Parameterized Optimization of Superplastic Aluminum Alloys by Gasostatic Forming: Experimental Insights and FEM Analysis

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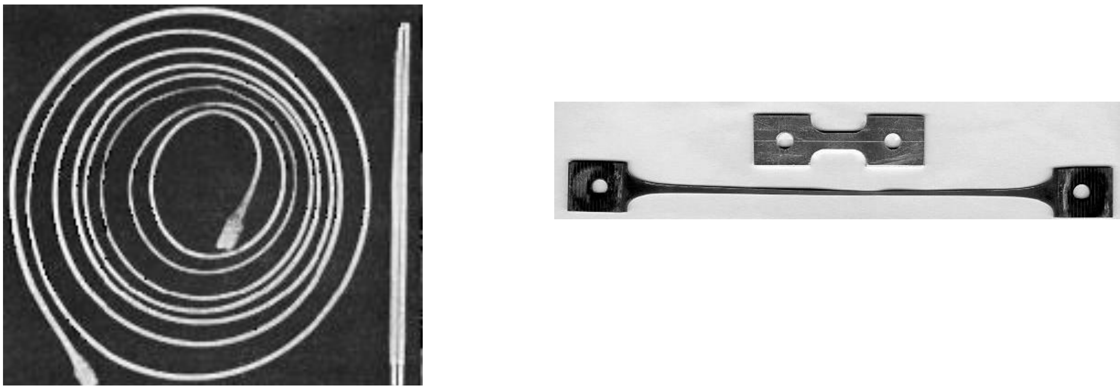
ABSTRACT: This study consists on a static structural analysis of superplasticity and a related study of superplastic deformation, with applications to the gasostatic forming of aluminium-based alloy raw materials. The extension of the project involved applying the finite element method for parameterized optimization, with the aim of demonstrating quasi-uniform thickness in the cross-section. To highlight the achievements of the addressed objectives, Design of Experiments (DOE) and Response Surface (RS) optimization methods were used, along with correlation and dependence graphs of input parameters versus output parameters. Correlating the data, based on Local Sensitivity Curves, in different variants, severall optimization methods such as Screening, Genetic Algorithm (GA), Kriging, and Multiple Objectives Genetic Algorithm (MOGA) were used. The authors has proposed this approach, to demonstrate the quality of superplastic forming: there was included the quasi-uniform distribution of the wall thickness of the deformed part and the fidelity of the loading process, i.e. air pressure, defined as a control function by the specially created numerical code (C and Matlab-mlx). The experimental data confirmed the optimization results, i.e., the quasi-uniform thickness distribution measured in the cross-section, thus validating the uniformity of the part wall thickness variation profile as a parameter and optimization objective. Using the resources, such as tests and research, and based on sample shape, dimensions and operation stability, information data sets collected from sheets of two different aluminium-based alloys: SUPRAL 100 (also known as Aluminum 2004) and FORMALL (also known by other commercial names AL-7475 or 5083-SPF), the blanks having different thicknesses, and the deformation occurred at different temperatures, important results, has been revealed in the next artocles' chapter.

1. INTRODUCTION

Superplasticity is the name given to the ability of a material to sustain extremely large deformations at low yield stresses at a temperature around half its melting point. A major advantage of superplastic deformation consists of the uniform, cross-sectional deformation, hence the quasi-constant wall thickness of deformed parts. Superplastic deformation, at a temperature above $0.4xT_{melt}$ (T_{melt} being the melting temperature of the material), with a constant strain rate (on the order of 0.001 [s^{-1}]), with the characteristic size of the structure below 10^{-3} [mm] eliminates these drawbacks, resulting in quasi-constant deformation in all directions. Research carried out worldwide to date has demonstrated a relationship between the technological parameters of gasostatic forming (gas pressure, deformation rate, temperature of the working environment), the initial dimensions of the blank, the thinning factor and the shape factor of the formed part. Superplasticity is therefore a metallurgical phenomenon, implicitly recognised by science since the 1920s but not exploited before 1960, when this therm was defined as the property of some metallic materials, generally alloys and, very rarely some pure metals, to be deformed for a long time, and uniformly, without the appearance of local deformation, the deformation depending on the deformation rate, deformation temperature and characteristic grain size of the structure, [1].

Historically, in 1934 C.E. Pearson, [2], [3], deformed a Bi-Sn two-phase eutectic alloy by almost 2000 % in tensile, and the image, representing this spiral wire, became emblematic for researchers in the field, [4].



a)- Bi-Sn alloy b)- Zn-22%Al alloy

Fig. 1- Superplastic deformation by simple tension, [2], [4]

The term "superplasticity" was introduced into scientific circles by Bocivar and Sviderskaia [5], [6], [7] in 1945, when they discovered the superplastic behaviour of Zn + 22% Al alloy (eutectoid alloy, having previously achieved an ultrafine structure), and later the term was adopted by researchers all over the world. The Zn + 22% Al eutectoid alloy then became, material for the study of superplasticity. Since 1960 the phenomenon has been studied for its promising practical applications and it has been established that the main conditions for the occurrence of superplasticity are: grain sizes to be in the range 1 ÷ 10[μm], low strain rates in the range $10^{-4} \div 10^{-1}$ [s^{-1}], a relatively high temperature (>0.5 T_{melt}, where T_{melt} is the melting temperature of the alloy [K]), with low values of strain forces. The first tests demonstrating the existence of this property in Zn + 22 % Al alloy were made in tensile and extrusion, so that in 1964 Backofen, [6], tried and succeeded, with collaborators at the Massachusetts Institute of Technology, to form, using air as a working agent, hollow parts with a rather complex configuration. Sheets of sheet metal with thickness s = 0.76 [mm] were used in a mould of diameter 100 [mm], air pressure 0.1 to 0.2 [N/mm^2].

During the same period D. S. Fields studied the same eutectoid Zn-A1 alloy (78%Zn-22%A1) stressed in uniaxial tensile at working temperature 271 [°C], and the results were correlated with the thickness distribution in "thermoformed" parts, [8]. Contrary to what has been published in the literature, up to Fields, strain was found to be an important variable. Depending on the strain rate and sheet temper, this alloy exhibits both strain hardening and strain softening. Fields used the same technological process, then called thermoforming, to make the computer casings of the time, stamping sheet metal blanks, a process later patented by IBM.

Superplasticity is used to form complex objects, by the application of gas pressure or with a tool, and often with the help of dies. Aluminum and titanium alloys parts are often superplastically manufactured and intended for use in the aerospace industry. More recently, superplasticity has been used to form parts for automotive applications. For application in the automotive industry, aluminum alloys are formed at a faster rate (compared to aerospace applications) to support high volume production, [4].

1.1 Theoretical and practical considerations on numerical analysis of superplasticity

In order to simulate mathematically, and mechanically, the pressure profile, thickness distribution and forming time in the superplastic forming process, numerous constitutive equations have been proposed to characterize the yield stress response of the material.

Numerical analysis of superplasticity and superplastic deformation is an interdisciplinary field of materials engineering, mechanics and computer science, which focuses on the study of material behaviour under extreme and sustained deformation conditions. In this article, we explore, as applicable as possible, key aspects of numerical analysis of superplasticity and superplastic deformation, highlighting significant contributions and future research directions in this area:

- Experimental Methods vs. Numerical Analysis: Numerical analysis of superplasticity complements experimental research by simulating the behaviour of materials under controlled conditions. This includes the use of simulation methods such as finite element, discrete particle or grid-based methods, which allow researchers to study material behaviour in detail and perform parametric analysis.
- Mechanical Modelling: A key aspect of numerical analysis of superplasticity is the development and the validation of mechanical models that describe the behaviour of the material under superplastic deformation conditions. These models take into account aspects such as strain rates, temperature, material texture and the influence of microstructure
- Materials Microstructure-Mechanical Properties Interaction: Since superplastic behaviour depends fundamentally on the microstructure of the material, numerical analysis addresses the complex relationship between microstructure and mechanical properties of the material. Simulations can identify key issues such as deformation limitations and failure zone.
- Superplastic Material Design: Numerical analysis of superplasticity plays a vital role in the development of superplastic materials, which may have important applications in industry. Research in this area can help to optimise the chemical composition and manufacturing processes for more efficient and economical superplastic materials.
- Advanced Manufacturing Technologies: Numerical simulations can be used to guide manufacturing technologies, such as superplastic forming, to produce components with complex geometries and superior performance.

