A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
Volume 60 2015 Issue 2
DOI: 10.1515/amm-2015-0214

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FORMING OF SPHERICAL TITANIUM CUPS FROM CIRCULAR BLANKS WITH CUTOUTS ON THE PERIMETER

TŁOCZENIE TYTANOWYCH CZASZ KULISTYCH Z WYKROJÓW OKRĄGŁYCH Z WYCIĘCIAMI NA OBRZEŻU

Despite substantial demand for drawn parts made of high-strength sheet metal (including titanium alloys) observed in the modern industry, particularly automotive and aviation, their application remains insignificant. This results from the fact that such sheet metal shows poor plasticity and its cold-forming is almost impossible. Low drawability makes it impossible to obtain even such simple shapes as spherical cups. The authors of this study developed circular sheet-metal blanks with cutouts on their perimeter. The blanks allow for cold forming of spherical cups from Ti6Al4V titanium alloy sheet metal using conventional rigid tools. The cutouts proposed in the study affect plastic strain distribution, which in turn leads to an increase in forming depth by about 30%. The numerical analysis, performed using the PamStamp 2G System software based on finite element method, was verified experimentally.

Keywords: sheet-metal forming, titanium sheet, FEM modelling

Mimo, iż nowoczesny przemysł, głównie motoryzacyjny i lotniczy, zgłasza zapotrzebowanie na wytłoczki z wysokowytrzymałych blach metalowych, w tym stopów tytanu, ich zastosowanie jest znikome. Wynika to z faktu, że blachy te mają małą plastyczność i ich tłoczenie na zimno jest niemal niemożliwe. Niska tłoczność uniemożliwia kształtowanie nawet tak prostych geometrii jak czasze kuliste. W ramach niniejszej pracy opracowano kołowy wykrój z wycięciami na obwodzie, który umożliwia kształtowanie na zimno kulistych czasz z blachy ze stopu tytanu Ti6Al4V przy użyciu klasycznych, sztywnych narzędzi. Zaproponowane wycięcia wpływają na zmianę rozkładu odkształceń plastycznych, co w konsekwencji prowadzi do zwiększenia głębokości tłoczenia o około 30%. Analizy numeryczne, wykonane programem PamStamp 2G bazującym na metodzie elementów skończonych, zweryfikowano doświadczalnie.

1. Introduction

Light alloys are expected to become key materials for these industries which require obtaining thin wall parts which are characterized by high strength and are lightweight. Such requirements are met by titanium alloys. The most frequent titanium alloy is two-phase Ti6Al4V (Gr 5). This alloy shows advantageous strength-to-weight ratio, high fatigue strength and fracture toughness. Furthermore, all titanium materials are resistant to the most of corrosion environments. These properties cause that drawn parts are becoming more and more popular in automotive and aviation industries, where both strength and weight of the structure are essential. The increase in the demand for products made of hard-deformed titanium alloys (e.g. Gr 5) stimulates searching for new solutions that allow for forming through cold bending and sheet-metal forming. Due to very low capability of plastic strain at the ambient temperature and strong spring-back effect compared to conventional deep drawing steel sheets, obtaining of products made of titanium sheet metal (Gr 5) using conventional methods is limited and requires expert knowledge and non-standardized approach to solving this problem [5-7]. Obtaining deep drawn parts with complex geometry from hard-deformed sheet metal requires modification of conventional methods of forming or application of modern technologies such as electromagnetic forming, explosive forming, impulse forming, hydroforming or incremental sheet forming [1-4,7-11]. It should be remembered that forming titanium alloys at increased temperature necessitates solving the problems of its tendency for reacting with oxygen, nitrogen and hydrogen. Absorption of these gases causes unfavourable structural changes and, consequently, deterioration of strength parameters [5,8-12]. The studies [13-15] showed that obtaining greater forming depth is also possible during forming of tailor-welded blanks (TWBs). Application of titanium TWBs for drawn parts allows for obtaining, during a single forming operation, parts with different strength properties while reducing the amount of waste generated and, consequently, costs of production.

