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NUMERICAL AND EXPERIMENTAL ANALYSIS OF THE PROCESS OF AVIATION DRAWPIECE FORMING USING RIGID AND RUBBER PUNCH WITH VARIOUS PROPERTIES

NUMERYCZNA I EKSPERYMENTALNA ANALIZA PROCESU KSZTAŁTOWANIA WYTŁOCZKI LOTNICZEJ Z ZASTOSOWANIEM STEMPLA SZTYWNEGO ORAZ ELASTYCZNEGO O RÓŻNYCH WŁAŚCIWOŚCIACH

This paper presents the results of the numerical analysis and experimental research of the forming process of aviation drawpiece made from 0.6 mm thick Inconel 625 sheet metal. First phase of testing was conducted using rigid steel tools for drawpiece forming. Results of conducted simulations show that during rigid tool forming, the middle of the drawpiece losses stability. In consequence, rigid tool forming leads to the formation of unacceptable wrinkles on the drawpiece. Subsequent experimental research confirmed wrinkles of the metal drawpiece in this area. It was assumed that in order to eliminate this negative phenomenon, minor changes in technology and tool construction would have to be made. The drawpiece will be shaped by means of a flexible tool, than re-shaped using rigid tools. In the second phase of the research, tooling design changes have been made. They consisted of replacing the steel punch with a specially designed stamp susceptible for deformation. FEM numerical simulations were performed for flexible punch forming made of polyurethane elastomer with different hardness (50, 70, 85 and 90 Sh A). On their basis, the effect on the mechanical characteristics of the elastomeric drawing process and the formation of wrinkles was shown. They can be effectively eliminated by the use of a punch with hardness of 90 Sh A, which has also been confirmed by experimental research. In addition, the paper presents a comparative analysis of the deformations in selected actual drawpiece areas and in the elastomeric punch with hardness 90 Sh A computer model. The actual drawpiece deformation schedule and the values were determined using photogrammetric system Argus v.6.3., while the computer modeled drawpiece was based on FEM calculations performed in the MARC / Mentat system. In conclusion the difficulties as well as the advantages and disadvantages in determining the deformation of sheet metal parts were indicated using photogrammetric system Argus and FEM.

Keywords: drawing, rubber-punch forming, Inconel 625 sheet metal, experiment, FEM, Argus system

W pracy przedstawiono wyniki analizy numerycznej oraz badań eksperymentalnych procesu kształtowania wytłoczki lotniczej z blachy Inconel 625 o grubości 0,6 mm. Pierwszą fazę badań przeprowadzono dla przypadku kształtowania wytłoczki z zastosowaniem sztywnych stalowych narzędzi. W wyniku przeprowadzonych symulacji tego przypadku wykazano, że podczas kształtowania sztywnymi narzędziami występuje utrata stateczności blachy w środkowym obszarze wytłoczki. W konsekwencji prowadzi ona do powstania niedopuszczalnych pofałdowań blachy widocznych na wytłoczce ukształtowanej za pomocą sztywnych narzędzi. Fałdowanie blachy w tym obszarze wytłoczki potwierdziły także późniejsze badania eksperymentalne. W celu wyeliminowania tego niekorzystnego zjawiska dokonano niewielkich zmian w technologii wytwarzania oraz konstrukcji oprzyrządowania. Założono, że wytłoczka będzie kształtowana za pomocą elastycznego narzędzia, a następnie dotłaczana za pomocą sztywnych narzędzi. Z uwagi na powyższe w drugiej fazie badań dokonano zmiany w konstrukcji oprzyrządowania. Polegała ona na zastąpieniu stempla stalowego stemplem elastycznym o specjalnie zaprojektowanym kształcie. Symulacje numeryczne MES przeprowadzono dla przypadków kształtowania stemplem elastycznym wykonanym z elastomerów poliuretanowych o różnych twardościach (50, 70, 85 i 90 Sh A). Na ich podstawie wykazano wpływ charakterystyki mechanicznej elastomeru na przebieg procesu wytłaczania oraz powstawanie pofałdowań. Można je skutecznie wyeliminować poprzez zastosowanie stempla o twardości 90 Sh A, co zostało potwierdzone również w badaniach eksperymentalnych. Ponadto, w pracy dokonano analizy porównawczej odkształceń w wybranych obszarach wytłoczki rzeczywistej oraz modelowanej dla przypadku kształtowania elastomerowym stemplem o twardości 90 Sh A. Rozkłady i wartości odkształceń na rzeczywistej wytłoczce określano z wykorzystaniem systemu fotogrametrycznego Argus v.6.3. natomiast na wytłoczce modelowej na podstawie obliczeń MES wykonanych w systemie MARC/Mentat. Wskazano na trudności, w zastosowaniu fotogrametrycznego systemu Argus oraz MES przy wyznaczaniu odkształceń na wytłoczkach.

