SET UP CONTROL OF SUPERPLASTIC FORMING OF ALUMINUM ALLOYS AND STRATEGY FOR RHEOLOGICAL CHARACTERIZATION OF MATERIALS BY BULGE TEST

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Abstract
The aim is to propose the set up control of superplastic forming of aluminum alloys in an autoclave and a new strategy for rheological characterization of materials by bulge test. The approach consists of a brief review of the basic theoretical concepts of Superplastic forming. The methodology is divided into three control systems: (a) thermal cycle, (b) pressurization cycle and (c) variation of strain rate. The development of the controls listed includes the activities related to the design of the sensors, the setting of the plant control system, definition of the system data acquisition up to the monitoring of process variables in real time, such as: temperature, pressure and deformation. New rheological strategy here means choosing forming conditions, determining the pressure cycle, description of the rheological test methods to determine the coefficients of interest (m, n and K). Based on the superplastic forming theory, it can be concluded that it is very difficult to control all the variables used to explain this process. For Superplastic forming, many steps of mechanical forming are reduced, with their corresponding time and cost savings. The process is widely applied in aluminum alloys. The value of this paper is to summarize the main features, to explain the modeling chosen and to propose a new strategy for rheological characterization of materials by bulge test.

Keywords*: Superplasticity, Superplastic forming, instrumentation. Rheological characterization. Control.*

1. INTRODUCTION

In the economic and environmental global situation, growing fossil fuel price, lack of flexibility in alternative fossil fuels, pollution and global warming represent a growing pressure in many industrial sectors, and the automobile sector efforts focus on reducing fuel consumption and emission rates; so as to attain this goal, it is necessary to reduce the car mass, and this requires a more extensive use of lightweight metal alloys. The barrier of the automobile industry is also felt in the aeronautic industry. In this context, the successful use of titanium and aluminum alloys in aerospace projects pushes some new technology processes forward, such as ***Superplastic forming***.

2. HISTORY

Many studies on the phenomenon of superplasticity have been conducted, considering the period technological limitations of the research, and they were important for establishing the limits to the use of this forming process.

Since the pioneer work by Bengough in 1912 (Bengough, 1912), the Superplastic phenomenon has been observed; however, the first results obtained are attributed to Pearson's work (Fig. 1) in 1934 (Pearson, 1934), with superplastic deformation of 1950% elongation in Bi-Sn alloy (it is worth noting that this material presents 5% elongation before rupture outside superplastic conditions, being classified as fragile).

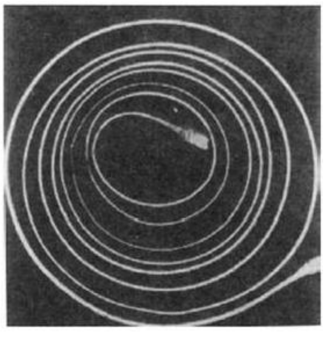

Fig. 1 - Pearson 1934, Bi-Sn alloy (1950%) (Pearson, 1934)

Bochvar (Bochvar & Sviderskaya, 1946), to whom the term superplasticity was attributed, based on the studies of Pearson (Pearson, 1934), made their research in the 1940s. Researches were resumed in the West, only in 1962, after the publication by Underwood (Underwood, 1962) for a Soviet review.

Before 1964, the research focus was on finding the maximum stretching through hot uniaxial tensile tests. The focus on technological research began only after the pioneering work by Backofen (Backofen, Turner, & Avery, 1964); the exponent m (strain rate sensitivity coefficient) began to be examined in more depth. Backofen, Turner & Avery, in 1964, from the MIT, published their much known paper in which, for the first time, a sheet of Superplastic AlZn eutectoid alloy was pneumatically formed as a bubble. This event marks the emergence of a new technology: *Superplastic forming.*

Prof. Backofen and his research group at the Massachusetts Institute of Technology made a replication of the Russian work and established the strain rate sensitivity importance as the neck-free tensile elongation characteristic of superplastic metals. They also investigated other alloy systems, such as titanium, copper and magnesium.

Davis Stuart Fields was granted his PhD in metallurgy by MIT in 1957, and co-authored several papers with Backofen.

When Backofen published in 1964, Dr. Fields was working at IBM Office Products Division in Lexington, Kentucky, and he discovered the extraordinary formability possible with superplastic metals through Backofen's work at an ASM meeting.