With advanced approaches in numerical analysis, significant breakthroughs in superplasticity are expected in the near future, bringing benefits to a variety of industries.

In order to justify the above statements, we will refer to a few authors and representative works, in the field of numerical analysis of superplasticity and superplastic deformation, allowing us to mention a small part of the established authors and their works, in the stated field.

Emeritus Professor of Metallurgy at Southampton University, T. G. Langdon has contributed significantly to the comprehensive presentation and numerical analysis of superplasticity of metallic, non-metallic and alloy materials, [9]-[16]. Important contributions in the numerical analysis of superplasticity, with emphasis on mechanical models and simulations for superplastic materials, have been made by M. Suéry [20], [21]. S. Mishra, [22]-[27] conducted studies and research in the areas of: mechanical behavior of micro and nanocrystalline Ti-6Al-4V alloys in the temperature range 250-675 [°C]. Compared to the microcrystalline state, the material in the nanocrystalline state had higher strength up to 400 [°C] and comparable strength above this temperature. Ductility was significantly higher for the nanocrystalline state above 500 [°C], including superplasticity above 600 [°C]. Transmission electron microscopy used, showed a considerable increase in grain size and dislocation activity during superplastic deformation. A comparison of the superplastic data in the nanocrystalline and microcrystalline cases respectively showed interesting differences in the kinetics of superplastic deformation.

1.2 Deformation sensitivity to the strain rate, (m)

The value of the strain rate exponent (often called senzitivity), m, has a strong influence on the ductility of superplastic materials. In general, large values of the coefficient m indicate a pronounced elongation to failure, but this is not a principle. For example, the maximum elongation of an Al-Cu eutectic alloy does not coincide with the maximum measured strain rate sensitivity (optimum strain rate), [9]-[16].

It has been experimentally shown that the elongation to failure depends on the value of m more than the small deformation and that the microstructural evolution during deformation can have a pronounced effect on the strain rate sensitivity. The tensile elongation at break of superplastics is composed of the uniform strain and that due to thinning developed during deformation, [17]-[22].

If the material is subject to a yield stress law:

$$\dot{\varepsilon} = k' \cdot \sigma^{\frac{1}{m}} \quad \textbf{(1)}$$

The part is loaded at:

$$p = \sigma \cdot a \quad \textbf{(2)}$$

where " **a**" is the cross-sectional area and the strain rate is:

$$\dot{\varepsilon} = -\frac{da}{dt} \cdot \frac{1}{a} \quad \textbf{(3)}$$

hence:

$$k' \cdot p^{\frac{1}{m}} = -a^{\left(\frac{1}{m}-1\right)} \cdot \frac{da}{dt} \quad \textbf{(4)}$$

It can be seen from equation (4) that as the exponent m increases, the cross-sectional change ratio is dependent on the size of the cross-sectional area, and any thinning of the specimen, necking for example, will develop at low velocity. If after a small increment of deformation the cross-sectional area is a, and that of the gated area is ($\beta \cdot a$, with $\beta < 1$), then the rearranged and integrated equation (4) becomes:

$$\int_{t}^{t+\delta t} k' \cdot p^{\frac{1}{m}} \cdot dt = -\int_{a_o}^{a} a^{\left(\frac{1}{m}-1\right)} \cdot da \qquad (5)$$

and:

$$\int_{t}^{t+\delta t} k' \cdot p^{\frac{1}{m}} \cdot dt = -\int_{\alpha a_o}^{\beta a} a^{\left(\frac{1}{m}-1\right)} \cdot da \qquad (6)$$

Eliminating **k'**also **p** from equations (5) and (6) gives:

$$a = \left(\frac{1-\alpha^{\frac{1}{m}}}{1-\beta^{\frac{1}{m}}} \right)^{m} \cdot a_o \qquad (7)$$

The uniform deformation is given by:

$$\varepsilon_u = -\ln\left(\frac{a}{a_0}\right) \qquad (8)$$

and the maximum elongation to failure, can be obtained by substituting β = 0:

$$\varepsilon_u = -m \cdot \ln\left(1-\alpha^{\frac{1}{m}}\right) \qquad (9)$$

If the initial discontinuity is small, then the elongation to failure is strongly dependent on the coefficient m. The variation of elongation at break with respect to m is plotted in experimental diagrams and graphs, [18].

It can be seen from these representations that for many superplastic alloys the elongations obtained are towards the lower limits prescribed by equation (9).

The uniformity of plastic flow, studied for a Zn-22Al alloy by plotting cylindrical segments on the specimen, is illustrated in [11]:

In the analysis of plastic yield stress presented in the paper, the material is assumed to be structurally stable and the value of m is constant. Experimental data show that the sensitivity to strain rate can vary significantly during superplastic flow. The actual variation of m with respect to strain depends on the complexity of the relationships between strain rate, temperature, grain growth and material curling or softening. For example, in Supral 200 alloy, grain growth during deformation not only causes a reduction in the maximum value of strain rate sensitivity with increasing deformation, but also leads to lower velocities at which this maximum is achieved.

If the deformation velocity is constant and higher than the velocity at which m is initially maximum, then the sensitivity will continuously decrease with increasing deformation.

If the strain rate is initially lower than the strain rate at the maximum value of the coefficient m, then the sensitivity increases in the initial stage of superplastic flow, reaches the maximum and then decreases. The actual magnitude of the increase in strain rate sensitivity depends on the relationship between microstructural instability at strain temperature and strain rate.

The maximum tensile elongation of superplastic materials is of negligible relevance when comparing the actual deformations they should reach during forming operations, but nevertheless the elongation is a great guide to the superplastic potential of the material.

1.3 Cavitation influence

Even though superplastic materials are characterized by pronounced deformations, it is known, and sufficiently well documented theoretically, also very well represented experimentally, the view, that during superplastic deformation, the metallurgical phenomenon called cavitation can occur. The alloys in which cavitation, [3], [4], [11], [12]-[14], [25]-[27], has been demonstrated are those based on Al, Cu, Fe, Pb, Ag, Ti, Zn. Professor Langdon and his research group were among the first to recognize the importance of internal, concomitant cavitation in limiting ductility [11], and it is now accepted that most superplastics yield through the process of internal nucleation, growth and interconnection of voids.

Cavities growth, developed as a metallurgical phenomenon, generated in metallic materials, especially alloys, a phenomenon that creates creep conditions at elevated temperatures has been frequently used to study cavity development in materials exhibiting superplasticity [28], [29]. Cavity growth mechanisms can be classified into two broad categories: diffusional cavity growth mechanisms and mechanisms governed by power-law constitutive equations. In superplastic materials, the cavity growth mechanism is the diffusional one developed under the assumption that surface diffusion is fast enough for vacancies and cavities to maintain their equilibrium shape. The (diffusional) growth of cavities occurs by stress-directed diffusion at the vacancy boundary from a region of the grain boundary plane adjacent to the cavity [28], [30]-[32]. A detailed analysis by Beert and Speight [33] presents these mechanisms, theoretically, mathematically modelled in detail.

The growth of cavities in the power-law regime, through the application of basic deformation laws, is enhanced by the plastic deformation of the material surrounding a cavity. The power-law cavity growth rate is defined for superplastic materials, which obviously exhibit fundamental characteristics such as: fine grain size after deformation which frequently reveals the presence of cavities larger than grain size.

