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INVESTIGATION OF SHEET-TITANIUM FORMING WITH FLEXIBLE TOOL – EXPERIMENT AND SIMULATION

BADANIE KSZTAŁTOWANIA BLACH TYTANOWYCH Z WYKORZYSTANIEM ELASTYCZNEGO NARZĘDZIA – DOŚWIADCZENIE I SYMULACJA

In the paper the results of investigation of sheet-titanium forming with flexible tool are presented. Titanium alloy sheets belong to a group of materials which are very hard to deform at ambient temperature. To improve sheet formability forming technology using a semi-flexible tool was implemented. Experiments were carried out on a specially designed for this purpose device. Due to the application of a rubber pad the stress state similar to triaxial compression was produced in the deformed material. Such a stress state made it possible to obtain higher material deformation without risk of fracture. The numerical simulations were used for analysing the flexible forming process. The ADINA System basing on the Finite Element Method (FEM) was applied.

Keywords: titanium sheet, flexible forming, numerical simulation

W artykule zaprezentowano wyniki badań procesu tłoczenia blach tytanowych za pomocą elastycznego narzędzia. Blachy ze stopów tytanu należą do grupy materiałów trudno odkształcalnych w temperaturze otoczenia. W celu zwiększenia tłoczności zastosowano technologię tłoczenia półelastycznym narzędziem. Doświadczenia przeprowadzono na stanowisku specjalnie zaprojektowanym w tym celu. Dzięki zastosowaniu gumowej wkładki w odkształcanym materiale wytworzony został stan naprężenia podobny do trójosiowego ściskania. Taki stan naprężenia umożliwił uzyskanie większych odkształceń materiału bez ryzyka pęknięcia. Do analizy procesu tłoczenia elastycznego wykorzystano symulacje numeryczne. Zastosowano program ADINA bazujący na Metodzie Elementów Skończonych (MES).

1. Introduction

Sheet-metal forming is one of the most important technologies in modern industry allowing for production light but strength parts such as: aircraft structures, car bodies and other structural parts, utensils or household equipment. It allows for obtaining good quality products in a very short time what is very important because of the high competition in the manufacturing market.

Although press-forming industry is still connected with steel industry, other materials than deep drawing steels such as: stainless steels, aluminium, magnesium or titanium alloys are being shaped more and more often. The main motivation behind using the new materials is to achieve both a decrease in construction weight and an increase in corrosion resistance, with measurable economic and ecological results.

Titanium and its alloys are noteworthy materials because of their unique properties, which include low specific gravity ($4430 \div 4850$ kg/m^3), high mechanical prop-

erties (tensile strength from $R_m \approx 240$ MPa for commercially pure titanium CP 1 to $R_m \approx 1750$ MPa for heat treated beta titanium alloys [1]) and good corrosion resistance. A combination of high strength and low weight makes titanium an extremely useful structural metal e.g. for aircraft body panels, sporting equipment and surgical implants [1-3].

Application of high strength, low plasticity and difficult-to-form materials for complex-shaped parts makes the conventional sheet forming technology face new challenges. "Conventional forming" here means any sheet-metal forming process using rigid tools: die, blank-holder and punch. Very often manufacture the structural parts is extremely difficult because conventional forming methods reach their limits [4-7]. In some applications radial drawing stresses and tangential compressive stresses pose a serious problem resulting in wrinkling, buckling, thinning and finally cracking. The

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presence of one or more of these imperfections can make the stamped part useless.

To improve sheet formability hot forming [8, 9] or unconventional deep drawing techniques are used. Generally, impulse forming including e.g. electromagnetic or explosive forming [11], and flexible sheet forming technology, such as hydroforming [12] or forming technology using a flexible tool half etc. [13-15] are used.