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1. Introduction

The aviation industry due to their specific production and security, places great emphasis on the quality and reliability of its products, thus the development process must take account of even the smallest imperfections, which in the future would result in failure of the aircraft and air accident. Therefore, the selection or development of effective methods for the production of aviation parts is a major challenge for the constructors. To meet the demands current market, reduce production costs and maximize profits, each of the companies is looking for effective and innovative technological solutions. Design of sheet metal parts and their manufacturing technologies for the aviation industry is a complex process, requiring both knowledge of plastic forming methods and the specific behavior of the materials that are used in the aviation parts of the process. Moreover, there are additional restrictions such as available machine park and other factors specific to the production. One of the main processes of manufacture of parts for the aviation industry is a sheet metal forming. The material is shaped in the way of plastic deformation. During the shaping of sheet metal parts can be phenomena that limit the proper process of drawing. These include among others: cracking, loss of stability of metal as strain location or wrinkles sheet metal, breaking the bottom of the drawpiece and the thinning of the wall, etc. [1, 2]. The occurrence of these phenomena, the process sets the practical limit of drawability sheet metal forming under the this circumstances. Any deviation from the preset conditions of geometric and strength as well as sheet metal surface imperfections for example: scratches, pitting, dents are considered to be drawpiece defects. They are unacceptable in the aviation industry. Therefore, the choice of the appropriate method of forming parts do not always provide good value product.

In the era the twenty-first century, more and more often goes to the computer simulation in the design processes. Numerical modeling were also used in the analysis of sheet metal forming processes. Running the simulation of drawing, with the possibility of simultaneous process evaluation of shaping sheet metal already in the design phase of the technological process and tooling eliminates or significantly restrict the necessity of always very expensive method of “trial and error”. However, the quality and similarity of numerical simulation results with the real process depends on many factors. Only the ability to use the software does not provide much success in this field. It is important to know the theoretical basis and broadly understood mathematical models, which are used in numerical analysis. No less important is the awareness of the physical phenomena involved in the process and the importance of their impact on the progress and quality of the final product. Knowledge of the occurrence of these phenomena, especially disadvantaged allows for build numerical models of technological processes to make them as much as possible into account.

Literature [3] says its about 60% of all sheet metal aviation parts are shaped using flexible tools. Most shaping tool made of rubber or polyurethane elastomers with different properties. Mechanical characteristics of elastomer material, which is made punch has an impact on the course of the technological process, deformation of the tool and its life.

This paper presents the use of FEM numerical analysis in the design process of the shaping process for aviation 0.6mm thick Inconel 625 sheet metal drawpiece. First phase of testing was performed using rigid steel tools for drawing process. However, due to the occurrence of unacceptable sheet metal wrinkles on the drawpiece in the simulation, replaced the steel punch with a specially designed flexible stamp. In the second phase of the research, sheet metal was punched using an elastomeric punch then re-shaped by a rigid steel punch, in order to improve the accuracy of dimensionally-shaped drawpiece. FEM numerical simulations were performed for flexible punch forming made of polyurethane elastomer with different hardness (50, 70, 85 and 90 Sh A). Selection of the hardness was treated the fact that with increasing the elastomer hardness the force, which is required to deform increases and reduces the life of the elastic punch. These reasons, it would be more advantageous use of elastomer with lower hardness. The significant effect of the hardness of flexible tools for drawing process. The results correctness of numerical simulations has been confirmed in subsequent industrial experiment. The experiment was performed only for the case of forming the rigid tools and forming an elastomeric punch having a hardness of 90 Sh A and then re-shaped by a rigid tools. In addition, schedules and strain values were subjected to comparative analysis in selected areas of drawpiece shaped by elastomer tool with the highest hardness. Comparison of replacement plastic strain which was calculated finite element method FEM and designated on the real drawpiece using photogrammetric system Argus v.6.3. In conclusion the difficulties as well as the advantages and disadvantages of both methods for determining the deformation on sheet metal parts.

