XII International Conference on Computational Plasticity. Fundamentals and Applications
COMPLAS XII
E. Oñate, D.R.J. Owen, D. Peric and B. Suárez (Eds)

NUMERICAL AND EXPERIMENTAL ANALYSIS OF COLD FORMING OF TITANIUM ALLOY SHEETS

J. ADAMUS

Czestochowa University of Technology
ul. J.H. Dabrowskiego 69, 42-201 Czestochowa, Poland
e-mail: janina_adamus@wp.pl, http://www.pcz.pl

Key words: Semi-flexible Forming Process, Titanium Alloy, Numerical Simulation.

Abstract. Due to an increasing demand for the titanium drawn-parts, mainly from the aerospace and car industries, the demand for expertise in sheet-titanium forming grows. Although titanium combine many valuable features like lightweight with high strength and excellent corrosion resistance, its application is still limited because titanium processing, especially cold forming of titanium sheets poses many problems.

In the paper technological problems with forming of titanium sheets is discussed. A special attention is paid to flexible forming. The experimental and numerical simulation results of semi-flexible forming are presented. The numerical analyses are carried out with the ADINA System v. 8.6 basing on the Finite Element Method (FEM). A spherical drawn-part made of Ti6Al4V titanium sheet is analysed. The material data, which are necessary for the numerical calculations, such as tensile strength R_m, yield point R_e, R-value and hardening coefficient n were determined experimentally. The numerical calculations show good convergence with the experiments.

1 INTRODUCTION

Due to an increasing demand for the titanium drawn-parts, mainly from the aerospace and car industries as well as medicine, the demand for expertise in sheet-titanium forming permanently grows [1-9]. Although titanium combine many valuable features like lightweight with high strength and excellent corrosion resistance, its application is still limited because titanium production and its processing is complex and extremely costly. The high titanium price mainly results from the fact that it extensively reacts with oxygen at high temperatures and therefore the Kroll process is the only available method of commercial-scale production of titanium but it requires the use of another expensive metal – magnesium.

Processing of titanium is as difficult as its production, especially cold forming of titanium sheets poses many problems. While sheets of commercially pure titanium, especially *CP 1* and *CP 2*, easily deform at ambient temperature with using techniques and stamping dies normally used for production of steel drawn-parts, both α and $\alpha + \beta$ titanium alloys, at ambient temperature, can be plastically deformed only to a limited extent because of the small quantity of plasticity (ratio of yield point R_e to tensile strength R_m is mostly more than 90%), [10-12]. According to low mechanical properties application of the drawn-parts of commercially pure titanium is limited to less reliable parts such as different casings (electronic equipment casings, notebook and mobile phone casings, watch casings etc.) and roofing. When high strength is required, as in the case of different medicine or vehicle drawn-parts, titanium alloys have to be used. Here, unfortunately, there is a problem.

Even in the case of deep drawing steel sheets forming the spherical or cone drawn-parts using traditional methods (traditional methods here means any sheet-metal forming using rigid steel tools such as: die, blank-holder and punch) is very difficult due to incomplete contact between the tools and the deformed material. Tangential compressive stresses pose a serious problem resulting in wrinkling mostly occurring in the area where the sheet has no contact with the tool. In order to prevent this phenomenon the draw beads causing the increase in tensile stresses are used. Unfortunately, in the case of forming titanium alloy sheets, it usually leads to material rupture. Due to extremely low drawability at ambient temperature titanium alloy sheets have to be formed at elevated temperature - usually above $500^{o}C$ [13, 14]. This in turn involves necessity of application of vacuum or protective atmosphere because with the temperature increase titanium susceptibility to gas absorption grows. However, the growing demand for titanium drawn-parts from the industry encourages scientists to search for the new methods allowing for forming of almost unworkable titanium alloy sheets at ambient temperature [15-17]. Generally, impulse forming including e.g. electromagnetic or explosive forming [18], and flexible sheet forming technology, such as hydroforming [19] or forming technology using a flexible tool half etc. [15, 16, 20-22] are used. Although uniform titanium alloy sheets are very difficult in forming some works [23-27] have reported on forming titanium welded blanks, in which the weld poses additional obstacle.