Titanium sheet besides CP 1 and CP 2 belong to a group of materials which are hard to deform at ambient temperature. Because the demand for drawn-parts made of titanium alloy sheets, especially Ti6Al4V, is growing the authors decided to analyse flexible forming, where a flexible tool half (e.g. rubber pad) applies pressure to form a blank around a solid tool half. As it is reported in [16-18] it is one of the oldest sheet forming methods originating from shearing thin sheet materials by the rubber pad and then used for other sheet and tube metal forming operations such as: blanking, bending, bulging, drawing, etc. Development of new synthetic elastomers, which are more resistant to wear than natural rubber, has extended the use of these techniques. Although this forming method seems to be very simple and has some advantageous (it only utilises one rigid forming element (punch) which does not need to be assembled precisely with the flexible pad so time and cost production can be reduced) it has not been widely used in mass production because of low productivity and lack of knowledge in this issue. In order to understand the process better the numerical simulations as the cheapest and most efficient tool for determining the important process parameters are used more and more often [19-21].

2. Goal and scope of the research

Examination of the possibility of cold forming hard deformable Ti6Al4V sheet was the main aim of this work.

The forming method using flexible pad was analysed. Both the experiments and numerical simulations were carried out. The experiments were performed on a specially designed for this purpose device. A titanium spherical cup was analysed as a preformed part used in fabrication of many shell products. The cup was made of Ti6Al4V titanium alloy sheet with thickness of 0.8 mm. The cup diameter was 48 mm. The chemical composition of the analysed alloy is given in TABLE 1 and sheet's microstructure is shown in Fig. 1. The mechanical properties, which have been determined in a tensile test, are presented in TABLE 2.

The numerical simulations were used for analysing the flexible forming process. The ADINA System v. 8.7 [22] basing on the finite element method (FEM) was used.

TABLE 1

Chemical composition of Ti6Al4V titanium alloy

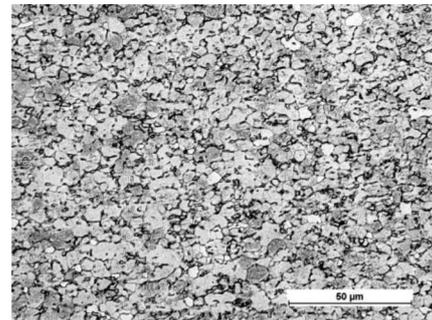| material	Content of element %								
	Al	V	C	Fe	Y	O	N	H	Ti
Ti6Al4V	6,3	4,1	0,003	0,2	<0,006	0,02	0,006	0,001	residue

Fig. 1. Microstructure of titanium sheet Ti6Al4V – light microscope

TABLE 2

Mechanical properties of Ti6Al4V titanium alloy

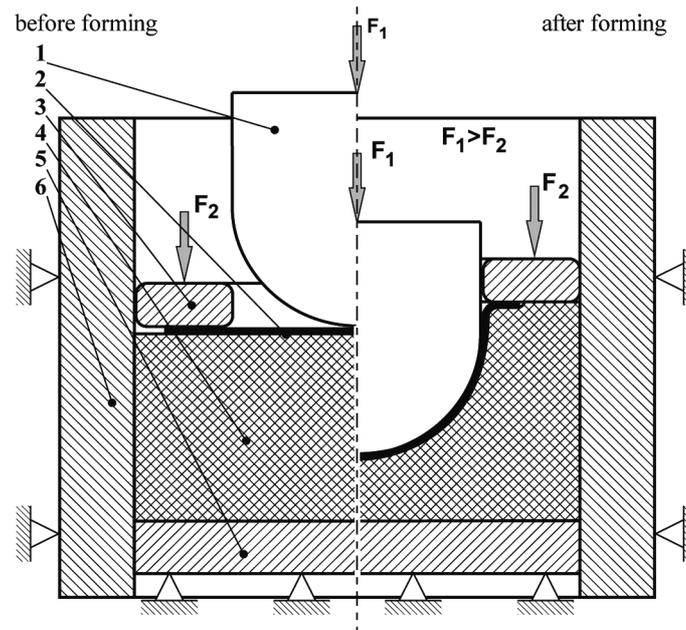| Young's modulus E [GPa]	Yield point $R_{0,2}$[MPa]	Tensile strength R_m [MPa]	Poisnon's ratio ν [−]	Strain-hardening coefficient n[-]	Material constant C [MPa]	Modulus of strain hardening m [MPa]
113.8	980	1048	0.342	0.05	1338	220

Fig. 2. Scheme of the device used for forming of the titanium alloy drawn-parts

3. Experimental results

A scheme of the device used for forming of the titanium cup is shown in Figure 2.