The third mechanism, recognized by science, revealed by experiments and industrial applications, called the superplastic diffusional growth model, was developed for the volume growth of cavities intersecting more than one grain boundary [2]. A complete analysis of cavity growth in fine-grained superplastics must include all three of the above mechanisms.

In general, cavities nucleate at the grain boundary and their successive growth and coalescence invariably leads to breakage, thus being, from a practical point of view, a phenomenon with effects contrary to the conservation of mechanical properties required of superplastically deformed parts, [28], [29]. It is evident that, in general, cavitation occurs and develops from pre-existing lattice defects that typically form during the thermomechanical processes required for the development of the superplastic microstructure.

An important prerequisite for cavitation during superplastic yield is the presence of local internal stretching stresses. Under homogeneous compressive conditions, cavitations are not observed, and those produced during superplastic yield in tension are cancelled during successive compressive flow.

In order to control cavitations, it is necessary to know and understand how both microstructure and deformation parameters influence and determine the occurrence of cavitations, i.e. their magnitude.

In most studies on cavitations, particular emphasis has been placed on the variation of the total volume fraction of cavities with respect to deformation at different strain rates and temperatures, [30] - [33]. The following relation for calculating the cavity volume fraction, C_v:

$$\mathbf{C_v = \sum N_{vi} \cdot V_i} \qquad \textbf{(10)}$$

where:

- $\mathbf{N_{vi}}$ - number of cavities per unit volume;
- $\mathbf{V_i}$ - volume studied.

The number of lattice voids of a given size is dependent on the number of pre-existing voids and the nucleation velocity, while the volume of a void is mainly controlled by the growth velocity. Even though during the later stages of deformation, when cavitations are high (about 10%), the growth process is affected by the spatial distribution of voids in the coalescent mass of voids, so that the growth process becomes partly dependent on the nucleation process, it is obvious that the variation of void volume fraction as a function of deformation, strain rate and temperature is not a simple one. The effect of changing strain rate and temperature at which deformation occurs can be complex and complicated by other factors such as grain growth and/or changing phase ratios.

The morphology of the cavities formed during superplastic yield is different from one material to another, and even in the same material deformed at different deformation rates, there are frequently notable differences, [33].

2) Experiments performing

2.1 Materials and their superplastic behaviour characteristics

Four aluminium alloys samples in the experimental determinations of this study, were used:

- SUPRAL 100 alloy - thickness 0.8 [mm];
- FORMALL 545 alloy - thickness 1.2 [mm];
- SUPRAL 100 alloy - thickness 1,29 [mm];
- Alloy ALCOA 7475 T-761 - thickness 2,0 [mm]

The semi-finished products were delivered under the necessary conditions of superplastic deformation, by a company specialized in superplastic deformation processing (forming or diffusion bonding) of titanium and aluminium alloys.

The "Aluminum 2004" alloy i.e. SUPRAL 100, used in this study, is a dynamically recrystallized Al and Cu based alloy of category 2xxx according to the British Standards Institution (BS) and American Aluminum Association (AA) standard.

Unlike Al-Cu-Zr alloys, Al-Zn-Mg-Cr alloys such as FORMALL 545, Al-7475, or Al-7075, for example, require a much more complex thermo-mechanical treatment to obtain the ultrafine grain structure.

After the semi-hot rolling follows a sudden heating to 500 [^oC] to achieve the quasi-completely recrystallised structure. The very fine dispersion of the large precipitates during rapid heating are the prerequisites for the formation of a very large number of recrystallisation nuclei, resulting in an ultrafine granular structure. Grain growth is limited during heating and superplastic deformation by fine insoluble Cr particles.

The characteristics of this alloys are:

Chemical and mechanical characteristics	**The “Aluminum 2004” alloy - SUPRAL 100**	**The "5083-SPF" alloy- Trade name Formall 545), [5],**
Chemical composition	%Cu-6.0; %Mg-1.0; %Zn-0.5; balance Al (finely dispersed impurities of (Fe,Mn); 3SiAl12 , Al7Cu2Fe, ZrAl3 and Mg2Si)	Cu-0,1 %; Mn-0,7; Si-0,4; Cr-0,15;Mg-4,45 %; Zn-0,25 %; balance Al
The optimum range of superplastic deformation temperature	400-480 [^{o}C]	400-550 [^{o}C]
The optimum range of strain rate	0.005-0.01 [s^{-1}]	0.0005-0.06 [s^{-1}]
Strain-rate exponent (m): 0,7	0.7	0.5
Yield stress resistance	220 [MPa]	125 [MPa];
Failure strength	300 [MPa]	200 [MPa]
Elongation to failure:	up to 1800 %	up to 1800 %
Grain size range	3- 6x10^{-3} [mm]	0.5- 3x10^{-3} [mm]

2.2 Samples

The specimens used for the experimental determinations were cut out, from sheet metal with:

- - thicknesses: 0.8; 1.2; 1.29 and 2.0 [mm], respectively
- - sample diameter 44.5 [mm] and 51 [mm], respectively

2.3 Experimental installation components

The experimental installation (Fig. 2) was designed to carry out the experimental trials and includes the following components:

- - Horizontal electric oven
- - Six-channel tensile bridge;
- - Inductive displacement transducer 100 [mm];
- - Proportional precision valve, is an air preparation and filtration unit. The proportional valve (or, proportional regulator) of pressure, converts an analog electrical signal (voltage or current) into a pressure signal, compensating also for interference with disturbing magnitudes.
- - The acquisition board has 16 multiplexed channels, unipolar or bipolar voltages, scanning frequency controlled by program or by the converter's internal oscillator (1 MHz). The converter works by the successive approximation method, with 12-bit resolution;
- - The source code, developed in C language specifically for this study and named "SUPERPLAST", acquires signals from the stroke transducer, the pressure transducer and controls the proportional pneumatic valve;
- Computing system;

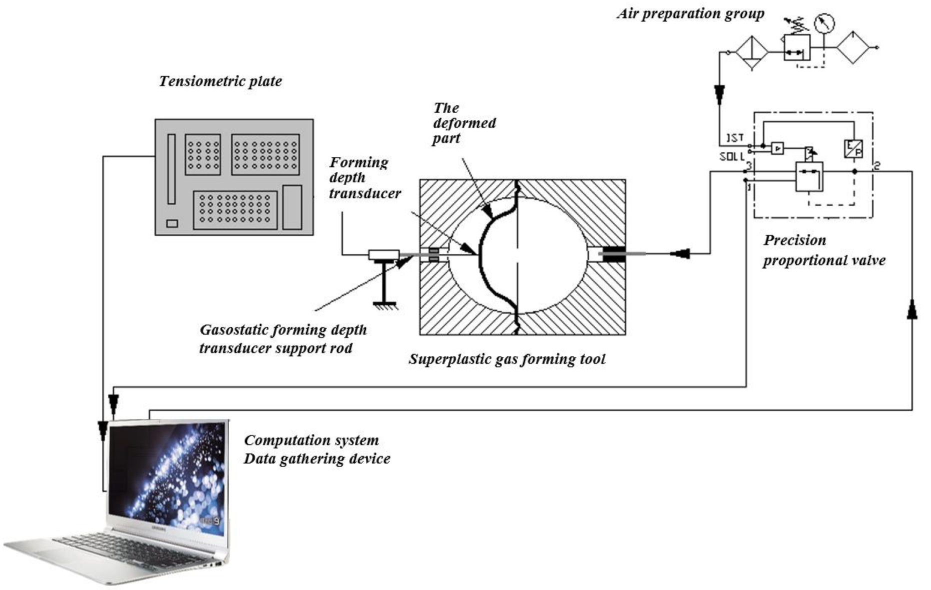


Fig. 2– Schematic diagram of the experimental facility

In fig. 2, the components of the experimental installation are shown in principle, in an indicative sketch, which creates an automatic command and control system that regulates the air pressure in the mould cavity, pressure exerted on the specimen, according to the speed of movement of the centre of the piece (hemisphere pole).