Titanium sheet metal drawability, limited with wrinkling of the drawn part perimeter and cracking of the material, depends not only on the material properties but also on the forming process, including the shape and state of initial material, tool design, friction and lubrication condition, forming rate, temperature etc. [2,16,17]. In order to evaluate the opportunities for sheet metal forming it is necessary to carry out specific analyses and tests. The valuable information which is neces-

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sary for proper planning of forming processes can be obtained from both empirical and numerical simulations. Numerical simulations of sheet metal forming allow for predicting the behaviour of sheet metal during individual phases of forming as early as at the stage of process design. Publications in this field focus primarily on mechanical properties, capability of plastic strain, including methods of determination of forming limit diagrams (FLD) with regards for the effect of anisotropy of mechanical properties, strain rate and temperature as well as opportunities for application of modern methods of forming and optimization of parameters of these processes [1,2, 17-22]. Authors of the studies [10] point to a very low, almost zero drawability of sheet metal made of titanium Gr 5 at the temperature of environment.

This study attempts to determine geometry of the blank that allows for obtaining the spherical cap from titanium sheet metal (Gr 5) in the process of cold forming using conventional rigid tools. The author of this study expect that application of equally distributed cutouts on the perimeter removes the excess of flange material, which usually exhibits substantial wrinkling at initial stages of forming and, consequently, inhibits further forming of the drawn part. The use of cutouts on the perimeter of a blank leads to changes in distribution of plastic strain in the drawn part and, consequently, allows for increasing the maximum depth of the drawn piece. This fact was demonstrated by the results obtained during experimental tests and numerical modelling of forming spherical cups from circular blanks with and without cutouts.

2. Aim and Scope of the Study

The aim of the study was to determine the shape of the blank for cold-forming spherical caps made of hard-deformed materials such as titanium sheets Gr 5 with thickness of 0.8 mm.

It was assumed that the cap will be formed using a conventional steel tool comprised of a punch, die and blank holder. The blanks were designed with cutouts equally distributed around the perimeter. Application of the cutouts was supposed to reduce forming resistance which occurs during forming of drawn parts from full blanks.

A series of numerical simulations were carried out using PamStamp 2G software in order to select optimal geometry of the blank in terms of quantity and shape of the cutouts. The software is based on the finite element method and is dedicated to sheet metal forming processes. The results of numerical analyses were supported by experimental tests.

3. Number and geometry of cutouts

A key element in numerical analysis was to determine geometry of cutouts. Two types of geometry of cutouts were proposed (Fig. 1), with opening angle of 3÷5° and depth of 3.6÷6.6 mm. All the cutouts were equally and radially distributed with respect to the centre of the circle of the initial disc with diameter of 60 mm. Depth of the cutouts depended on the width of the holding ring and desired forming depth.

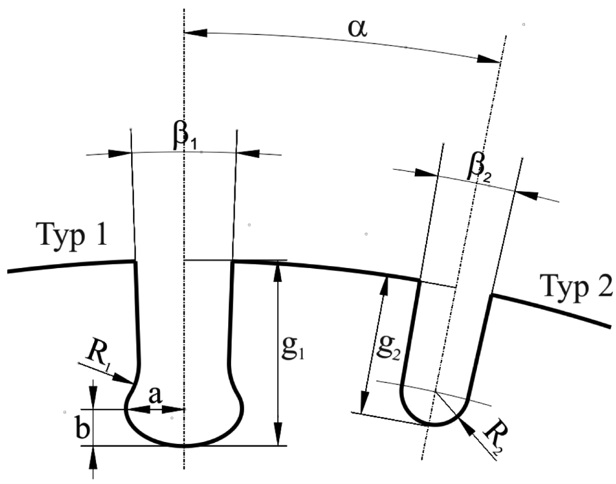

Fig. 1. Geometry of the cutouts: type 1 and type 2: α – angle between cutouts, $\beta_1\beta_2$ – cutout opening angle, R_1 and R_2 – cutout rounding radii, g_1 and g_2 – cutout depths, a, b – radii of major and minor axes of the ellipse, respectively