2. The numerical model of drawing process

Numerical calculations were performed Finite Element Method using commercial software MARC / Mentat 2010, which is often used to analyze nonlinear and contact issues. In order to FEM calculation two numerical models were built. First for the case of rigid drawing tools (Fig.1a). Geometric deformable surface models of tools (punch, die and blank-holder) were made in 3D CAD. Then, in the file format * .igs imported into the MARC/Mentat and positioned relative to each other. The second numerical model (Fig. 1b) was built for the case of drawing an elastomeric punch with a specially designed shape. Other tools (die, blank-holder) were the same as in the first model. For the discretization flexible stamp (Fig. 1b)

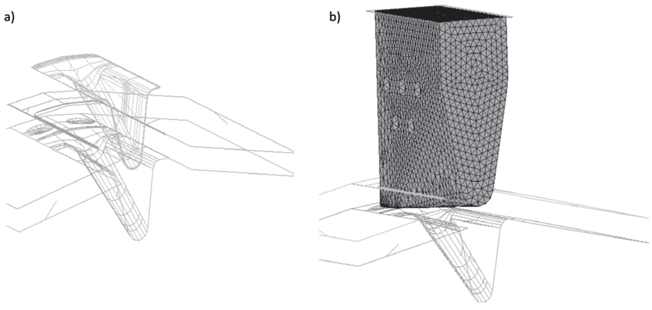

Fig. 1. Model of die: a) with rigid tools, b) with elastomeric tools

was used approx. 30 000 three-dimensional tetrahedral elements tetra 157 type 4 [4]. While the discretization of the deformable sheet metal model used 4-node bilinear elements quad 4 type 75 [4] with a formula which takes into account the effects of transverse shear [5], improving the behavior of the elements of the coating during bending. The authors of [6] presented the results of the influence of the type of finite elements on the forces shaping the size and distribution of strain, which show that, compared with the elements of the type of solid, shell-type elements give results more compatible with the experiment. The use of this type of mesh coating drawing process models allows to obtain well accuracy of the calculations and savings as shorter calculation time [7]. The numerical model of the deformable sheet metal cutaway (Fig. 2) consisted of 5695 elements.

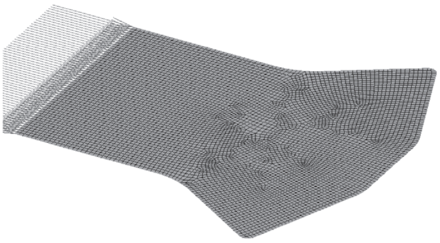

Fig. 2. Sheet metal cutaway model used for drawpiece together with the finite element mesh and the condition of continuity resulting from the assumption of symmetry of the planar model

To describe the mechanical properties of the shaped sheet metal material, used elastic-plastic constitutive material model with nonlinear strain hardening of the form:

$$\sigma = \begin{cases} E\cdot\varepsilon & (\varepsilon < \sigma_0 / E) \\ K\cdot\varepsilon^n & (\varepsilon \geq \sigma_0 / E) \end{cases} \qquad (1)$$

where: E - Young's modulus, ε - strain, σ_0- yield stress, K - strain hardening coefficient, n - strain hardening exponent.

Mechanical properties of drawpiece material was experimentally determined in the attempt uniaxial tensile test with extensiometer measurement both the length and width of the sample. The attempts are uniaxial tensile was carried out on a Zwick / Roell Z030 testing machine. Experimentally determined parameters tested mechanical and plastic sheets made of Inconel 625 with a thickness of 0.6 mm are shown in Table 1. Due to the small value of the coefficient of planar anisotropy for tested sheet metal Δr = -0.038 (Tab. 1), all calculations are performed using an isotropic yield condition Huber-Mises. The numerical calculations used the Prandl-Reuss'es plastic flow rule and the implicit scheme of integration of differential equations at the time of the Newton-Raphson method. To describe the kinetics of strain used an updated material Lagrangian description of the multiplicative decomposition of the deformation gradient tensor on the section of the plastic and elastic. Coulomb friction model was used for describe the phenomenon of friction between the tool and the sheet metal shaped The value of friction coefficient between the sheet metal and steel tools assumed μ = 0.1, and between the sheet metal and the elastomeric punch μ = 0.25 [8, 9].

