

Fig. 7. Tearing in the blank at a temperature of 500°C and a diameter of 580 mm.

It should be noted that by moving the material from the flange region towards the die curvature, the friction increases at higher temperatures owing to the ineffectiveness of the lubricant. Therefore, excessive shear stresses will be improved on the outer surface of the material in the bend region of the die, and also compressive stresses will be improved on the inner curvature of the blank. Since the material is weak in compression due to the Bauschinger effect, the inner curvature of the blank may become the site for the initiation of failure [13].

The maximum punch force (F_p) and minimum thickness of the blank (t) at the dome and at a temperature of 500˚C are listed in Table 5. It can be concluded from Table 5 that the results of the simulation and experiment are close to each other.

Table 5. Comparison of t and F_P in the simulation and experiment at a temperature of 500˚C

Run	F_P (ton)	t (mm)
Simulation	45.2	8.59
Experiment	41.6	8.91
Error	7.9%	3.5%

In addition, the execution of the hot deep drawing process at a temperature of 400˚C and blank diameter of 600 mm led to wrinkling. Fig. 8 indicates wrinkling in the blank that was obtained from the results of the simulation and experiment. The maximum punch force (F_p) and minimum thickness of the blank (t) at a temperature of 400˚C and blank diameter of 600 mm are given in Table 6. As can be seen in Table 6, the results of the simulation are approximately accurate, since they are close to the results of the experimental tests.

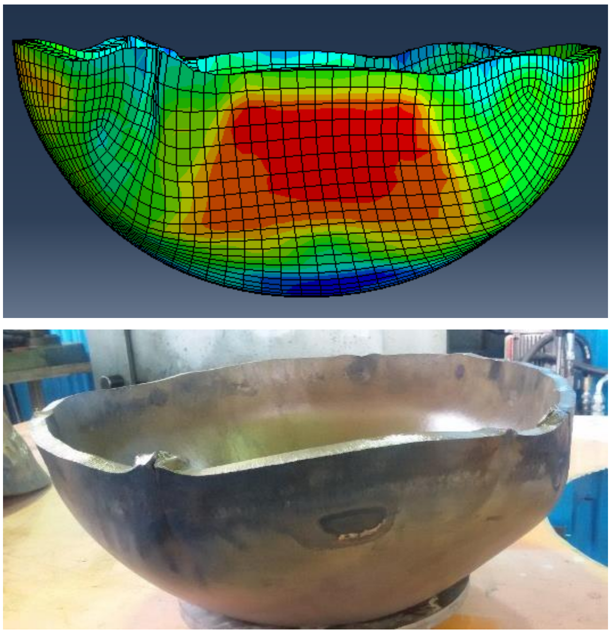

Fig. 8. Wrinkling in the blank at a temperature of 400˚C and blank diameter of 600 mm.

Finally, by executing the hot deep drawing process at a temperature of 400˚C and blank diameter of 580 mm, the accurate shape of the hemisphere was obtained. Fig. 9 presents the final shape of the hemisphere obtained from the hot deep drawing process of CP titanium blank. The maximum punch force (F_p) and minimum thickness of the blank (t) at a temperature of 400˚C and blank diameter of 580 mm are listed in Table 7. It can be concluded from Table 7 that the results of the simulation and experiment are close to each other.

Fig. 9. Final shape of the hemisphere obtained from the hot deep drawing of CP titanium.

Table 6. Comparison of t and F_p, in the simulation and experiment at a temperature of 500˚C and blank diameter of 600 mm

Run	F_p (ton)	t (mm)
Simulation	47.3	8.62
Experiment	44.5	8.95
Error	5.9%	3.6%

Table 7. Comparison of t and F_p in the simulation and experiment at a temperature of 500˚C and blank diameter of 580 mm

Run	F_p (ton)	t (mm)
Simulation	54.5	8.65
Experiment	49.4	9.21
Error	9.3%	6.1%

4. Conclusions

In this paper, the hot deep drawing of CP titanium was investigated using numerical and experimental studies. The main conclusion of this paper is given as follows:

By proper selection of the deep drawing parameters, the process can be performed for CP titanium without the blank holder.

Based on the results of the finite element analysis, the optimal condition of the parameters can be predicted by the numerical simulation of the process.

It was observed from the results that in order to prevent wrinkling, the die radius should be increased and the blank diameter should be decreased.

The numerical and experimental results indicated that the optimal condition of the parameters for conducting the hot deep drawing process without any wrinkling and tearing of the CP titanium blank is T= 400˚C, R_d= 80 mm and D= 580 mm.

Acknowledgement

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بررسی عددی و تجربی اثر پارامترهای فرآیند کشش عمیق گرم قالب باز بر روی شکل‌پذیری تیتانیوم خالص تجاری

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چکیـــده

در مطالعه حاضر، تجزیه و تحلیل المان محدود کشش عمیق گرم تیتانیوم تجاری خالص (CP) بدون ورق‌گیر انجام می‌شود تا تأثیر عوامل دما (T)، شعاع قالب (R_d) و قطر پولکی (D) بر روی حداکثر نیروی سنبه (F_p) و حداقل ضخامت پولکی (t)، مورد بررسی قرار گیرد. آزمایش‌های کشش ابتدا برای استخراج خواص مکانیکی ورق‌های تیتانیوم CP در دماهای مختلف برای شبیه‌سازی فرآیند طراحی کشش عمیق گرم، انجام شد. نتایج حاصل از شبیه‌سازی عددی برای انجام آزمایش‌های تجربی در شرایط بهینه عوامل دما، شعاع قالب و قطر پولکی استفاده می‌شود. نتایج تجربی فرآیند در شرایط مطلوب عوامل ذکر شده، نشان داد که بین تحقیقات عددی و تجربی، توافق خوبی وجود دارد. نتایج نشان می‌دهد که نیم‌کره تیتانیوم بدون ایجاد چین و چروک، پارگی و هرگونه اکسیداسیون با قطر پولکی ۵۸۰ mm و دمای شکل‌دهی ۴۰۰°C حاصل می‌شود.

واژه‌های کلیدی: کشش عمیق گرم، شکل‌پذیری، تیتانیوم خالص تجاری، تجزیه و تحلیل المان محدود، روش‌شناسی سطح پاسخ