2.4 The gasostatic forming die

The forming die, fig. 3, is made of refractory steel and consists of two half-molds that are assembled by thread.

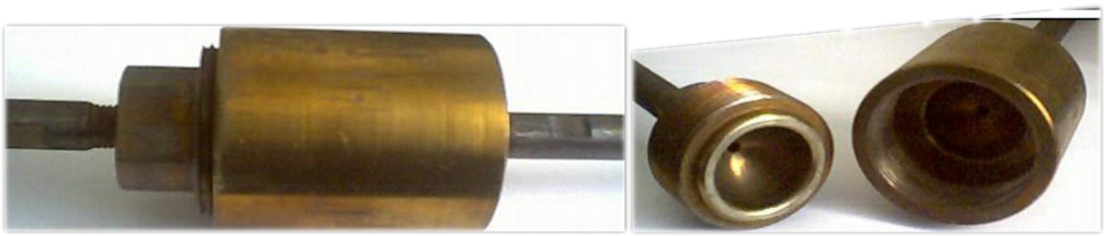


Fig. 3- The gasostatic forming die

To seal the active zones, a soft Cu-based alloy sealing washer is placed between the blank and the upper die, and at the bottom this is achieved by the R3 radius rib, which creates a sealing protrusion when the die is assembled to start the gasostatic forming process.

2.5 Effect of loading scheme

It was found that the different loading schemes had little effect on the final thickness distribution in the model component. This contradicts the findings of Zelin and Guillard [34], who pointed out that a low forming pressure and a high ratio of deformation pressure to flange backpressure favors uniform thickness through its effect on the strain rate . The technological parameters are determined, with experimentally verified approximations, and validated by positive results, in order to obtain constant results, unaffected by errors, [35]-[40].

The air pressure is determined with equation (11):

$$p = \frac{4s_o \cdot h \cdot \sigma \cdot K_s}{r_o^2 \left(1 + \frac{h^2}{r_o^2}\right)^2} \qquad \textbf{(11)}$$

where:

Parameter symbols and short definition	Parameter analitical values estimation
$\mathbf{s_o}$-sample's thickness	$\mathbf{s_o}$=1,2 [mm])
h-hemispherical dome height	**h**=24 [mm]
$\boldsymbol{\sigma}$ -yield stress, at forming temperature	$\boldsymbol{\sigma}$=32 [N/mm^2]
m- strain rate sensitivity	**m**=0,5
$\mathbf{K_s}$-transversal variations of thickness coeficient	$\mathbf{K_s}$=0,7
$\mathbf{r_o}$- hemispherical dome radius	$\mathbf{r_o}$=16 [mm]

The strain rate, as an essential technological parameter influencing the pressure regulation procedure, which beeing carried out with a proportional regulator included, is determined analytically according to the equation, [41]-[48]:

$$\dot{\varepsilon}_e = \left(\frac{2}{3}\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}\right)^{\frac{1}{2}} \qquad \textbf{(12)}$$

Although, from experiments, *the strain rate value* of $\dot{\varepsilon} = \mathbf{0{,}0001[s^{-1}]}$ and *the true strain rate* as $\mathbf{v_{12}}$**=0,0012[mm/s]**, were accepted.

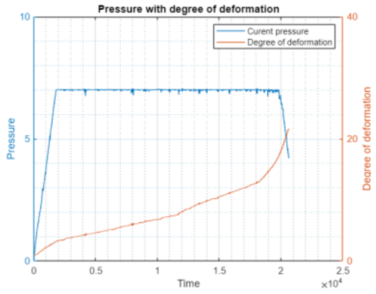
3. Results and Discussions

The experiments has been achieved on a number of 11 sampels of FORMALL alloy, having 51[mm], in diameter, thickness 1,2[mm], at forming temperature T_{def}=510[^{o}C] with a strain rate value $\dot{\varepsilon} = \mathbf{0{,}1x10^{-3}[s^{-1}]}$:

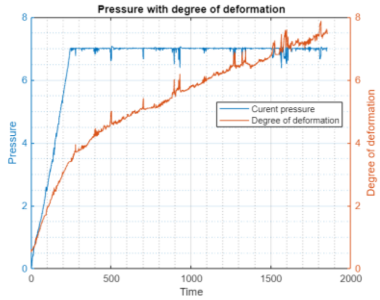
Fig. 4 – Gasostatic deep drawing parts

3.1 Numerical Analysis of collected meassurements

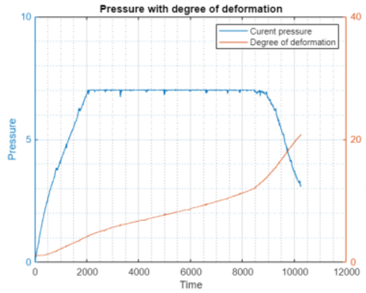
Numerical analysis, using data measured during superplastic deformation, collected and processed for reading in MATLAB was performed based on graphs representing the evolution of the deformation process with strict monitoring of the air pressure> Measurements were taken in raw form, analogue signals, then converted to digital signals, and then converted to xls format dat a files. Representative graphs are shown in Fig. 5:



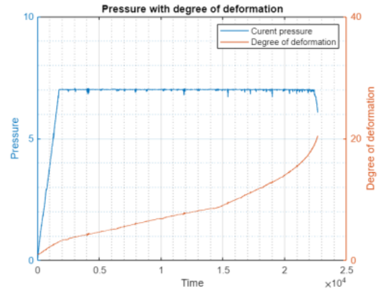
a)-sample GAZO082



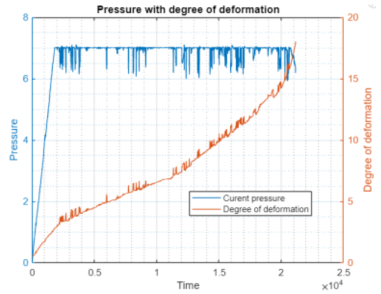
b)-sample GAZO083



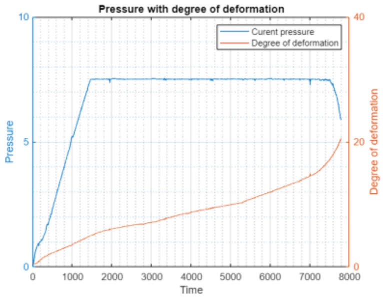
c)-sample GAZO084



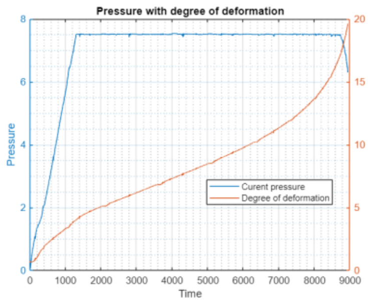
d)-sample GAZO085



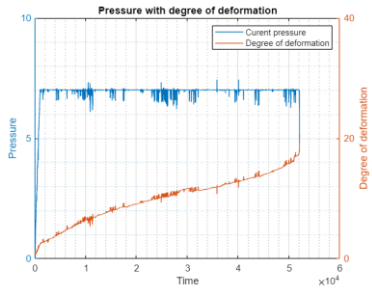
e)-sample GAZO086



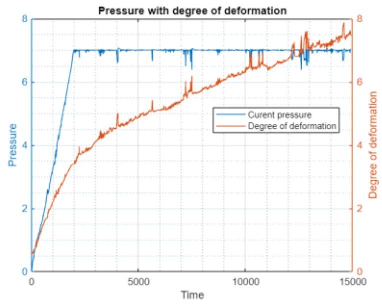
f)-sample GAZO087



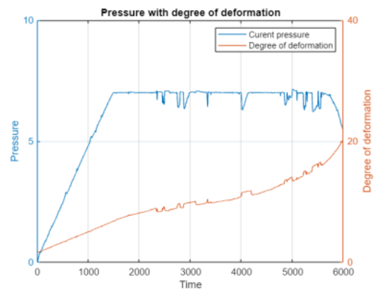
g)-sample GAZO088



h)-sample GAZO121

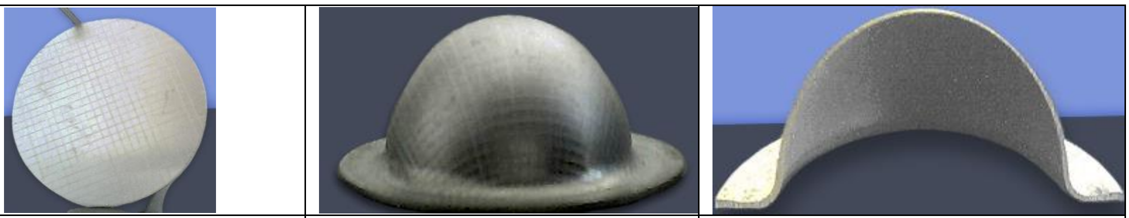


i)-sample GAZO-plate



j)-sample GAZOCARO

Fig.5- Pressure and deformation degree charts



a)- grided sample	b)-deformed part	c)-deformed part-LASER sectioned

Fig. 6 - Three stages of the deformation degree study

In fig. 6, three different stages of the study of a specimen are shown: the initial specimen, showing the equidistant grid; the finished piece (punched); the sectioned piece, to measure its thickness.

3.2 Finite Element Method and Optimization Procedure Analysis

The results of Finite Element Analysis in ANSYS Workbench-, in which we started the study with an Explicit Dynamics Analysis System, are highlighted in fig. 7, and fig. 8 using two output parameters, ”Equivalent (von Mises) Stress” and “Total deformation”, at three different stages:

Equivalent von Mises stress | Total Deformation

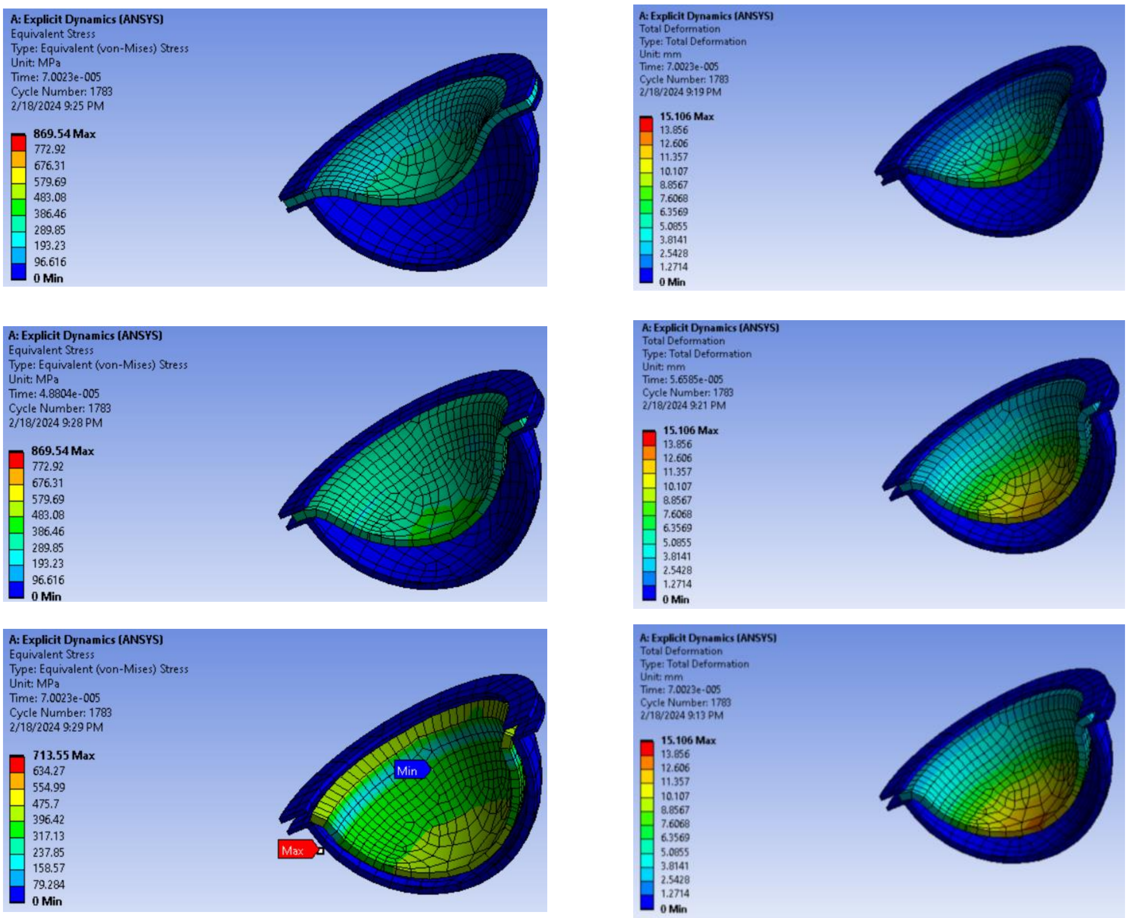


Fig. 7-Two output parameters, ”Equivalent (von Mises) Stress” and “Total deformation”- three different stages

3.3 Direct Optimization
-Method Design of Experiments

Design of Experiments (DOE) is a robust method for optimising and improving processes and products. By using DOE, time and resources can be saved, as it allows significant and accurate information to be obtained with minimal experimentation/simulation effort. DOE involves carefully selecting a set of experiments, varying key parameters in a controlled way, to assess their impact on response variables. This helps identify optimal combinations of input parameters. The DOE method allows quantification and analysis of the effects of input parameters on response variables, which contributes to understanding the complex relationships between variables in the process. In process optimisation, DOE can be used to find the ideal input parameter settings that maximise or minimise a given performance or characteristic. DOE can be used in a variety of areas, from manufacturing to scientific research, to improve the efficiency and quality of products or processes. A key aspect of DOE is the analysis of data from experiments/simulations, which can reveal unexpected trends and interactions between key parameters. Design of Experiments can be a valuable tool in the decision-making process, helping to achieve consistent and predictable results in the optimization of complex systems. The types of DOE available in DesignXplorer (DX) are:- Central Composite Design;- Optimal Space-Filling Design;- Box-Behnken Design;- Sparse Grid Initialization; - Latin Hypercube Sampling Design. Not all of these DOE types were used in this study.

3.4. Creating the Response Surface in Direct Optimization using Screening procedure

The Screening procedure is essential in direct optimisation, as it allows resources to be focused on the variables with the greatest impact on outputs, thus reducing the time and costs associated with the optimisation process. This method involves the identification and selection of input variables - key variables that influence the outcome or performance of the system, followed by the creation of an RS model describing the relationship between these variables and outputs. The definition of input variables and objectives includes: identification of input variables, namely only those that can influence the outcome, and setting the optimisation objective, such as maximising yield or minimising cost. The choice of the appropriate screening method to identify significant input variables may include univariate analysis, principal factor analysis or other statistical methods such as analysis of variance (ANOVA) or regression methods. Construct the Response Surface model using the collected data, materialised as a mathematical or statistical model describing the relationship between the input variables and the desired outcome. This model can be a polynomial function, a neural network or another type of regression model. Model validation and optimisation using a percentage of the experimental data, used to optimise the input variables to obtain the desired outcome. This can be done using optimization methods such as the Gradient Algorithm or Evolutionary Algorithms. The optimization results are analyzed and interpreted to determine the impact of the input variables on the outcome and to identify strategies to improve system performance. The procedure of creating and optimizing a RS model using the screening procedure in direct optimization is useful for identifying and exploiting complex relationships between input variables and the desired outcome in an efficient and systematic way. This enables data-driven decision making and continuous improvement of system or process performance.