The following three types of blanks were used in the study (Fig. 2):

– blank A, with radial cutouts of type 2
– blank B, with radial cutouts of type 1
– blank C, with alternate cutouts of type 1 and 2

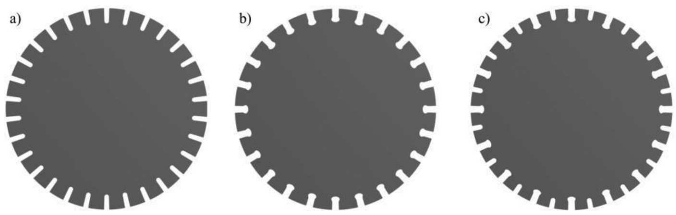

Fig. 2. Distribution of cutouts in blanks: a) blank A, b) blank B, c) blank C

4. Numerical analysis

The numerical model of the tool represents the actual stamping die which was used in the experimental studies. The surface model of the tool is presented as Fig. 3. Blank holder force was adjusted so that sheet wrinkling effect should be prevented. The friction coefficient adopted for the calculations was μ =0.3 (dry conditions) on all contact surfaces i.e. ”blank holder – sheet metal – die” and ”sheet metal – punch”. Boundary conditions were set so that they should allow for sheet metal forming process.

Material properties of titanium alloy Gr 5 determined empirically were presented in TABLE 1.

TABLE 1

Material properties used for definition of material model: E – Young's modulus, R_{p02} – yield point, ν – Poisson's ratio, ρ – specific gravity, K – material constant, n – strain-hardening exponent

Property	E, GPa	R_{p02}, GPa	ν, -	ρ, kg/m^3	K, GPa	n, -
Ti6Al4V	114	0.964	0.37	4400	1.172	0.039

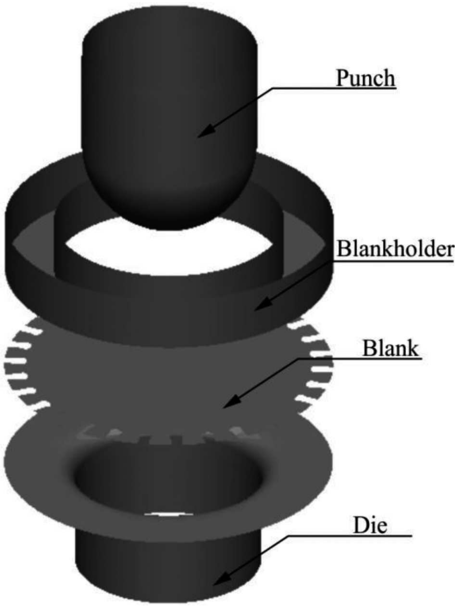

Fig. 3. Forming tool and blank – surface model

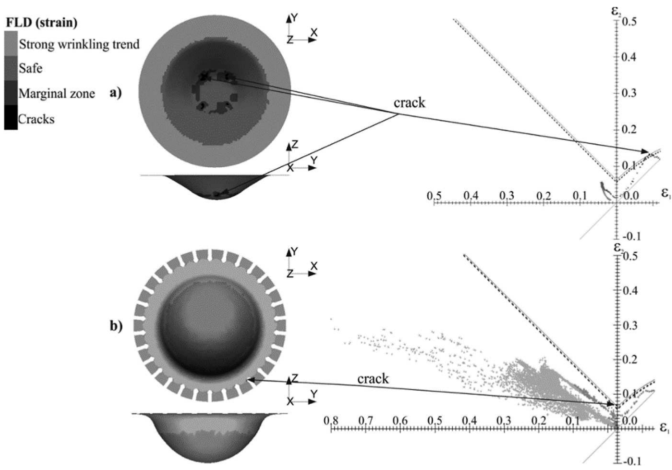

Fig. 5. Comparison of strain in the drawn part with forming limit curve: a) blank with no cutouts, b) blank B with 30 cutouts