By April 1965, Fields had written the world's first superplastic forming patent application using a large range of sheet- and tube-forming techniques formerly used for thermoforming plastics. After that, Fields (Fields & Stewart, 1971) studied the uniaxial tension ZnAl eutectoid alloy and the results were related to the thickness distribution in thermoformed parts.

All this work being developed in the USA was soon to be noted by the world scientific community.

The Electricity Council Research Center, Capenhurst, was the first industry with laboratories to study SPF. In 1969, the first conference on SPF was held in Capenhurst. The participation of some groups, including some from Hinxton Hall, Cambridge, British Aluminium Research Division and Press Steel Fisher Division of British Leyland, was remarkable.

In 1971, ISC Alloys Ltd., Avonmouth Bristol, UK, was founded as the first commercial superplastic forming company in the world; the motivation was the production of complex-shaped components using ZnAl eutectoid alloy with low-cost tooling and forming times.

Immediately after the first demonstration of superplasticity in a dilure-aluminum alloy, in 1969, much development activity was undertaken to scale up the special processing requirements needed to achieve a viable production route.

So far, the largest uniform elongation in uniaxial tension has been approximately 8000% achieved with commercial bronze. This is clearly depicted in Fig. 2.

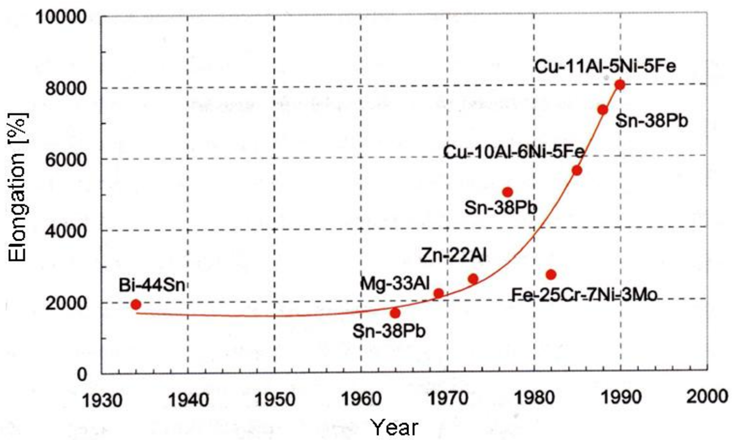

Fig. 2 - 1970, the turning point (Vulcan, 2006)

In the early 1970s, another development was also underway within the Aerospace Industry; this was the SPF of titanium alloy and the new concept now known as SPF/DB, two-process combined SPF and diffusion bonding (DB). This technology advanced considerably throughout the 1970s and early 1980s with the aid of government funding. (Barnes, 2007)

The first truly commercial application of SPF titanium was in 1981, some 13 years after Johnson had first demonstrated SPF with a titanium alloy. This first commercial application was a jack housing produced by British Aerospace Filton for the A310 Airbus aircraft. (Barnes, 2007)

Fig. 3 - Aluminum alloy EN AW 7475 superplastic forming (Robert, 2009)

Aluminium alloys (Fig. 3) used for superplastic forming are mostly known by their brand name or the name of the product in the market. In automotive construction, aluminium alloy AA5083 is used for the internal parts of automotive industry with superplastic forming. There are many companies in the market today that provide this material with different names; Table 1 lists some of them:

Table 1 - List of companies and trade names for the aluminium alloy AA5083. (Vulcan, 2006)

Company	Commercial names
ALCAN	Formal®545
ALCOA	5083-SPF
Sky Aluminium	ALNOVI-1

Fig. 4 illustrates the application of aluminum alloy in several industrial areas. (Vulcan, 2006)

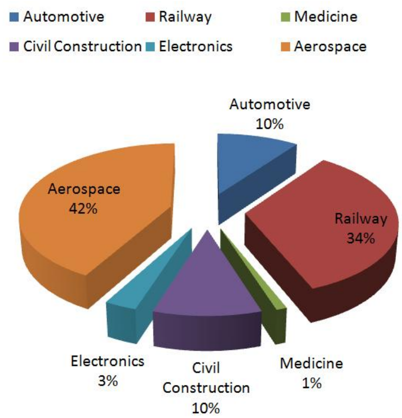

Fig. 4 - Market distribution for aluminum alloy superplasticity forming pieces. (Vulcan, 2006)

The SPF titanium production expanded in the 1980s. Just 10 years later, in 1991, one aerospace contractor, Rohr Industries, Chula Vista, had 10 full-time production presses and was producing more than 400 different part numbers at an annual output of more than 20,000 SPF titanium parts. (Barnes, 2007)

Due to the rapid progress in this area in recent years, research into a larger number of materials besides that into metallic materials (Chokshi, Mukherjee, & Langdon, 1993) also increased, such as ceramics, composites, intermetallic, and more recently nanomaterials (Xu, 2009).