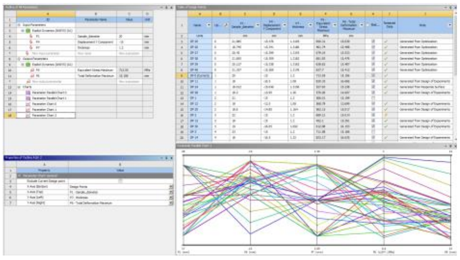
3.5. Ansys Explicit Dynamics System

Ansys Explicit Dynamics System is a transient application that can perform a variety of engineering simulations, including modeling the nonlinear dynamic behavior of solids. A typical simulation using this application, consists of configuring materials, building the model, analyzing the interactions and applied loads, setting the "steps" of the operation (simulation), highlighting the nonlinear dynamic response of the model, over time, calculated for the values of the loads and interactions. The Explicit Dynamics application has the components (objects) arranged in a tree structure that leads the operator through the different steps of a simulation.

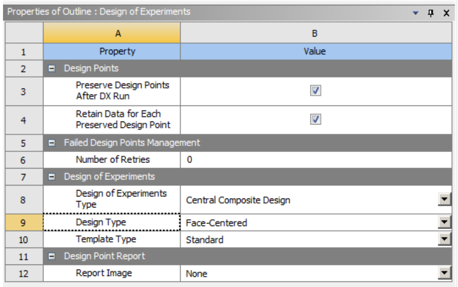
The state of stresses and strains is captured in a few representative PrintScreens in terms of layout and content, in Fig. 7. These images also reflect the areas stressed at approximately the same time in the range of the deformation process progress, and the values of the two output parameters, "Equivalent (von Mises) Stress" and "Total deformation", in three different stages are also highlighted.

Solving a problem with the Explicit Dynamics Application, starts with discretizing a domain (mesh) with assigned materials, defining and setting material properties, loads, constraints and assigned initial conditions. This initial condition, when integrated over time, will produce motion in the nodes of the mesh. The motion of the nodes produces deformation in the mesh elements, the deformation resulting in a change in the volume (hence density) of the material in each element. The strain rate is used to derive material strain rates using various element formulations. Analysis using the Explicit Dynamics Application is used to support the Design of Experiments (DOE) application in the Parametric Optimisation module with the generation of a Response Surface (2D or 3D). The objective is to find an efficient and applicable algorithm that quantifies the influence of design variables on product performance. By doing so, correct decisions can be made based on accurate information, even in case of unexpected design changes or constraints. A good design point is often the result of a compromise between different objectives. Design exploration describes the relationship between design variables and product performance using Design of Experiments (DOE) and Response Surface (RS). DOE and RS provide the necessary information, through analysis of results, and data provided by design points in DOE to perform simulation-based product development, and objective function evaluations. Having this data, the dependence of product performance on design variables can be considered known, so it becomes easy to understand and identify what changes are needed to meet the requirements for the product. Knowing that each point of the RS is, a design point, it follows that once the response surfaces are generated,it becomes obvious that these results can be used at any point during product development without the need for additional simulation to test a new configuration. In Fig. 8 the results of parameterized optimization of superplastic deformation by gasostatic forming of hemispherical flanged parts made of aluminum-based alloys using DOE and RS are shown.

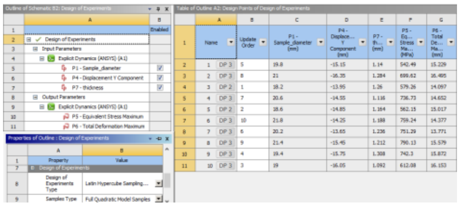
The input parameters are Sample_diameter-P1; Displacement Y Component-P4; thickness-P7, and the output parameters are: Equivalent Stress Maximum-P5 and Total Deformation Maximum-P6 (The ID of parameters P4 and P7 were automatically changed by Ansys during the simulation. This in no way influences the results!). Details of these parameters are given in Fig. 8,a). In fig. 8.b) the two DOE variants for the two algorithms Genetic and Krigging respectively are shown with the following appropriate and assigned DOE types as shown in fig. 8. b).

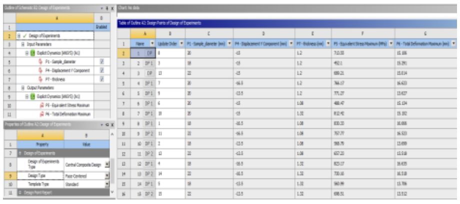


a)- Parameters Set and Design Poins- - Values generated from DOE and RS

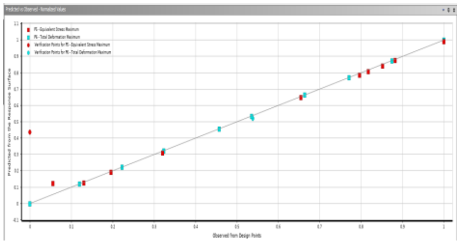


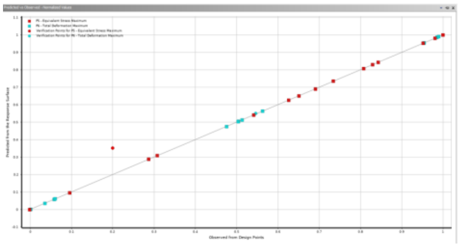
b)- Design of Experiments Type configuration



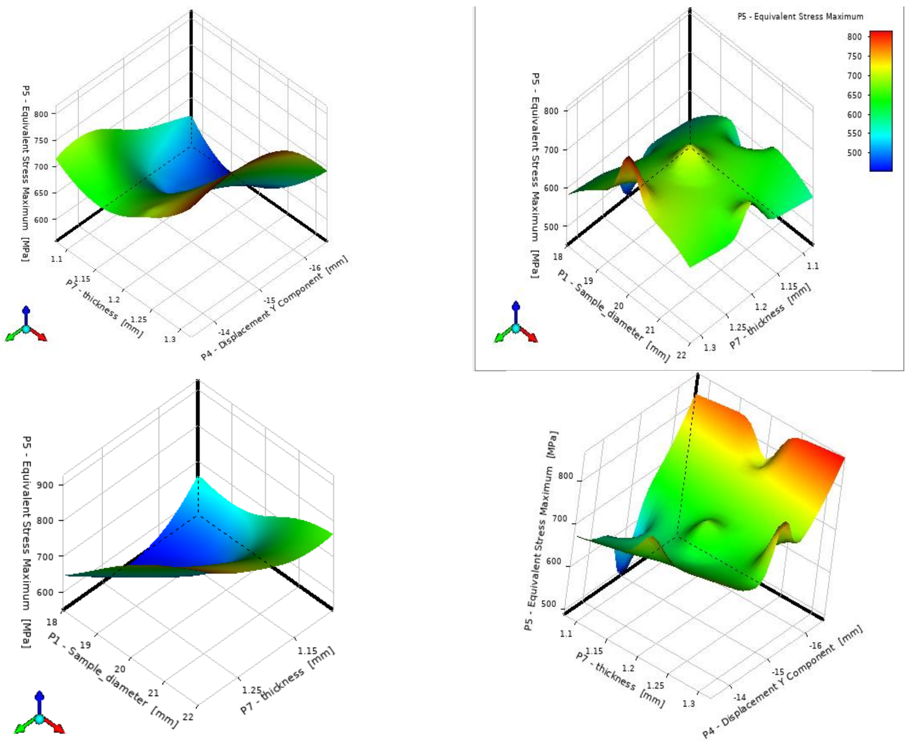


c)-Design of Experiments
- there are two DOE variants for the two algorithms Genetic and Krigging are shown