The device consists of 6 components: punch (1), blank (2), blank-holder (3), material filling the working chamber – flexible pad (4), support plate (5) and working tube chamber (6). For working the device needs a double-action press.

In the analysed case the rubber pad was implemented as the pressure carrying medium. Other materials as synthetic elastomers (polyurethane, avothane) or ceramic balls can also be used. The rubber pad (4) is housed in the working chamber, which consists of a steel ring (6) and bottom support plate (5). The support plate can be fixed or may move. The working chamber is placed on a hydraulic press platen. The sheet-titanium blank is pressed down to the elastic pad by a blank-holder (3). A hemispherical punch (1) attached to the upper press platen moves up and down. The operation can be performed by applying compressive load to the flexible pad. The tool can be configured in three options. In the first option F_1 force is applied to the punch (1) and F_2 force is applied to the blank-holder (3), so the support plate (5) does not move under the applied load (Fig. 1). The second option assumes that F_1 force is applied to the punch (1) and F_2 force is applied to the support plate (3) so the blank-holder (5) does not move and the third option assumes that F_1 force is applied to the support plate (5) and F_2 force is applied to the blank-holder (3) so the punch (1) does not move. Each time a relationship $F_1>F_2$ has to be satisfied. The experiment was carried out according to 1st option. In this case when the rigid punch moves down the rubber pad deforms elastically and provides a counter-pressure so the blank is pressed against the punch all the time. The stress state similar to triaxial compression exists in the deformed material. Such a stress state enables obtaining higher material deformation without risk of fracture.

Due to the application of the device a spherical cup with a diameter of 48 mm was formed. Production of such drawn-parts by conventional forming tool is impossible because of low formability of the titanium alloy sheet and domination of tensile stress state which promotes material fracture. Although the process seems to be simple it requires experience and knowledge how to select the correct process parameters to avoid fracture or wrinkling of the deformed material as a result of improper compression of the flexible pad.

4. Numerical model and calculation results

In this study finite element analysis (ADINA System) was used for better understanding of the flexible pad forming process. The process parameters such as the holding-down force and frictional conditions were explored with FE model.

An axisymmetric numerical model of the process with large displacement and strain formulations was used. A nonlinear static analysis was performed. The solution to the static equilibrium equations was obtained using the modified Newton iterations, with line searches. The results were achieved in 250 calculation steps with an automatic step incrementation.

A homogeneous elastic-plastic properties with isotropic type of strain hardening were assumed for the titanium sheet. This material model is based on the von Mises yield condition associated with flow rule using the von Mises yield function. The material data given in TABLE 2 were implemented in the calculations. The sheet model consisted of 848 axisymmetric 9-nodes solid elements.

The Sussman-Bathe material model [23, 24] was adopted for the rubber. This model is based on the following equation:

$$W_D = w(e_1) + w(e_2) + w(e_3),$$

where W_D – strain energy density, $w(e)$ is a function of the principal logarithmic strain (Hencky strain) and e_1, e_2, and e_3 are the principal logarithmic strains. This strain energy density expression assumes a totally incompressible material. The rubber model consist of 20,400 axisymmetric 4-nodes solid elements.

Shaping tools such as the punch, blanking-holder etc. were modelled as perfectly rigid.

A geometry and the boundary conditions of the analysed process is shown in Fig. 3. The punch can move along Z axis. A displacement $\Delta l=27$mm was applied to the punch. Simultsneously maximal value of the punch force was limited to $F_{Smax} \leqslant 2.5$ MN. The blank-holder moves along Z axis.

Two variants of the holding-down force were considered. In the first variant of the calculations, during the forming process the force applying to the blank-holder increases linearly from $F_D =0$ kN to $F_D =50$ kN. In the second variant of calculations, the constant holding-down $F_D =50$ kN was applied. A displacement of the blank-holder depends on the rubber deformation. Apart from the contact with the tool and rubber any boundary conditions have not been assigned to the sheet. Sheet deformation depends only on the tool position and the rubber deformation. In the simulation as in the experiment both immobile working chamber and supporting plate were applied.