Results of numerical simulation for forming of a disc without cutouts were presented in Fig. 4. Maximum depth of the drawn part without defects was 9.5 mm, with maximum plastic strain of 0.228. Depth of material of the drawn part ranges from 0.633 to 0.809 mm. The highest reduction in material thickness is observed at a specific distance from the drawn part and the increase in the material thickness caused by compressive stresses occurs on the drawn piece perimeter.

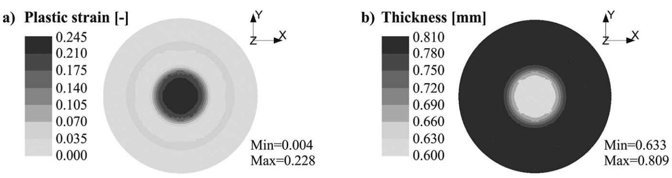

Fig. 4. Distribution of plastic strain (a) and thickness (b) for the process of forming of the circular blank without cutouts

Comparison of strain distribution in drawn pieces obtained from the blank without cutouts and the blank with thirty cutouts of type 1 with forming limit curve is presented in Fig. 5. For the drawn part obtained from the disc without cutouts, the loss of stability in the form of cracking in the upper part of the spherical cap manifests itself for the punch depth of 9.5 mm. For the specimen with cutouts, the depth of the drawn part at which first cracking is observed is 15.2 mm. Cracking in this specimen is initiated in the flange part of the drawn piece near cutouts.

Distribution of plastic strain for blanks A, B and C at the forming depth of 12.7, 15.2 and 13.0 mm are presented in Fig. 6. These depths correspond to the point at which lost of continuity of drawn part material occurs. The highest strain in all the cases occurs in the area of the ”bottom” of cutouts and, based on the analyses, their values depend on cutout geometry. The greatest depth and the lowest values of strain were obtained for the blank B. A substantial change was observed in the distribution of strain compared with the distribution of strain during forming of the blank without cutouts (Fig. 5). The character of these changes depends on the quantity and depth of cutouts on the blank perimeter. Value of plastic strain in the volume of spherical cap material obtained during forming of blanks A, B and C does not exceed 0.2 (cracking for disks without cutouts was observed at the value of plastic strain of 0.22).

Distributions of wall thickness for drawn parts obtained from blanks A, B and C are presented in Fig. 7. An insignificant reduction in the thickness in the central part of the spherical cap and substantial increase in the thickness on the flange near cutout rounding is observed in all the analysed cases. Similar pattern was observed for maximum plastic strain where the highest increases were observed also in the area of cutout rounding. Analysis of distribution of drawn part thickness made of blanks without cutouts and blanks with cutouts revealed that, despite greater (even by 37%) depths of drawn parts, reduction in the thickness in the central part of the spherical cap for blanks with cutouts is lower compared to reduction in the thickness of drawn parts obtained from the blanks without cutouts. For the discs without cutouts, minimum thickness was 0.633 mm, whereas for the blanks with cutouts, the smallest thickness ranged from 0.638 to 0.656 mm.

Major strain distribution in drawn parts obtained from blanks A, B and C were presented in Fig. 8. Maximal major strains were observed at cutout roundings. The area of substantial strain occurs in the upper part of the spherical cap. However, they do not exceed permissible values that point to probability of cracking of drawn parts.