2.1 Analysis of the process shaped drawpiece rigid tools

Numerical modeling of forming process using steel tools was designed to see if it is possible to obtain a predetermined shape drawpiece in one operation. This would reduce production costs and time associated with retooling the machine and performing additional operations. Further stages of the process drawing steel tools are shown in Figures 3 and a ÷ d. In the initial phase of shaping sheet metal by using a rigid stamp process runs correctly (Fig. 3a). However, as a rigid tool going into in the middle of the drawpiece, sheet metal loses its stability (Fig.3b), bulge out (Fig. 3c), which in turn results in an unacceptable product wrinkling (Fig. 3d).

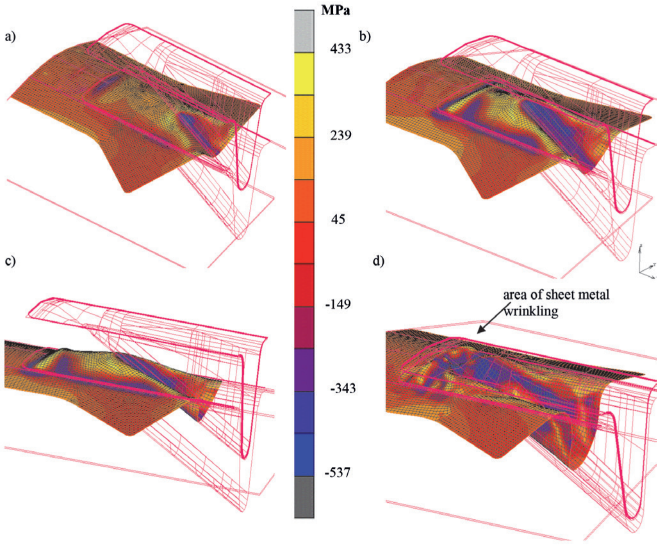

Fig. 3. Drawing process using rigid tools. Process stage: a) 30%, b) 50%, c) 75%, d) 90% (mean normal stress distribution)

Simulations were performed for parts which were shape

TABLE 1

Mechanical and plasticity properties of test material

E [GPa]	R_e [MPa]	R_m [MPa]	A_{80} [%]	Strain hardening parameters		The coefficient of anisotropy	
				n	K [MPa]	Normal	Planar
218	546	945	46	0,259	1649	$\bar{r} = 0{,}502$	$\Delta r = -0{,}038$

rigid tools, among others, for different values of force and friction conditions blank-holder. However, the change of these parameters is not allowed to eliminate the phenomenon of wrinkling a sheet metal, which always occurred in the central area of the drawpiece.

The subsequent experimental industrial experiments performed for this case forming (rigid tools in one operation) confirmed the simulation results. For experimental drawpiece in a central area (Fig. 4) showing clearly the corrugations of the sheet.

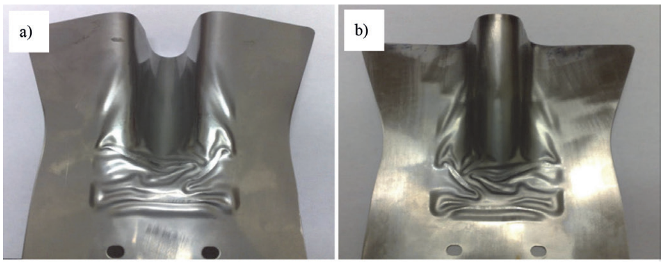

Fig. 4. Experimental, real drawpiece formed in one operation rigid tools: a) view from above, b) view from below

2.2 Analysis of the process shaped drawpiece elastomeric tools

Due to the lack of capacity to perform drawpiece in one operation rigid shaping tools already at the design of the technological process, changes were made in the design of tooling. Additionally introduced drawpiece shaping operation elastomeric punch, and then re-shape using rigid tools. To eliminate wrinkles drawpiece, elastomeric punch has been designed to provide the downforce sheet metal to the die in the critical area from the very beginning of the process. However, not only properly designed shape of the elastomeric punch can get the correct aviation product, are also important mechanical properties of the elastomer tools, which are responsible for its life, wear and drawing process. For this reason a numerical simulation was performed for punch made of polyurethane elastomers with different hardness (50, 70, 85 and 90 Sh A). The influence of the elastomer hardness is the forming tested drawpiece process. To describe the mechanical properties of the elastomers used two-parameter Mooney-Rivlin's model [10]. The numerical values of the material constants C_{10} and C_{01} for elastomers with tested hardness are shown in Table 2.