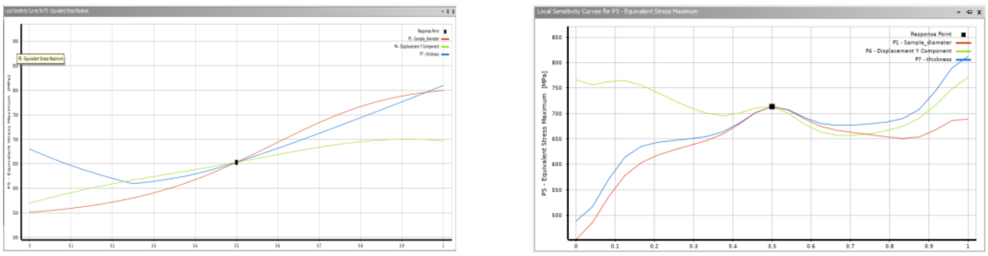




d)-Goodness of Fit in Response Surface
- there are two graph variants for the two algorithms Genetic and Krigging are shown

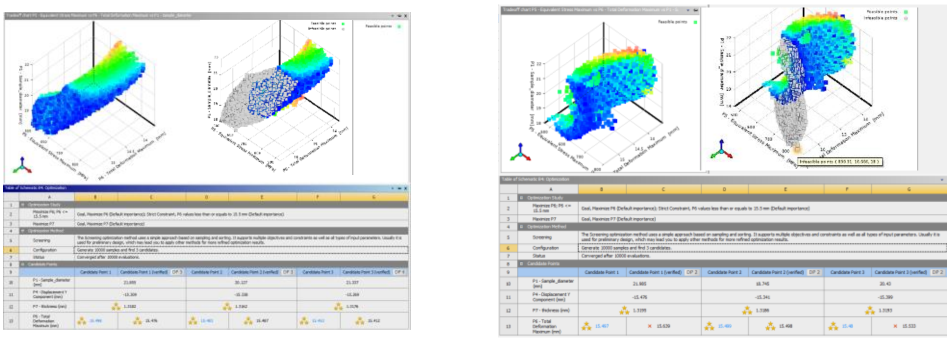


e)-Response Surface



f)-Local Sensitivities Curves in Response Surface

g)-Three Candidate Points and the same three Candidate Points Verified



h)-TRADEOFF

Fig. 8 The results of parameterized optimization of superplastic deformation by gasostatic forming of hemispherical flanged parts, using DOE and RS .

4. Conclusion

An major advantage of superplastic deformation is the uniform, cross-sectional deformation, hence the quasi-constant wall thickness of the deformed parts. In the case of conventional plastic deformation by high speed (cold or hot) forming, the formed parts are obtained by "pulling" from the flange, the material being forced to copy the outer shape of the punch, i.e. the inner shape of the active plate. For this reason, in the areas of the radii of the joint (of the pocket or the active plate), the spatial state of stress induces a spatial state of deformation which results in non-uniform deformation and local thinning of the material. Superplastic deformation, at temperature above 0.4 Tmelt, with constant strain rate of order of magnitude 0.001 [s-1]), with characteristic size of the structure below 0.01 [mm] eliminates these drawbacks, the deformation being quasi-constant in all directions. Research to date has demonstrated a relationship between the technological parameters of gasostatic forming (gas pressure, deformation rate, temperature of the working environment), the initial dimensions of the blank, the thinning factor and the form factor of the formed part [49]-[55].

In order to make a comparison with the existing experimental results in the field, as well as to determine experimentally other values of the form factor, we have carried out tests on specimens taken from two different Al-based alloys (SUPRAL 100, FORMALL) of different thicknesses at different deformation temperatures.

On the basis of the research carried out and presented in the paper, the following conclusions can be expressed:

- The grid elements drawn on the specimen (squares) turned into curvilinear squares with equal sides after deformation. These linear geometrical elements, on the outer surface of the spherical cupola, are dimensionally and morphologically identical on a spherical cap, approximately 20% of the total height of the stamped piece. Starting from this height, in a southerly direction, up to the flange of the moulded part, the elements of the two-dimensional grid change shape and dimensions, following the law of variation of the thickness of the part (with absolute values). Thus, while at the top of the spherical dome, the deformed quadrilaterals are identical over a spherical area, towards the base of the hemisphere, the quadrilaterals have curvilinear shapes, with progressively smaller dimensions.
- The identical behaviour of the material is evident on the studied areas: the curvature radius area; the spherical (lateral) area respectively in the area of the sphere pole.

- The stability of the behaviour of the studied material demonstrates its superplastic qualities.

REFERENCES

[1] E. A. Brandes, G. B. Brook-*Smithells Metals Reference Book: Seventh Edition (2013)*,10.1016/C2009-0-25363-3

[2] Pearson, C.E.- Journal of Institute of Metals, 40, 1934, pag. 41-54.

[3] Pilling, J. & Ridley, N.- 3rd. Int. Aluminium-Lithium Conf. Ed. C. Baker, P.J.Gregson, S.J. Harris & C.J. Peel, publ. Institute of Metals, London, 1985, pag. 184-190.

[4] Pilling, J. & col.- Superplasticity in Crystalline Solids, Publ. by Institute of Metals, London, 1989.

[5] Z.P. Chen, P.F. Thomson, A study of post-form static and fatigue properties of superplastic 7475-SPF and 5083-SPF aluminium alloys, Journal of Materials Processing Technology, Volume 148, Issue 2, 2004, https://doi.org/10.1016/S0924-0136(03)00867-7, (https://www.sciencedirect.com/science/article/pii/S0924013603008677)

[6] Bochvar, A.A. & col. – Izvest. Akad.. Nauk., 9, 1945, pag. 821

[7] Backofen, W.A. & col.- Trans. ASM 57, 1964, pag. 980-990.

[8] D. S. Fields, Jr. and T. J. Stewart - Strain Effects in The Superplastic Deformation pf 78Zn-22A1 *J. mech. Sci.* Pergamon Press. 1971. Vol. 13, pp. 63-75.

[9] Langdon, T.G., *The physics of superplastic deformation,* Materials Science & Engr., A137, 1991, pp. 1-11.

[10] T. G. Langdon and R. B. Vastava, in *Advances in Fracture Research*, edited by D. François, Pergamon Press, Oxford, England, 1981, Vol. 4, p. 1635.

[11] Langdon, T.G.- "Superplastic Forming of Structural Alloys", Ed. N.E.Paton and C.H . Hamilton, publ. TMS-AIME, Warrendale, 1982, pag. 27-40.

[12] P. Yavari and T. G. Langdon, Acta Metall. **30**, 2182 (1982).

[13] P. Yavari, D. A. Miller, and T. G. Langdon, Acta Metall. **30**, 871 (1982).

[14] P. Yavari, F.A. Mohamed, and T.G. Langdon, Acta Metall. **29**, 1495 (1981).

[15] F.A. Mohamed and T. G. Langdon, Metall. Trans. **5**, 2339 (1974).

[16] S.V. Raj and T.G. Langdon, Acta Metall. **37**, 843 (1989).

[17] Avery, D.H. & col.- "Surfaces and Interfaces II", Ed. J.J.Burke, N.L.Reid and V.Weiss, publ. Syracruse Univ. Press, New York, 1968, pag 371.

[18] Ghosh, A.K.- "Deformation of Polycrystals" – Mechanics and Microstructure, Ed. N.Hansen, Publ. Riso National Laboratories, Denmark, 1981, pag. 277-282.

[19] Ghosh, A.K. - "Superplastic Forming of Structural Alloys", Ed. N.E.Paton & C.H.Hamilton, publ. TMS-AIME, Warrendale, 1982, pag. 85-103.

[20] Suery, M.- "Superplasticity", Ed. B.Baudelet & M.Suery, publ. CNRS Paris, 1985.