In the paper forming a spherical titanium drawn-part using a semi-flexible tool is analysed. Although such a forming is one of the oldest sheet forming methods and seems to be quite simple it has not been widely used in mass production. It is because of low productivity and lack of knowledge in this issue. In order to understand the flexible pad forming process better the ADINA System [28], which is based on the finite element method (FEM), was used. An influence of such forming parameters as holding down force and frictional coefficient on the forming process are considered.

2 GOAL AND SCOPE OF THE RESEARCH

The former author’s examinations showed that titanium alloy sheets are hard deformable. Forming Ti6Al4V sheets using rigid tools at ambient temperature is impossible [10,15,16]. Therefore it was decided to investigate semi-flexible forming. Such a forming method causes additional compressive stresses in the sheet and therefore it is possible to produce deeper drawn-parts.

A specially designed for this purpose device was used for forming. The numerical simulations of semi-flexible forming were carried out with the ADINA System v. 8.7.

A spherical drawn-part was analysed as a preformed part for manufacture various shell parts. It was made of 0.8 mm thick titanium sheet. The drawn-part diameter was 48 mm. Such a diameter results from the fact that originally, the analysed method was applied for production of an output part of bowl milling cutter used in orthopaedics for making holes in the pelvis bones for the acetabulum hip endoprosthesis [29].

3 NUMERICAL MODEL

Although the process seems to be simple it requires experience and knowledge how to select the correct process parameters to avoid wrinkling or even fracture of the deformed material as a result of improper compression of the flexible (rubber) pad. Therefore, the numerical simulations with the ADINA System were carried out for better understanding of the semi-flexible forming process. The System is based on the finite element method (FEM).

An axisymmetric numerical model of the forming process with large displacement and strain formulations was applied. A nonlinear static analysis was carried out. 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 deformed material, i.e. titanium sheet. This material model is based on the von Mises yield condition associated with flow rule using the von Mises yield function. The following material data: Young's moduls E=113.8 GPa, yield point $R_{0,2}$ =980 MPa, tensile strength R_m=1048 MPa, Poisnon's ratio ν=0.342, strain-hardening coefficient n=0.05, material constant C=1338 MPa and modulus of strain hardening m=220 MPa were implemented in the numerical calculations. The sheet model consisted of 848 axisymmetric 9-nodes solid elements.

The Sussman-Bathe material model [30,31] was adopted for an elastic material (rubber), which fills the working chamber. This model is based on the following equation:

$$W_D = w(e_1) + w(e_2) + w(e_3) \tag{1}$$

where: W_D - strain energy density,

$w(e)$ - function of the principal logarithmic strain (Hencky strain),

e_1, e_2, e_3 - the principal logarithmic strains.

This strain energy density expression assumes a totally incompressible material. The elastic material model consists of 20,400 axisymmetric 4-nodes solid elements.

Forming tools, such as: the punch, blank-holder etc., were modelled as perfectly rigid.

A numerical model of the semi-flexible forming process is shown in Figure 1.

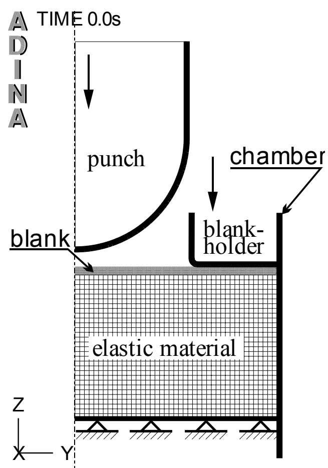

Figure 1: A numerical model of the analysed process

During the numerical simulations it is assumed that: the punch can move along Z axis, a displacement Δl=27mm is applied to the punch and simultaneously a maximal value of the punch force is limited to $F_{Smax} \leq 2.5$ MN. The blank-holder also moves along Z axis. 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 only depends on the tool position and deformation of the elastic material which fills the working chamber. In the simulations as in the experiment both immobile working chamber and supporting plate were applied.