Nowadays, there are many innovations associated with superplasticity. The goal is a fully controlled process; it means that all the variables of the process, such as temperature, strain rate and position (in some cases, tool movement) must be controlled to optimize this already known process.

3. SUPERPLASTIC FORMING

3.1 Technological and economic factors

The hardening of material is practically inexistent and spring-back is zero; these features characterise a very good finished product, with dimensional accuracy, avoiding finishing interventions. In the aerospace industry, superplastic forming has been used for thirty years.

The forming process is expensive, the working temperature is very high (60% of melting temperature), the average size of grains must be less than 10 µm, the strain rate less than 10^{-2} s^{-1}.

Materials with small grain size have a very expensive treatment. The different heat treatment kinds employed contributed to the improvement of the alloy mechanical properties. According to the alloys characteristic, the applied cooling rate and alloy additions seem to be a good compromise for mechanical properties. (L.A. Dobrzański, 2009)

The traditional forming limit diagram is described by a curve in a plot of major strain vs. minor strain. This curve defines the boundary between elastic or stable plastic deformation (lower curve) and unsafe flow (upper curve). The risk of failure is determined by the distance between the actual strain condition in the forming process and the forming limit curve. (J. Majak, 2007)

The possibility of using SPF is limited by the slow strain rates, which is an intrinsic characteristic of the process and must be localised inside the area of the available forming risk; that slow strain makes the lead time long.

To use the SPF technology, it is necessary to take into account both technological and economic factors.

3.2 Metallurgical Requirements of Materials for Superplastic Forming

- Very fine grains: d < 10;
- High resistance to grain growth;
- Strain rate has a very pronounced effect on the flow stress σ_e.
- High resistance to pore formation

3.3 SPF mathematical model

The mechanism that controls the fundamental behaviour of the high temperature plastic phenomenon in polycrystalline materials is related by the known equation (1) proposed by MBD Mukherjee-Bird-Dorn, which has been used for over three decades, showing good results with materials such as metal alloys.

$$\dot{\varepsilon} = \frac{C_m DGb}{kT}\left(\frac{b}{d}\right)^q \left(\frac{\sigma}{G}\right)^{\frac{1}{m}} \quad (1)$$

D= diffusion coefficient; C_m= Dimensionless constant, incorporating all structural parameters except grain size;
G= Shear modulus [N/mm²]; [Mpa] b= Burgers vector [µm]; K = Boltzmann constant [1,381 x 10-23 J/K];
T = Absolute temperature [K]; d = Average grain size [µm]; σ = Applied stress [N/mm²]; [Mpa]; q = Dimensionless exponent; m = Strain rate exponent.

The diffusion exponent of equation **(2)** is also calculated:

$$D = D_0 e^{-\frac{Q_c}{RT}} \quad (2)$$

D_0 =Independent coefficient of diffusion [m²/s]; Q_c= Activation energy of creep process [kJ/ mol]; R = Gas Constant 8.314 [J/ mol x K];

Substituting (2) in (1) one has:

$$\dot{\varepsilon} = \frac{C_m D_0 e^{-\frac{Q_c}{RT}} Gb}{kT}\left(\frac{b}{d}\right)^q \left(\frac{\sigma}{G}\right)^{\frac{1}{m}} \quad (3)$$

Equation (3) can be rewritten to relate the flow stress (σ_e), the strain rate ($\dot{\varepsilon}$) and strain (ε); in its rewritten form, it is called a Norton-Hoff power law equation (4).

$$\sigma_e = C.\varepsilon^n \dot{\varepsilon}^{\,m} \quad (4)$$

C = material constant; m= rate exponent; n= strain hardening coefficient.