Friction between contact surfaces is another important factor having the influence on the forming course. Therefore, in the third variant of calculations the friction coefficient was changed in comparison to the first variant. The surface contact according to the Coulomb hypothesis was assumed in the numerical model. The process parameters for three calculation variants are presented in TABLE 3.
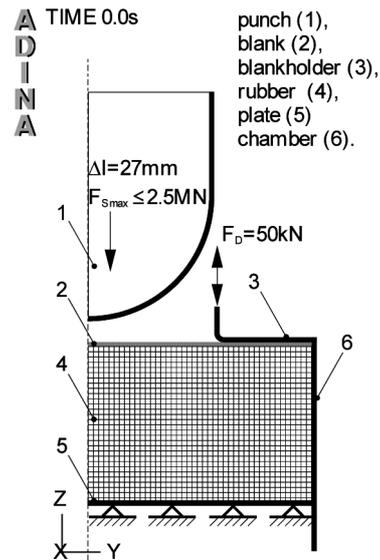

Fig. 3. FEM model of the analysed process

A comparison between the calculation results for the first and second variants of calculations are presented in Fig. 4.

The analysis of calculation results showed that there is a peculiar area in the cup representing by P points, in which the sheet undergoes repeated bending. At the beginning of the forming process the sheet is bent over the fillet radius of the blank-holder as a result of rubber deformation. As the punch moves down the sheet undergoes bending in opposite side and P points change their

TABLE 3

Process parameters for the analysed calculation variants

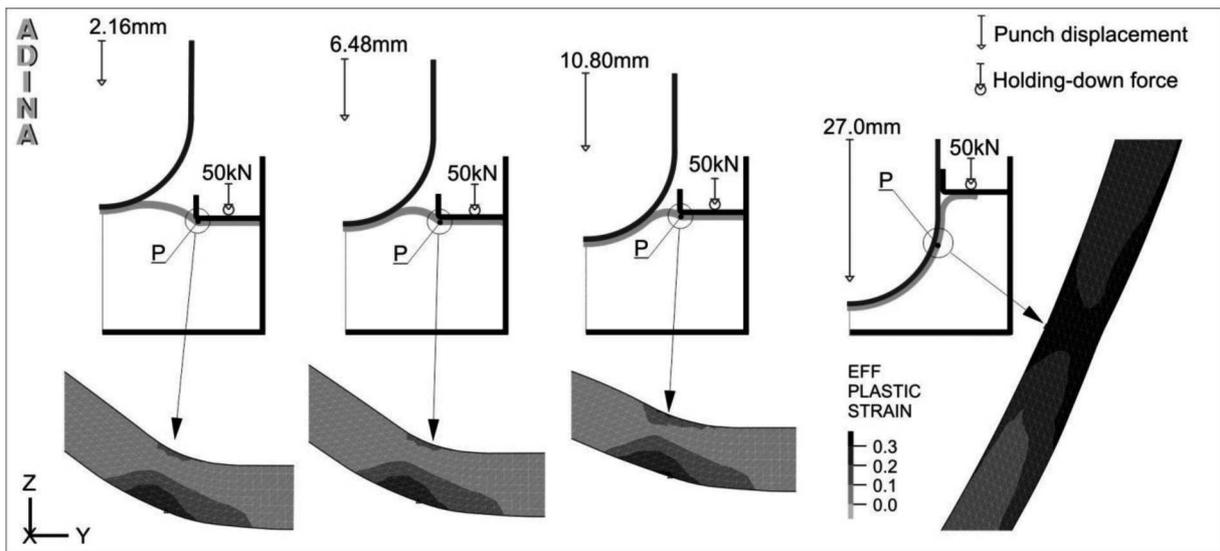| Parameter / Variant	1st variant	2nd variant	3rd variant
Friction coefficient between sheet and blank-holder	$\mu = 0.04$	$\mu = 0.04$	$\mu = 0.1$
Friction coefficient between sheet and punch	$\mu = 0.6$	$\mu = 0.6$	$\mu = 0.5$
Friction coefficient between sheet and rubber	$\mu = 0.04$	$\mu = 0.04$	$\mu = 0.1$
Holding-down force F_D	Variable force vs time 0÷50kN	Constatnt force 50kN	Variable force vs time 0÷50kN