The process parameters such as the holding-down force and frictional conditions are explored. In the numerical model the surface contact according to the Coulomb hypothesis was assumed.

4 NUMERICAL CALCULATION RESULTS – DISCUSSION

In the numerical calculations different variants of the holding-down force were considered. At the beginning the constant values of the holding-down force were implemented. Then it was assumed that the forces applied to the blank-holder increase linearly.

An analysis of the numerical simulation results, as was also discussed in [16], showed that there is a peculiar area in the drawn-parts representing by *P* points (Fig. 2), in which the deformed sheet experiences repetitive bending.

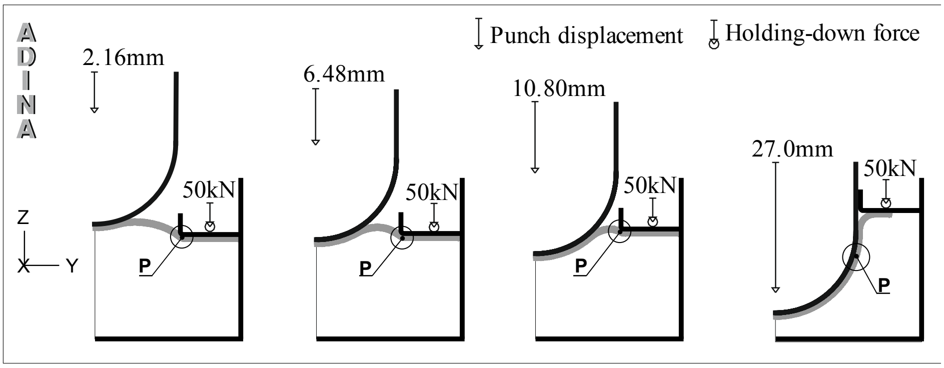

Figure 2: Scheme of sheet deformation and plastic strains in the drawn-part area representing by P points

During the forming process, when the punch starts to move down the sheet can be bent over the fillet radius of the blank-holder as a result of the rubber deformation. The rubber presses the sheet to the punch but sometimes, when the punch and holding-down forces are improperly chosen, as the punch moves down the sheet undergoes bending in opposite side. In the area representing by P points, where the sheet is repetitively bent, the highest plastic strains occur. It explains why during the first experimental tests, cracking of the drawn-parts was initiated in this area most frequently.

An example of the strain distribution for the carried out calculations is presented in Figure 3.