In the high temperature plastic regime, the influence of n (hardening exponent) is very small and the influence of m (exponent of strain rate sensitivity of flow stress) dominates in the Norton Hoff's Equation; that is why expression (5) is applicable. (Vulcan, 2006)

$$\sigma_e = C.\dot{\varepsilon}^{\,m} \quad (5)$$

3.4 Behaviour of Flow Stress, m Value and Fracture Elongation within the Three Zones at Superplasticity

Fig. 5 clearly depicts the correlations between the m values, logarithmic strain rate and rupture elongation.

As summarized in Table 2, the logarithmic strain rate has a very strong effect on flow stress in zone II. Both elongation at rupture and the m value also have their maxima in this zone. Zone I is rate insensitive, hence m and the attainable rupture elongation have their minimum values here. Similar conditions exist in zone III, i.e. low gradient of the flow stress curve with increasing strain rate. The m value also decreases in this zone. In summary, superplastic forming behaviour only occurs in the region of rate zone II. The m coefficient increases with a strain rate up to the maximum, as can be observed in Fig. 5.

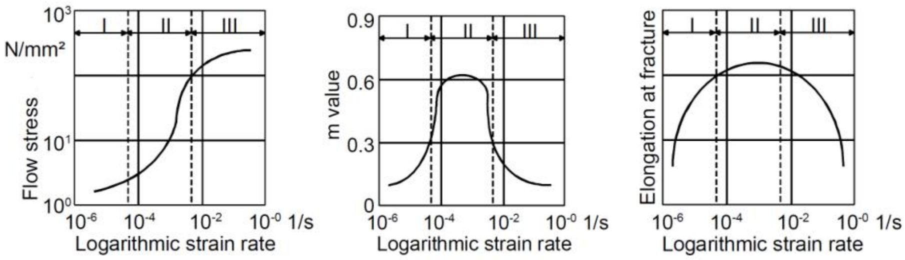

Fig. 5 - Relation between Flow stress, Elongation at fracture and m with strain rate. Adapted (Siegert & Werle, 1994)

Table 2. Change in Microstructure in the Three Rate Zones (Sieger & Werle, 1994)

Zone I	Zone II	Zone III
Flow stress is almost independent of strain rate, low m values, only small deformations possible	Strain rate has a pronounced effect on flow stress, high m values, large deformations possible	Flow stress is almost independent of strain rate, low m values, only small deformations possible
Limited elongation of individual grains	Almost no elongation of individual grains; Whole groups of grains glide as a packet; Grains move along parallel planes and a few exchanges of neighboring grains occur.	Individual grains heavily deformed due to multiple slide.

The Superplastic forming characterizing Parameters (equation (6) are, besides temperature and strain rate, microstructure as well. :

$$\sigma_e = f(microstructure, \varepsilon \,, \dot{\varepsilon} \,, T) \quad \textbf{(6)}$$

The forming mechanism is characterized by a curve (Fig. 6) deeply enough investigated for relating the observable characteristics with mechanical theories based on metallurgical microstructural investigations. The shape of the curve is called Sigmoid.

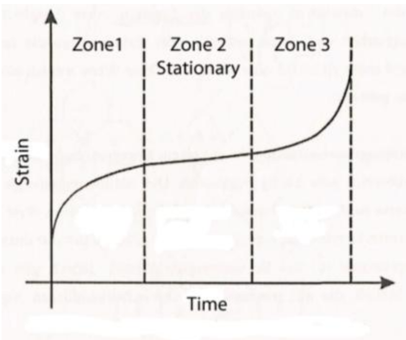

Fig. 6 - Sigmoidal curve - Strain vs. Time (Samekto, 2005)

In zone 1, the speed influence on the deformation mechanism is very low, and the exact indication of this fact is still not very well understood. The results in this region are often limited and inconsistent. (Samekto, 2005) From the viewpoint of microstructure, the limited elongation of individual grains occurs in this zone.