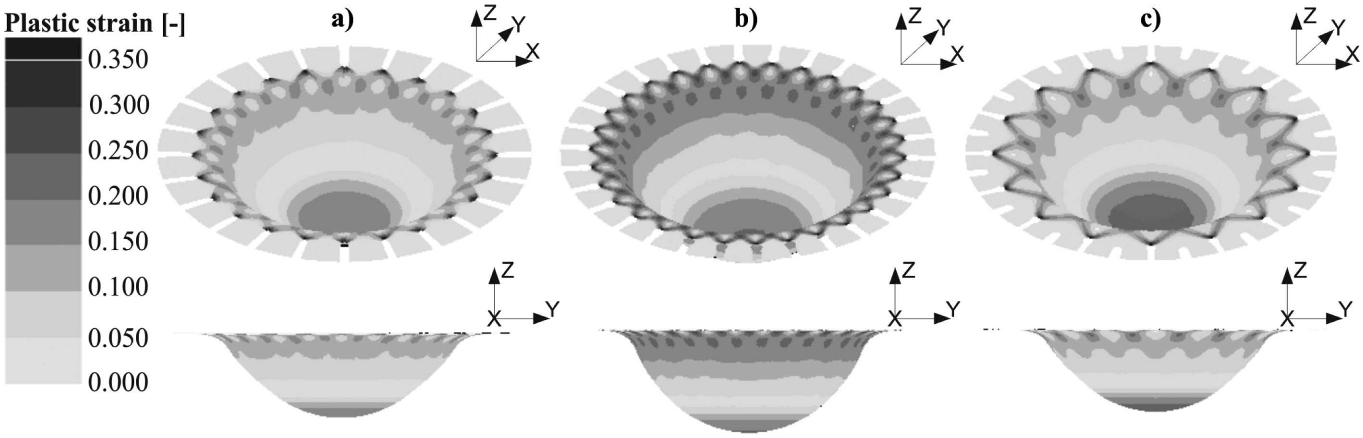

Fig. 6. Distribution of plastic strain in selected drawn parts: (a) blank A with twenty four cutouts, (b) blank B with thirty cutouts, (c) blank C with thirty two cutouts

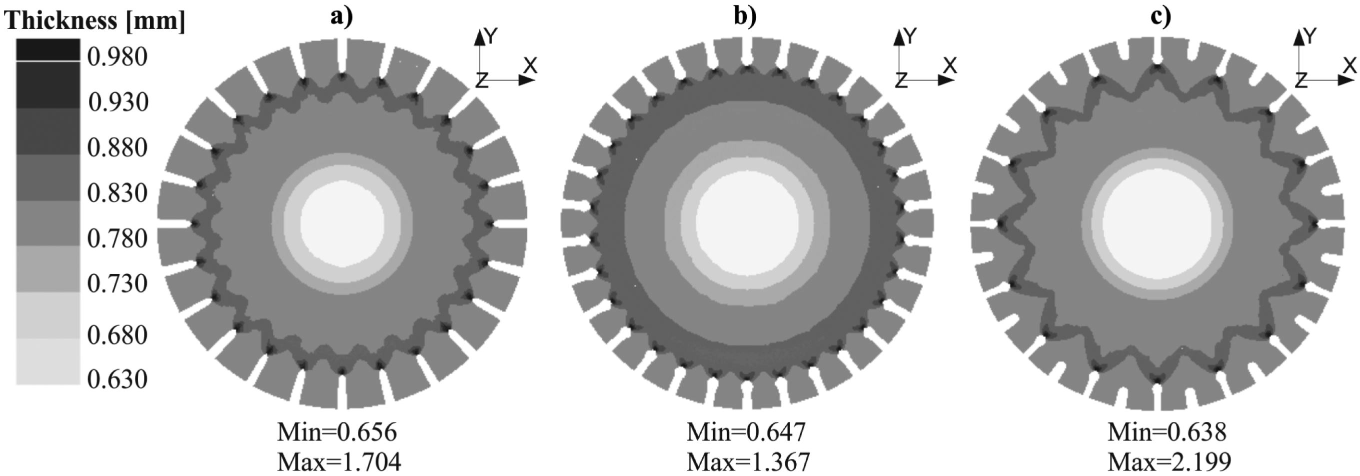

Fig. 7. Distribution of drawn part wall thickness for: (a) blank A with twenty four cutouts, (b) blank B with thirty cutouts, (c) blank C with thirty two cutouts