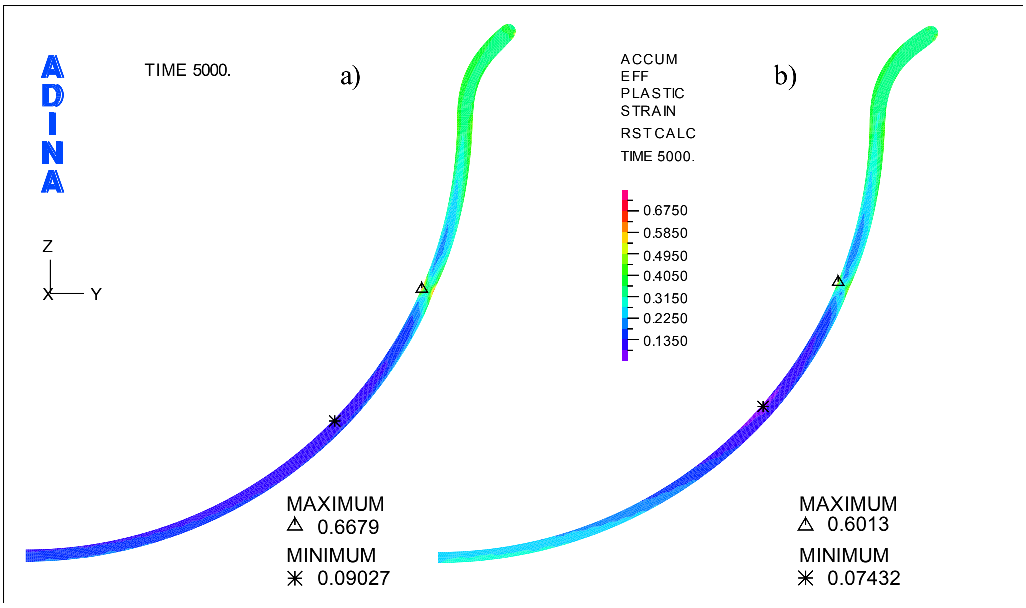

Figure 3: Strain distribution in the drawn-part: a) a constant holding-down force, b) a linearly increasing holding-down force

A comparison between the plastic strain values for forming with a constant holding-down force F_{H-D}=50kN (Fig. 3a) and the holding-down force which increases linearly from F_{H-D}=0kN to F_{H-D}=50kN (Fig. 3b) shows that local strains are stronger in the case of the constant holding-down force. The maximum plastic strain for the constant holding-down force is ε_{max}=0.6679 while for the linearly increasing holding-down force is ε_{max}=0.6013.

The analysis of the numerical calculation results showed that the holding-down force is only one of the essential factors affecting the forming course and plastic strain distribution in the drawn-parts. Frictional conditions existing between the deformed material and tool surfaces, which are specified by a frictional coefficient, are the second important factor. Therefore, two different cases have been analysed. In the first case (Fig. 4a) frictional coefficient μ=0.4 was assumed for all contact surfaces, what simulates dry conditions. In the second case (Fig. 4b) the frictional coefficient μ=0.4 was assumed only for the frictional pair: "punch - deformed material (titanium)", and μ=0.12 (as in the case of lubricated surfaces) for the frictional pairs: "deformed material (titanium) - blank-holder" and "deformed material (titanium) - elastic material (rubber)". The strain distribution for these two cases is shown in Figure 4. As it is seen from Figure 4 lubrication essentially improved frictional conditions and made the material flow more easier so the plastic strain distribution was more uniform. Thinning of the drawn-part walls decreased. The sheet thickness at the pole of the drawn-part was of 0.52 mm for forming in dry conditions and 0.59 mm for forming with lubrication. At the same time thickness at the drawn-part edge was of 0.95 mm for forming in dry conditions and 0.97 mm for lubrication.