In zone 3, Individual grains are heavily deformed due to multiple slide; sensitivity coefficient m usually assumes values close to 0.2 and strain hardening coefficient n is bigger than 3, thus the creep rates are sensitive to changes in grain size. The predominant mechanism of deformation is the conventional dislocation movement, such as the movement of atoms and gaps. (Samekto, 2005)

In zone 2, the existence of a stationary region is known, in which the strain rate is constant. It is commonly accepted that the existence of the steady state is the result of a balance between hardening and softening. The maximum value of m is and should be equal to or greater than 0.5. This value places the superplasticity phenomenon in this zone. (Samekto, 2005)

It is important to make explicit that there is currently no single model that is able to describe all the metallurgical and mechanical aspects involved in the SPF process. The parameters obtained by mechanical tests are not always exactly reproduced during forming, in which certain features observed during the tests are undesirable, such as Cavitation. The refinement of parameters such as temperature, time of shaping, thickness of the wall, backpressure, control model implemented and control monitoring conditions, is a barrier to the SPF process optimization. (Marinho, 2011)

4. THE CONTROL SYSTEM PROJECT SUMMARY DESCRIPTION

The control system project is divided into tracking variables: Strain measurement, pressure measurement and temperature measurement.

Fig. 7 shows the Control instrumentation setup.

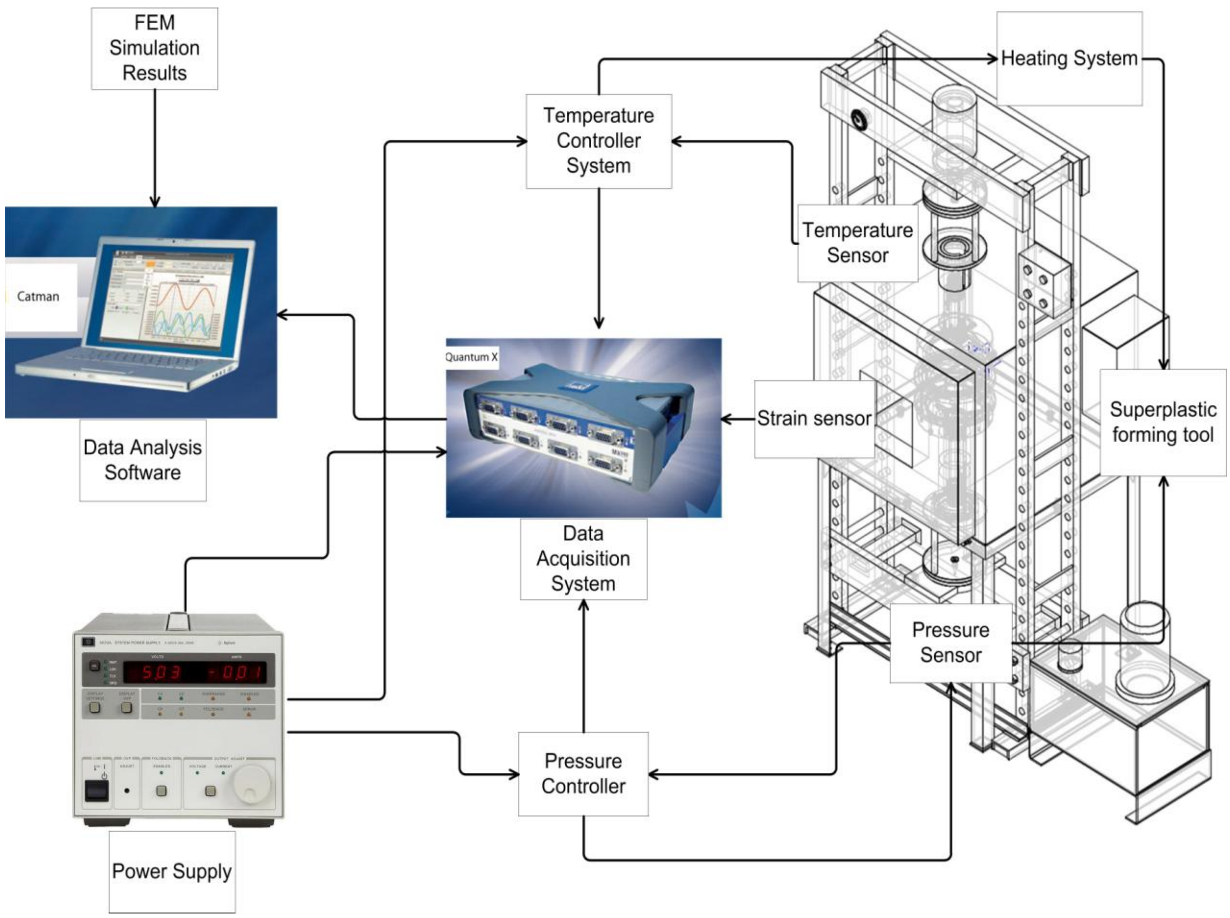

Fig. 7 Experimental Setup (Marinho et al., 2011)

4.1 Strain

4.1.1 System chosen for strain measurement

The solution uses the modern optic measurement system ARAMIS from GOM (Brunswick, Germany).