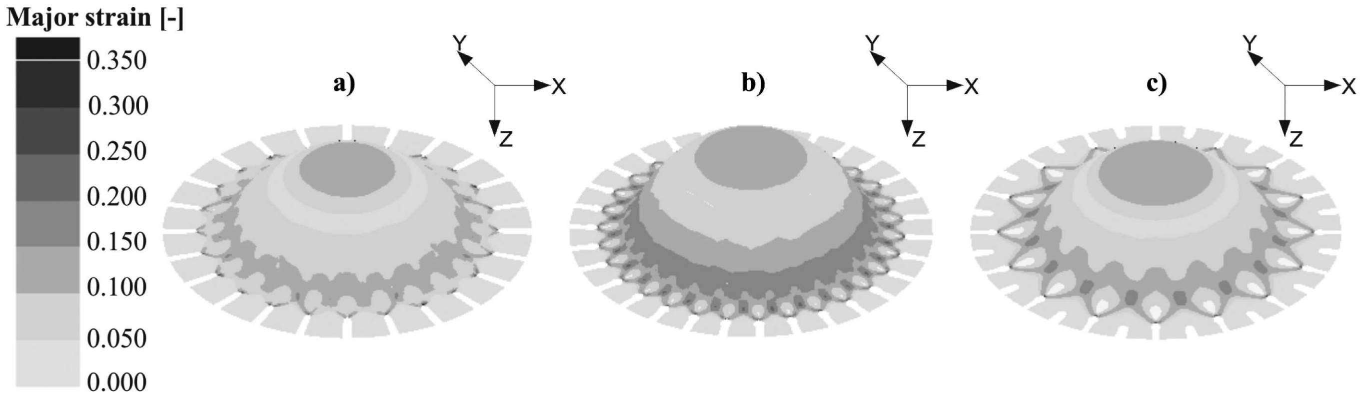

Fig. 8. Major strain distribution in drawn parts obtained from: (a) blank A with twenty four cutouts, (b) blank B with thirty cutouts, (c) blank C with thirty two cutouts

Numerical analyses allowed for selection of the most beneficial geometry of the blank in terms of shape and number of cutouts. The best results were obtained for the blank B, with the highest forming depth being 15.2 mm; for other cases, this value was by 14 to 16% lower. Numerical simulations performed for different number of cutouts showed the necessity of using at least 20 cutouts on the disc perimeter. The satisfactory forming results were obtained for even number of cutouts between 24 and 32. The number of over 32 cutouts generates the risk of premature cracking of drawn parts in the area of flange. It is necessary to complete the cutouts with an adequate rounding. The cutouts with triangular shape initiate cracking at the triangle vertex, even at insignificant forming depths. In order to avoid cracking, the rounding in the form of semicircles and ellipses was introduced. Excessively deep cutouts are the causes of cracking of drawn parts in the areas of transformation of the spherical cap into the flange part i.e. in the drawing radius of the die at the point of sliding of the flange material from under the blank holder.

5. Experimental tests

In the previous tests of forming of spherical cap from disks with 60 mm in diameter, the material coherence was lost at the punch depth of ca. 9 mm. Therefore, the experimental test were carried out for the sets of numerically modelled blanks with varied number and depth of cutouts. The tests were carried out in a stamping die with an internal hole of 30 mm and fillet radius of 5 mm, hemispherical punch with diameter of 28 mm and holder ring with internal diameter of 34 mm. Dry friction conditions were maintained during tests, which corresponds with the friction coefficient adopted for the calculations of μ =0.3.

The results of forming of the blank B with thirty cutouts with the same depths were presented in Fig. 9. The drawn parts at the moment of cracking had depth of ca. 20 mm. The cracking, noticeable in Fig. 9, was initiated at the rounding of the cutout, where notches are formed during cutting.