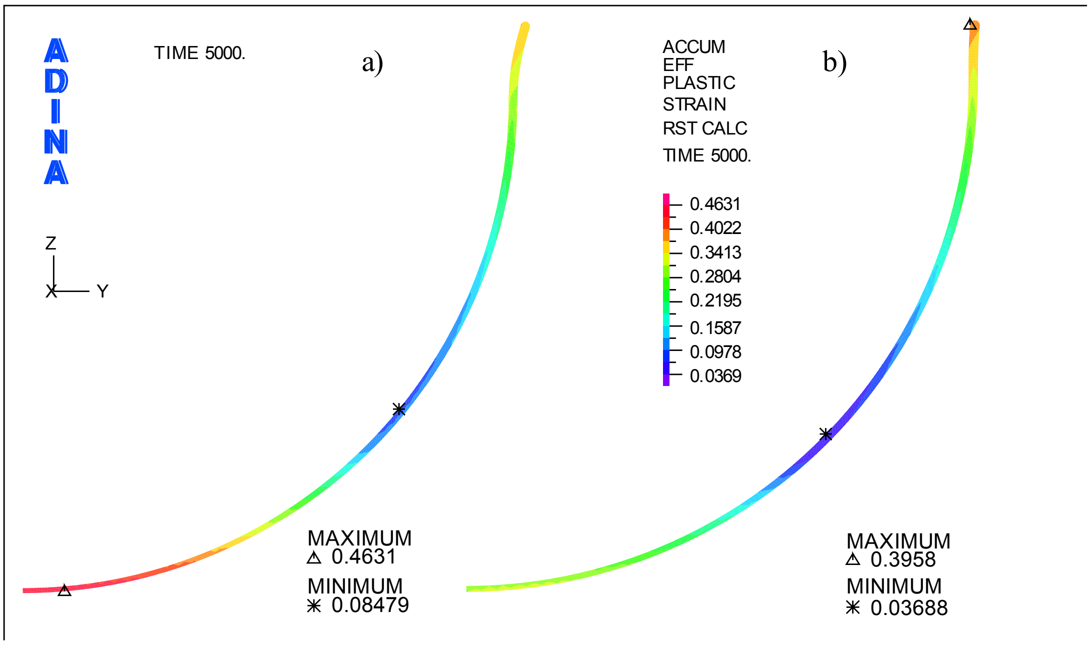

Figure 4: Plastic strain distribution: a) dry condition for all frictional pairs, b) dry condition for the frictional pair "punch - deformed material" and lubrication for the frictional pairs "deformed material - blank-holder" and "deformed material - elastic pad"

4 EXPERIMENTAL RESULTS

In order to verify the calculation results a thickness of the real drawn-part wall was measured and compared to the calculation results. The numerical calculation simulates the real forming process, which was carried out on a device according to the scheme shown in Figure 5.

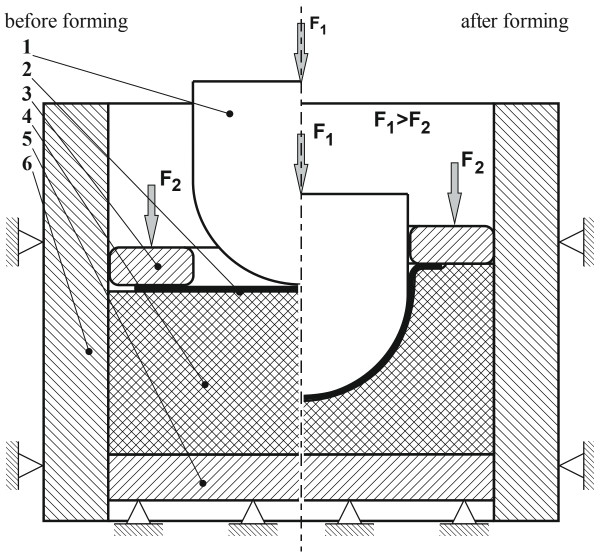

Figure 5: Scheme of the device used for forming of the titanium alloy drawn-parts: 1– punch, 2 – blank, 3 – blank-holder (ring), 4 – elastic material (e.g. rubber), 5 – support plate, 6 – working tube chamber [32,33]

A comparison of the drawn-part wall thickness between the test and calculation results is shown in Figure 6.

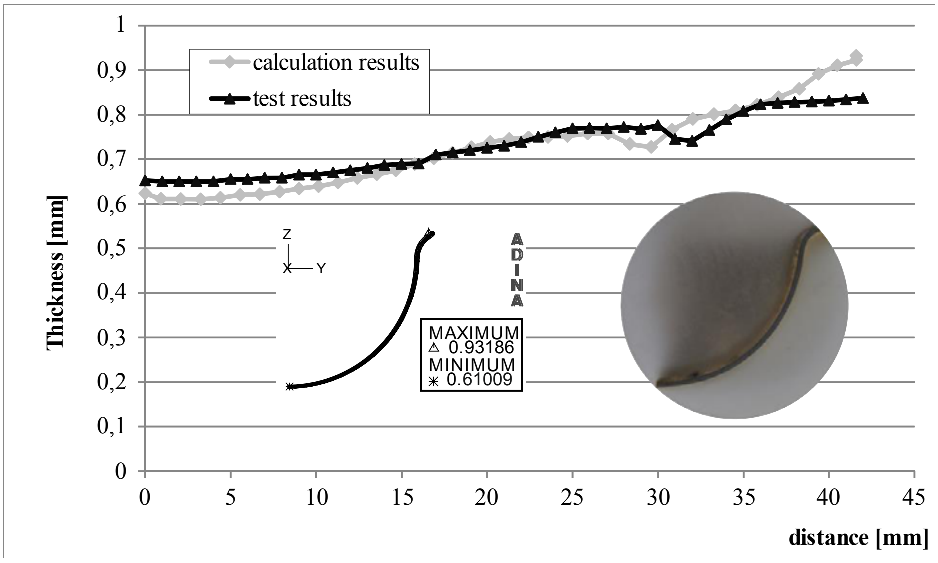

Figure 5: A comparison of the drawn-part wall thickness between the test and calculation results