TABLE 2

The values of the material constants in the Mooney-Rivlin model [9,11]

Hardness Shore A	C_{10}	C_{01}
50	0,302	0,076
70	0,736	0,184
85	1,715	0,428
90	2,824	0,706

After the analysis, the four test hardness punch can be seen that the smaller the hardness of punch material, the greater is the deformation of the sheet metal drawpiece process. Figure 5 shows the deformation of punch with a hardness of 85 Sh A and its greatest load (Fig. 5a) and the sheet metal after the complete unloading of the visible forming height H_{max} (Fig. 5b).

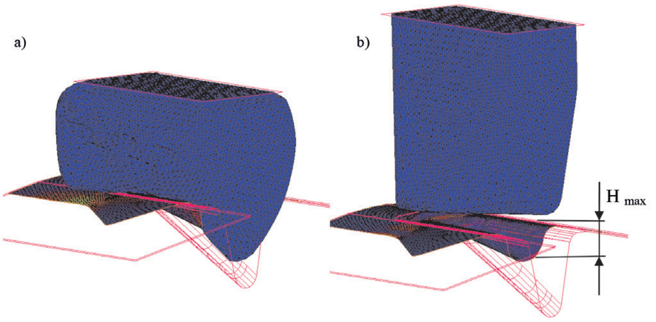

Fig. 5. Sample deformation of the drawing punch 85 Sh A hard: a) punch under full load, b) sheet metal after punch release (H_{max}– maximum depth of forming)

The research showed that the hardness of the punch material affects the degree of shaped drawpiece and the maximum depth of forming - H_{max}. A punch with the lowest hardness (50 Sh A), the degree of shaping sheet metal is minimal, and Hmax is only 14.5mm. Comparing these same characteristics obtained for the punch with a higher hardness (70 Sh A), the maximum depth of forming increased to 18.7 mm. For an elastomeric punch having a hardness of 85 Sh A to provide H_{max} equal 28.45mm. Despite the increase in depth of the forming sheet metal for these three cases, a single wrinkle drawpiece was observed, which means that the downforce in the area where corrugation sheet metal occurred was not sufficient. Thus, for the elastomer punch with a hardness of 50, 70 and 85 Sh A is not eliminated negative wrinkling sheet metal. For this reason in a further simulation punch material hardness is increased to 90 Sh A. This resulted in a value equal to the maximum depth of the forming equal 35.2 mm. Furthermore, on the shaped drapiece using an elastomeric punch with hardness of 90 Sh A wrinkles were not observed (Fig. 6a). From the simulations show that only the use of an elastomeric punch having a hardness 90 Sh A allows proper shaping drawpiece without wrinkles. This was confirmed by subsequent industrial experiments, which uses an elastomeric punch having a hardness 90 Sh A (Fig. 6b).

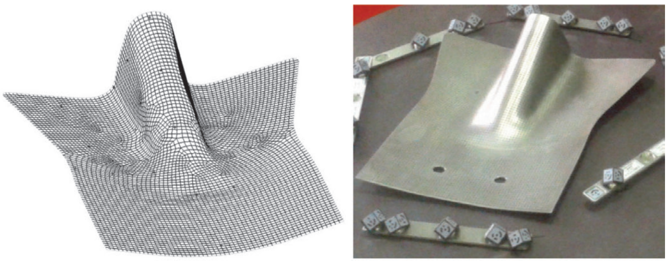

Fig. 6. View of drawpiece shaped elastomeric punch with hardness 90 Sh A a) FEM model b) industrial experiment

3. Analysis of strain on drawpiece

In order to more detailed comparison of the results with the FEM modeling of the experiment, it performed a comparative analysis of equivalent strain in specific areas drawpiece modeled FEM and the experimental. Comparative research were carried out for drawpiece shaped elastomeric punch having a hardness of 90 Sh A and re-shaped rigid tools. In case FEM simulation of replacement equivalent plastic strain values on each node elements can be directly identified as one of the typical results of calculations. For the experimental drawpiece to determine the equivalent strain in selected areas of the drawpiece used photogrammetric system Argus v.6.3, the company GOM. The photogrammetry method based on a comparison of the subject image before and after deformation. On cutaway sheet metal was applied electrolytically grid of measurement points of the same, known distance of the initial. During drawing operations, regularly applied points were moved. Thus, after shaping drawpiece, based on photogrammetry camera automatically locates the points and calculates the coordinates of each of them in 3D. By comparing the amount of movement of specific points on drawpiece, it is possible to analyze the amounts of strain in this section [12]. Measurement of strain by photogrammetric system is carried out using a camera recording points on drawpiece, rotary table, on which is placed the object with the coded points, light sources and computer software Argus v.6.3 (Fig. 7). On aviation drawpiece defined 15 measurement points located in different areas of variable curvature (Fig. 8). The selected points were read strain values calculated by FEM system in MARC / Mentat, and calculated using the optical system Argus.