a)
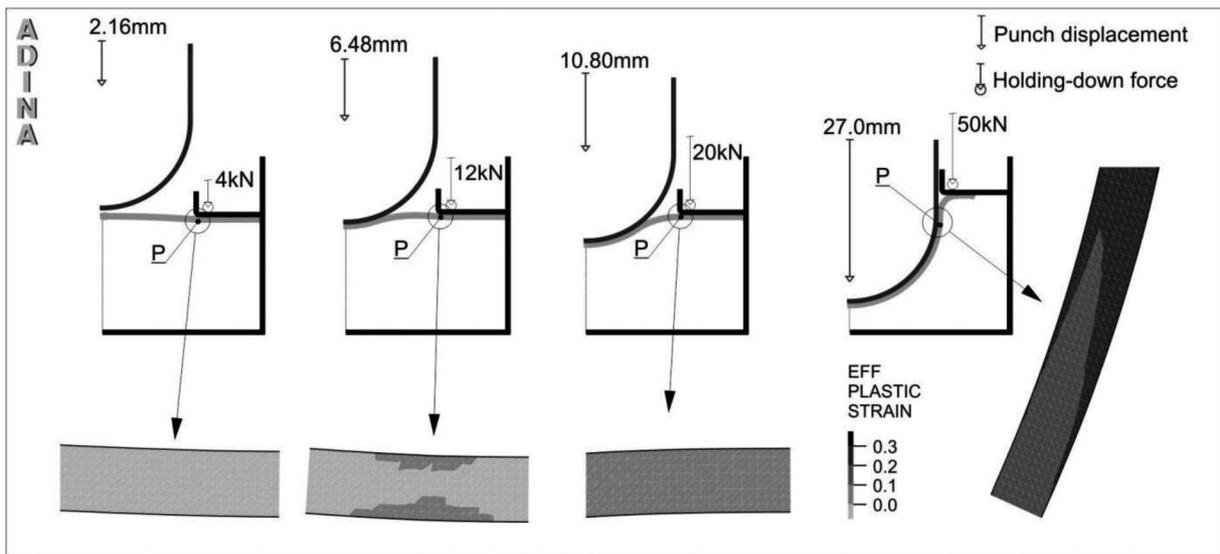
b)

Fig. 4. Scheme of sheet deformation and plastic strains in the vicinity of P point: a) 1st variant, b) 2nd variant

position. The highest plastic strains occur in this area. It explains why during the experiments the cups crack in this area most frequently. Comparison of the 1st (Fig. 4a) and 2nd (Fig. 4b) variants shows that local strains are stronger in the 2nd one. Maximal plastic strains for the 1st variant is $\varepsilon_{max} = 0.3832$ while for the 2nd is $\varepsilon_{max} = 0.5194$.

A summary of the minimal thicknesses and maximal strains occurring in the cup for the analysed variants is give in TABLE 4.

As it is seen from TABLE 4 both holding-down force and frictional conditions have an essential influence on thinning of the cup walls and value of plastic strains.

Change in friction coefficient allow for the decrease in the cup wall thinning and growth in the maximal plastic strain in comparison to the 1st variant.

TABLE 4

Minimal thicknesses of the cup wall and maximal strains for the analysed variants

	g_{min} [mm]	ε_{max}
Variant 1	0.57984	0.3832
Variant 2	0.69166	0.5194
Variant 3	0.56925	0.4038

5. Summary

The carried out experiments confirmed that flexible forming is capable of manufacturing drawn-parts of hard-to-deform sheets like titanium alloy Ti6Al4V. This method can greatly improve the formability of the shaped blank thanks to a flexible contact surface between the rigid punch and the rubber pad.

The other advantage of rubber pad forming over conventional forming is that the quality of its products is high – the obtained drawn-parts had good surface finish as no surface tool marks are created.

The investigations showed the effectiveness of finite element simulations in understanding flexible (rubber pad) forming, what could be used in future design of the forming process. However, numerical simulations of the rubber pad forming process are complicated because the method involves coupling of the deformation of the blank and rubber. Because of the large deformation of the rubber pad, a severe mesh distortion may occur.

Further studies, will be focused on searching for important process parameters, allowing for minimising of thinning and obtaining of the uniform plastic strain distribution.

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