As it is seen from Figure 6 in the real drawn-part there is a little bit smaller thinning of the sheet at the pole of the drawn-part and thickening at the cup edge.

5 CONCLUSIONS

- The carried out experiments confirm that semi-flexible forming allow for stamping almost unworkable titanium sheets at ambient temperature. An elastic contact between the elastic material e.g. rubber and rigid punch improves forming conditions. Inducing the additional compressive stresses in the deformed material allows for achieving higher rates of deformation.
- Quality of the drawn-parts is high – there is no any marks of the tool on the outer surface of the produced parts.
- Effectiveness of the numerical simulations in exploration of the elastic forming method was proved. However, the numerical simulations are very complicated because they need to combine deformation of the sheet-metal and rubber (large deformation of the rubber causes significant mesh distortion) they explains why the real drawn-parts crack.
- In future, the numerical simulations will be concentrated on the design of such processes and searching the process parameters allowing for decrease in thinning of the drawn-part wall and more uniform plastic strain distribution.

ACKNOWLEDGEMENTS

Financial support of Structural Funds in the Operational Programme - Innovative Economy (IE OP) financed from the European Regional Development Fund - Project "Modern material technologies in aerospace industry", Nr POIG.01.01.02-00-015/08-00 is gratefully acknowledge

REFERENCES

[1] Yamada M. An overview on the development of titanium alloys for non-aerospace application in Japan. *Mater. Sci. Eng. A* (1996) 213: 8-15.
[2] Rack H.J., Qaz J.I. Titanium alloys for biomedical applications. *Mater. Sci. Eng. C* (2006) 26 (8): 1269–1277.
[3] Niinomi M., Nakai M., Hieda J., Cho K., Akahori T., Hattori T., Ikeda M. Research and development of low-cost titanium alloys for biomedical applications. *Key Eng. Mat.* Cost-Affordable Titanium IV (2013): 133.
[4] Faller K., Froes F.H. The use of titanium in family automobiles. *Journal of Metals* (2001) 53 (4): 27-28.
[5] Kosaka Y., Fox S. P. Recent development of titanium and its alloys in automotive exhaust applications. *Proceedings of the Symposium: Titanium alloys for high temperature applications. TMS 2006 Annual Meeting in San Antonio, Texas, USA* (2006): 69-80.
[6] Li C.L., Ye W.J., Mi X.J., Hui S.X., Lee D.G., Lee Y.T. Development of low cost and low elastic modulus of Ti-Al-Mo-Fe alloys for automotive applications. *Key Eng. Mat*. Cost-Affordable Titanium IV (2013): 114.
[7] Boyer R.R., Briggs R.D. The use of β titanium alloys in the aerospace industry. *J. Mater. Eng. Perform.* (2005) 14 (6): 681-685.
[8] Jones T., Kondoh K., Mimoto T., Nakanishi N., Umeda J. The development of a Ti-6Al-4V alloy via oxygen solid solution strengthening for aerospace and defense applications. *Key Eng. Mat*., Cost-Affordable Titanium IV (2013): 118.
[9] Yang H., Fan X.G., Sun Z.C., Guo L.G., Zhan M. Recent developments in plastic forming technology of titanium alloys. *Science China Technological Sciences*, (2011) 54 (2): 490-501.
[10] Adamus J. Stamping of the Titanium Sheets. *Key Eng. Mat.* (2009) 410-411: 279-288.
[11] Adamus J. Theoretical and experimental analysis of the sheet-titanium forming process. *Arch. Metall. Mater.* (2009) 54/3: 705-709.
[12] Adamus J., Lacki P. Forming of the Titanium Elements by Bending. *Comp. Mater. Sci.* (2011) 50/4: 1305-1309.
[13] Motyka M., Sieniawski J. The influence of initial plastic deformation on microstructure and hot plasticity of α+β titanium alloys. *Archives of Materials Science and Engineering* (2010) 41/2: 95-103.
[14] Ceretti E., Fiorentino A., Marenda G.P., Cabrini M., Giardini C., Lorenzi S., Pastore T., Cold and warm formability of titanium sheets. *Metall. Ital.* (2012) 104 (10): 29-36.
[15] Adamus J., Lacki P. Possibility of the increase in titanium sheets' drawability. Key Eng. Mat. (2013) 549: 31-38.
[16] Adamus J., Lacki P. Investigation of sheet-titanium forming with flexible tool –