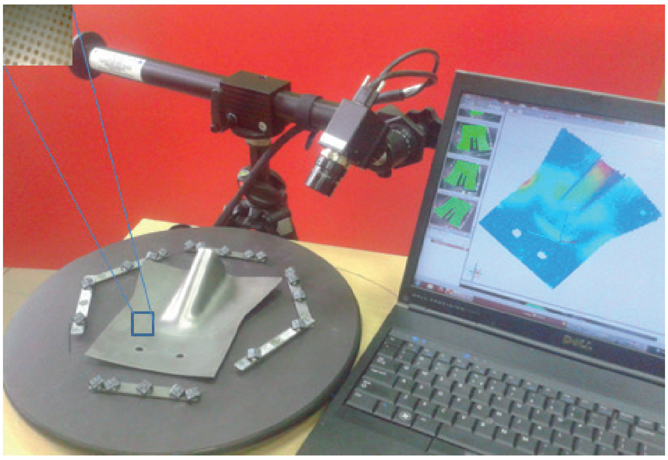

Fig. 7. Position of deformation measuring by optical method Argus

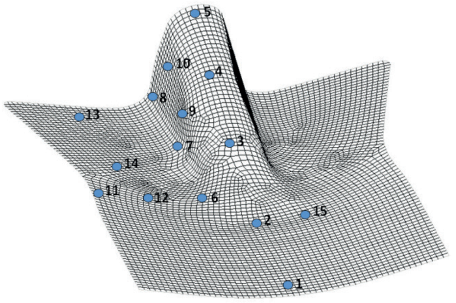

Fig. 8. Points on drawpiece, which set out the extent of strain

The numerical values of equivalent strain designated Argus and FEM methods for drawpiece in selected fifteen points are shown in Table 3. Plus and minus values of the equivalent strain between the FEM methods Argus indicate that it cannot determine which method provides higher values of strain. Comparing reading method photogrammetric Argus, larger values of equivalent strain was observed at points 1, 3 ÷ 5, 7, 10, 12÷ 14. In other six points, FEM shows higher values of strain. Based on the data presented in Table 3, were plotted, which graphically illustrates the distribution of strain of fifteen identified measurement points, of the applied two methods, ie. MES and Argus (Fig. 9). Analyzing the results of the two methods should be noted that in areas of flat moldings (points 1, 2, 6, 11 ÷ 15) the numerical values of both deformation designated Argus method and FEM are very close. The biggest differences are in the points lying on the curvatures of sheet metal (points 3 to 5 and 7 to 10). Given the method of measuring equivalent strain in a photogrammetric method Argus can be concluded that for the determination of the strain curvatures sheet metal, this method is less accurate than in the areas of flat sheet metal. For this reason the deformation in the areas of curvature calculated by FEM seem to be more reliable.

TABLE 3

The values of replacement deformation in the selected measurement points by the Argus and FEM system

Number of measuring point on drawpiece	The value of the equivalent strain		The difference between the Argus and FEM
	Argus	MES	
1	0,0272	0,0115	0,0157
2	0,0987	0,114	-0,0153
3	0,0735	0,0366	0,0369
4	0,099	0,0431	0,0559
5	0,1043	0,0685	0,0358
6	0,0466	0,044	-0,0026
7	0,0815	0,0623	0,0192
8	0,0386	0,0587	-0,0201
9	0,0311	0,0486	-0,0175
10	0,0728	0,0359	0,0369
11	0,1394	0,1464	-0,0070
12	0,0491	0,0439	0,0052
13	0,0045	0,0012	0,0033
14	0,0646	0,0466	0,0180
15	0,0931	0,1037	-0,0106