[21] Suery, M. & col.- "Superplastic Forming of Structural Alloys", Ed. N.E.Paton & C.H.Hamilton, publ. TMS-AIME, Warrendale, 1982, pag. 105-127.

[22] I. Charit, R.S. Mishra, Low temperature superplasticity in a friction-stir-processed ultrafine grained Al–Zn–Mg–Sc alloy, Acta Materialia, Volume 53, Issue 15, 2005, Pages 4211-4223, ISSN 1359-6454, https://doi.org/10.1016/j.actamat.2005.05.021.

[23] R. S. Mishra, M. W. Mahoney, A. K. Mukherjee et col. - High superplasticity in a friction stir processed 7075 Al alloy, *Scripta Materialia (1999)*,10.1016/S1359-6462(99)00329-2

[24] I. Charit, R.S. Mishra, High strain rate superplasticity in a commercial 2024 Al alloy via friction stir processing, Materials Science and Engineering: A, Volume 359, Issues 1–2, 2003, Pages 290-296, ISSN 0921-5093, https://doi.org/10.1016/S0921-5093(03)00367-8.

[25] S. K. Panigrahi, R. S. Mishra, R. C. Brennan & K. Cho (2020) Achieving extraordinary structural efficiency in a wrought magnesium rare earth alloy, Materials Research Letters, 8:4, 151-157, DOI: 10.1080/21663831.2020.1719227

[26] S.S. Nene, K. Liu, S. Sinha, M. Frank, S. Williams, R.S. Mishra-Superplasticity in fine grained dual phase high entropy alloy, Materialia, Volume 9, 2020, 100521, ISSN 2589-1529, https://doi.org/10.1016/j.mtla.2019.100521.

[27] McFadden, S., Mishra, R., Valiev, R. *et al.* Low-temperature superplasticity in nanostructured nickel and metal alloys. *Nature* **398**, 684–686 (1999). https://doi.org/10.1038/19486

[28] Ghosh, A.K. and Hamilton, C.H., *MechanicM behaviour and hardening characteristics of a superplastic Ti-6A1-4V alloy,* Metallurgical Transactions A 10A, 1979, pp. 699-706.

[29] Ghosh, A.K. and Hamilton, C.H., *Superplastic forming of a long rectangular box section - analysis and experiment,* Process Modeling, ASM., Altan, T. and Gegel, H. (eds), 1979, pp. 303-331.

[30] Atul H. Chokshi, The development of cavity growth maps for superplastic materials, Journal Of Materials Science 21 (1986) 2073-20822, https://doi.org/10.1007/BF00547949

[31] A.H. Chokshi, Cavity nucleation and growth in superplasticity Materials Science and Engineering A 410–411 (2005) 95–99

[32] Stowell, M.J.- “Superplastic Forming of Structural Alloys”, Ed. N.E. Paton & C.H.Hamilton, publ. TMS-AIME, Warrendale, 1982, pag. 321-336.

[33] M. V. Speight, W. B. Beert~ and G. Roberts, Growth of Intergranular Cracks by Diffusion, *Materials Science and Engineering*, 36 (1978) 155 - 163 155

[34] Michael Zelin, Stephane Guillard, Amiya K.Mukherjee, Superplastic Behavior of AA7475 Aluminum Alloy, Materials Science Forum Vols 243-245 (1997) pp 137-142, Trans Tech Publications, Switzerland, doi:10.4028/www.scientific.net/MSF.243-245.137

[35] Ahmed, H. & Pearce, R.- “Superplasticity In Aerospace – Aluminum”, Ed. R. Pearce&L. Kelly, Publ. Cranfield Institute Of Technology, Bedford, 1986, Pag. 146-159.

[36] Chandra, N.-Membrane Element Analyssis Of Axisymetric And Non- Axisymetric Superplastic Metal Forming Processes, " Superplasticity And Superplastic Forming " ,Ed. C.H. Hamilton & N. E. Paton , Warendale, 1989 .

[37] Ridley, N. & Pilling, J.- “Superplasticity”, Ed. B.Baudelet & M. Suery publ. CNRS Paris, 1985.

[38] Ridley, N.- “Superplastic Forming of Structural Alloys”, Ed.N.E.Paton & C

[39] H.Hamilton, publ.TMS-AIME, Warrendale, 1982, pag. 191-207.

[40] Ridley, N. & col.- “ICSMA 7”, Ed. H.J. McQueen et al. Publ. Pergamon Press, Oxford, 1985, pag. 853-858.

[41] Kobayashi**,** S**.**-Metal Forming and the Finite Element Method, Oxford University Press, New York, 1989.

[42] Rama, S.C. and Chandra, N., *Development of a pressure prediction method for superplastic forming processes,* Int. J. Nonlinear Mech., 26(5), 1991, pp. 711-725.
[43] Zienkiewicz, O.C.. and Taylor, R.L., *The Finite Element Method,* 4th. ed., McGraw-Hill, 1989.
[44] Zienkiewicz, O.C. and Godbole, P.N., *Flow of plastic and viscoplastic solids with special reference to extrusion and forming processes,* Int. J. Num. Meths. Engrg. 8, 1974, pp. 3-6.
[45] Zienkiewicz, O.C., Jain, P.C.and Ofiate, E. *Flow of solids during extrusion: some aspects of numerical solutions,* Int. J. Solids Structures, 14, 1978, pp. 15- 38.
[46] Zienkiewicz, O.C., Ofiate, E. and Heinrich, J.C., *Plastic flow in metal forming: 1. Coupled thermal, 2. thin sheet forming, Applications of Numerical Methods to Forming Processes,* Proc. Winter Annual Meeting of ASME, AMD-28, 1978, pp. 107 120.
[47] Ofiate, E. and Zienkiewicz, O.C., *A viscous shell formulation for the analysis of thin sheet metal forming, Int. J. Mech. Sci.* 25(5), 1983, *pp.* 305- 335.
[48] Zhang, W.C., Wood, R.D. and Zienkiewicz, O.C., *Superplastic forming analysis using a finite element viscous flow formulation,* Aluminium Technology '86, Book 4, Session C, The Institute of Metals, London, 1986, pp. 111.1-111.6.
[49] Argyris, J.H. and St. Doltsinis, *J., A primer on superplasticity in natural formulation*, Compt. Meths. Appl. Mech. Engrg., 30, 1984, pp. 83-132.
[50] Bonet, *J. The incremental flow formulation for the numerical analysis of plane stress and thin sheet forming processes,* Comp. Meth. Appl. Mech. Engrg., 114, 1994, pp.103-122.
[51] Bonet, J., Wood, R.D. and Collins, R., *Pressure control algorithms* for *the numerical simulation of superplastic forming, Int. J. Mech. Sci.,* 36(4), 1994, pp.297-309.
[52] Bonet, J., Bhargava, P. and Wood, R.D., *Finite element simulation of 3-dimensional superplastic forming with diffusion bonding,* in Proc. Int. Conf. *NUMIFORM92 Numerical Methods in Industrial Forming Processes*, 1992, pp. 843-849, Ed. by Chenot et al., Balkema, 1992.
[53] Bonet, J., *Incremental flow procedures* for *the finite element analysis of thin sheet superplastic forming processes. J. Mat. Proc. Technol.,* 45, 1994, pp. 243-248.
[54] Bonet, J. and Bhargava, P, *A uniform deformation gradient hexahedron element with artificial hourglass control, Int.J. Num. Meth. Engrg.,* 38(16), 1995.
[55] Bonet, J., Wood, R.D. and Zienkiewicz, O.C., *Finite element modelling of* the *superplastic forming of thin sheet* in Proc. Int. Conf. *Superplasticity and Superplastic Forming,* Hamilton, C. H. and Paton, N. E. (eds), The Minerals, Metals and Materials Society, U.S.A., 1988, pp. 706.