experiment and simulation. *Arch. Metall. Mater.* (2012) 57/4: 1247-1252.
[17] Rojek, J., Hyrcza-Michalska, M., Bokota, A., Piekarska, W. Determination of mechanical properties of the weld zone in tailor-welded blanks. *Arch. Civ. Mech. Eng.* (2012) 12 (2): 156-162.
[18] Psyk V., Risch D., Kinsey B.L., Tekkaya A.E., Kleiner M., Electromagnetic Forming-A review. *J. Mater. Sci. Technol.* (2011) 211/5: 787-829.
[19] Kandil A. An experimental study of hydroforming deep drawing. *J. Mater. Process. Technol.* (2003) 134: 70-80.
[20] Thiruvarudchelvan S. The potential role of flexible tools in metal forming. *J. Mater. Sci. Technol*. (2002) 122: 293-300.
[21] Thiruvarudchelvan S., Sritharan T. Properties of hemispherical cups drawn using a flexible tool. *J. Mater. Sci. Technol.* (2003) 134: 310-317.
[22] Liu Y., Hua L. Fabrication of metallic bipolar plate for proton exchange membrane fuel cells by rubber pad forming. *J. Power Sources* (2010) 195: 3529–3535.
[23] Sinke J., Iacono C., Zadpoor A.A., Tailor made blanks for the aerospace industry. *Int. J. Mater. Form.* (2010) 3/1: 849-852.
[24] Lacki P., Adamus J., Więckowski W., Winowiecka J. Evaluation of drawability of titanium welded sheets. *Arch. Metall. Mater.* 58/1 (2013) 139-143.
[25] Lacki P., Adamus K. Numerical simulation of welding thin titanium sheets. *Key Eng. Mat.* (2013) 549: 407-414.
[26] Lacki P., Adamus K.: Numerical simulation of the electron beam welding process. *Computers and Structures* 89/11-12 (2011): 977-985.
[27] Lacki P., Adamus K., Wojsyk K., Zawadzki M. Numerical simulation of electron beam welding process of Inconel 706 sheets. *Key Eng. Mat.* (2011) 473: 540-547.
[28] ADINA R&D Inc.: *ADINA: Theory and modeling guide*. ADINA R&D Inc., 2009.
[29] Szota, M., Jasinski, J., Lubas, M., Jeziorski, L., Lacki, P. Ways of improving durability of surgical bowl cutter. *Arch. Metall. Mater*. (2008) 53 (1): 145-149.
[30] Sussman T., Bathe K.J. A model of incompressible isotropic hyperelastic material behavior using spline interpolations of tension-compression test data. *Commun. Numer. Meth. Engng.* (2009) 25/1: 53-63.
[31] Sussman T., Bathe K.J. A Finite Element Formulation for Nonlinear Incompressible Elastic and Inelastic Analysis. *J. Computers and Structures* (1987) 26-1/2: 357-409.
[32] Lacki P., Adamus J. *Patent application No P398250*, 07.02.2012.
[33] Lacki P., Adamus J. *Patent application No P.398236*, 27.02.2012.