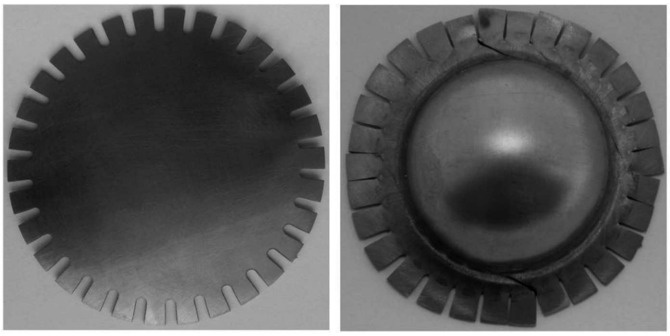

Fig. 9. Results of forming for blank A with thirty cutouts

Results of forming of the blank A with fifteen cutouts with depth of 3.5÷5 mm are presented in Fig. 10 Fig. 8. The drawn parts at the moment of cracking had depth of ca. 19 mm. Cracking which is observed in Fig. 10 was probably initiated as it was the case before at one of the notches created during cutting on the perimeter of the blank and it propagates in two directions. The cracking reaches the rounding radius of the drawn part at the transition of the spherical cap into the flange part. Upper part of the drawn part (cap) is free of defects.

Results of forming of the blank with thirty cutouts obtained based on the blank B were presented in Fig. 11. The cutouts with varied depths and elliptical ends were used, adjusted to the direction of sheet metal rolling. The drawn part without defects with the height exceeding 21 mm was obtained using the blank presented in Fig. 11.

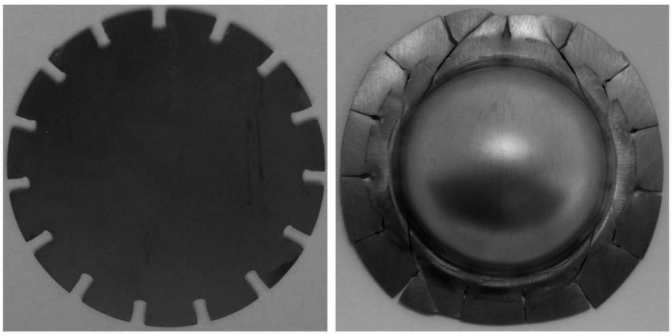

Fig. 10. Results of forming for blank B with fifteen cutouts

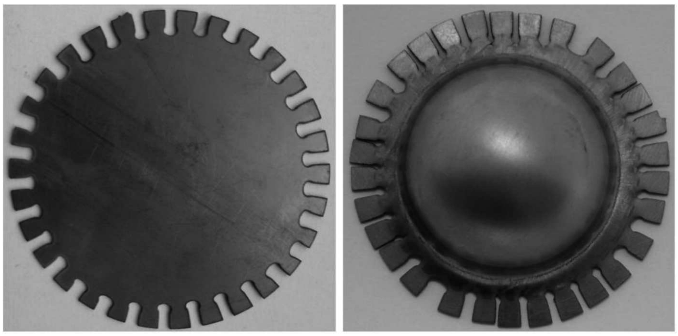

Fig. 11. Results of forming for blank B with thirty cutouts

The experimental tests revealed the significant effect of geometry of cutouts and their number on the forming process and its results.

6. Conclusions

Numerical analyses and experimental tests demonstrated opportunities for obtaining a full spherical cap from hard-deformed sheet metal (titanium Gr 5) using conventional tools for cold forming and initial material in the form of circular blanks with cutouts on the perimeter. The cutouts cause the increased forming depth by at least 30%.

The essential effect on forming results is from geometry and number of cutouts. In the case of the spherical cap, the greatest forming depths were obtained for at least 24 cutouts.

Due to the fact that the cutouts might generate notches that initiate cracking in the area where they are cut, the cutouts should have the depth lower than the expected width of the flange in the drawn part and should be ended elliptically.

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 acknowledged.

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Received: 20 April 2014.