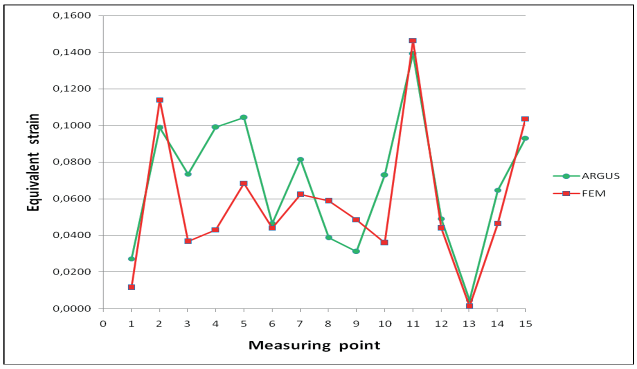

Fig. 9. The distribution of strain at the measuring points drawpiece designated Argus and FEM method

4. Conclusion

1. Based on the results of numerical simulations can be concluded that the correct aviation drawing part directly affect the material properties of the elastomeric punch. With the decrease of the hardness of deformable material punch its deformation increases, with a simultaneous decrease of the maximum depth of forming drawpiece.
2. Appropriate selection the hardness of the elastic punch can eliminate the disadvantage of the corrugation sheet metal. Numerical simulations have shown that only the drawing punch elastomer with a hardness of 90 Sh A allows for drawpiece without defects as wrinkle.
3. Comparing the results of measuring the deformation by MES and Argus can be seen that in flat areas on drawpiece equivalent strain values are close substitute. Larger divergences are present at the measuring points located in areas of high curvature.
4. While analyzing the strain cannot determine which method is more effective and accurate. On the discrepancy of results may indeed affect a lot of factors. The optical method Argus measurement uncertainty can be caused by, inter alia, type of camera used, inadequate light source or poor quality measuring net. On the other hand the results of FEM calculations depend on the correctness of the defined mathematical models that describe the simulated process. However, in the case under examination can be concluded that the measurement points lying on the curvatures of equivalent strain calculated FEM are more reliable than those determined using photogrammetric.

REFERENCES

[1] S. Erbel, K. Kuczyński, Z. Marciniak, Obróbka plastyczna, PWN Warszawa 1981 [in Polish].

[2] Z. Gronostajski, Badania stosowane w zaawansowanych procesach kształtowania plastycznego, Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław 2003 [in Polish].

[3] M. Ramezani, Z. M. Ripin, Rubber-pad forming processes: Technology and applications, Woodhead Publishing 2012.

[4] MSC Software, MSC.Marc Volume B: Element Library (2010).

[5] MSC Software, MSC.Marc Volume A: Theory and User Information (2010).

[6] F. Feresthteh-Saniee, M. H. Montazeran, J. Mater. Process. Tech. **140,** 555-561 (2003).

[7] A. Żmudzki, A. Śledzińska, M. Pietrzyk, H. Woźnika, A. Plewiński, T. Drenger, Obróbka Plastyczna Metali **16**, 50-62 (2005) [in Polish].

[8] E.L. Deladi. Static friction in rubber-metal contacts with application to rubber pad forming processes. PhD thesis, Print Partners IPSKAMP, The Netherlands 2006.

[9] M. Ramezani, Z. M. Ripin, R. Ahmad, J. Mater. Process. Tech. **209,** 4925–4934 (2009).

[10] MSC Software, Nonlinear Finite Element Analysis of Elastomers (2010).

[11] M. Money, Journal of Applied Physics **11,** 582 (1940).

[12] W. Frącz, F. Stachowicz, T. Pieja, Acta Metallurgica Slovaca **19** ,1, 51-59 (2013).

[13] J. Slota, M. Jurcisin, I. Gajdos, E. Spisak, Acta mechanica et automatica **7**, 117-123 (2013).

[14] J. Sińczak, Podstawy procesów przeróbki plastycznej, Wydawnictwo Naukowe AKAPIT, Kraków 2001 [in Polish].

[15] A. Del Prete, G. Papadia, B. Manisi, Key Engineering Materials **473**, 637-644 (2011).

[16] M. Schneider, H. Friebe, K. Galanulis, Validation and optimization of numerical simulations by optical measurement of tools and parts, International Deep Drawing Research Group, 327-332 (2008).

[17] MSC Software, MSC.Marc Volume B: Element Library (2010).

[18] ARGUS USER GUIDE, http://www.gom.com/ (2011).

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