ARAMIS helps to better understand material and component behavior and is ideally suited to monitor experiments with high temporal and local resolution. It is a non-contact and material independent measuring system providing, for static or dynamically loaded test objects, accurate 3D surface coordinates, 3D displacements and velocities and Surface strain values (major and minor strain, thickness reduction). Emphatically, the proposed rheological model would not be possible without this optical measuring system. The proposed model works with yield stress (Fig. 8) and thickness in function of time for the development of this new kind of characterization.

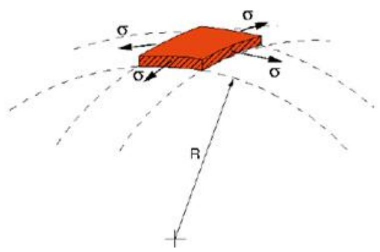

Fig. 8 - Yield Stress representation for ARAMIS (GOM, 2000)

4.2 Pressure

4.2.1 Pressure measurement

The pressure variation must be controlled to avoid cavitation; this phenomenon happens when a counter pressure is not applied. (Abu-Farha, 2007)

4.2.2 System chosen for pressure measurement

The pressure system will operate based on the following pressure Law (7). The instrumentation requires two pressure valves - the first one to apply pressure for deformation and the second one to control the cavitation through the application of counter pressure.

$$P(t) = \frac{4\sigma_{eq}(t)he(t)}{h^2 + {R_0}^2} \qquad \textbf{(7)}$$

4.3 Temperature

4.3.1 Temperature measurement

Several techniques for measuring temperature have already been implemented on superplastic forming tools, from thermocouples to laser interferometers. As previously discussed, the temperature is closely related to the window of superplasticity; it is directly related to the yield stress of the material that requires a dedicated control. (Samekto, 2005)

4.3.2 System chosen for temperature measurement

The instrument chosen for measuring the controlled environment is thermocouple, which will be installed in the furnace environment along the inner wall and this device does not have to be in contact with the formed sheet. The temperature measurement device of the piece real temperature showed to be a problem after examining the characteristics of the bulge test tool. The solution chosen was an infrared radiation pyrometer (no-contact, data acquisition possibility, infrared band chosen possibility).

5 . SUMMARY OF THE INTEGRATED CONTROLLER SYSTEM

Trying to improve the controlling methods and the monitoring process, some items have to be considered during the forming, such as: Optimum superplastic forming temperature; related to this is the best strain rate value; Thickness of the plate and failure induced by initiation, growth and coalescence of Cavitation. The approach with independent controller system (Fig. 10) that will be implemented in this project is a first tryout to control this process control and to develop the tool. (Marinho, 2011)

Two curves are well kown from the Superplastic Theory, S-shape (Fig. 9.a) and Pick-shape (Fig. 9.b); these curves, represented by Fig. 9, show hightlighted points, which are the searched points for the proposed control.

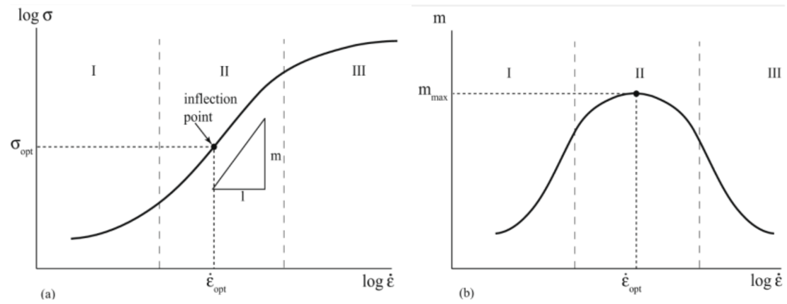

Fig. 9 - Typical behaviour of superplastic materials: (a) Curve showing the Sigmodal behaviour of the flow stress logarithm versus strain rate logarithm. (B) the strain rate sensitivity "m" versus strain rate logarithm (Snippe Q.H.C.,2009)

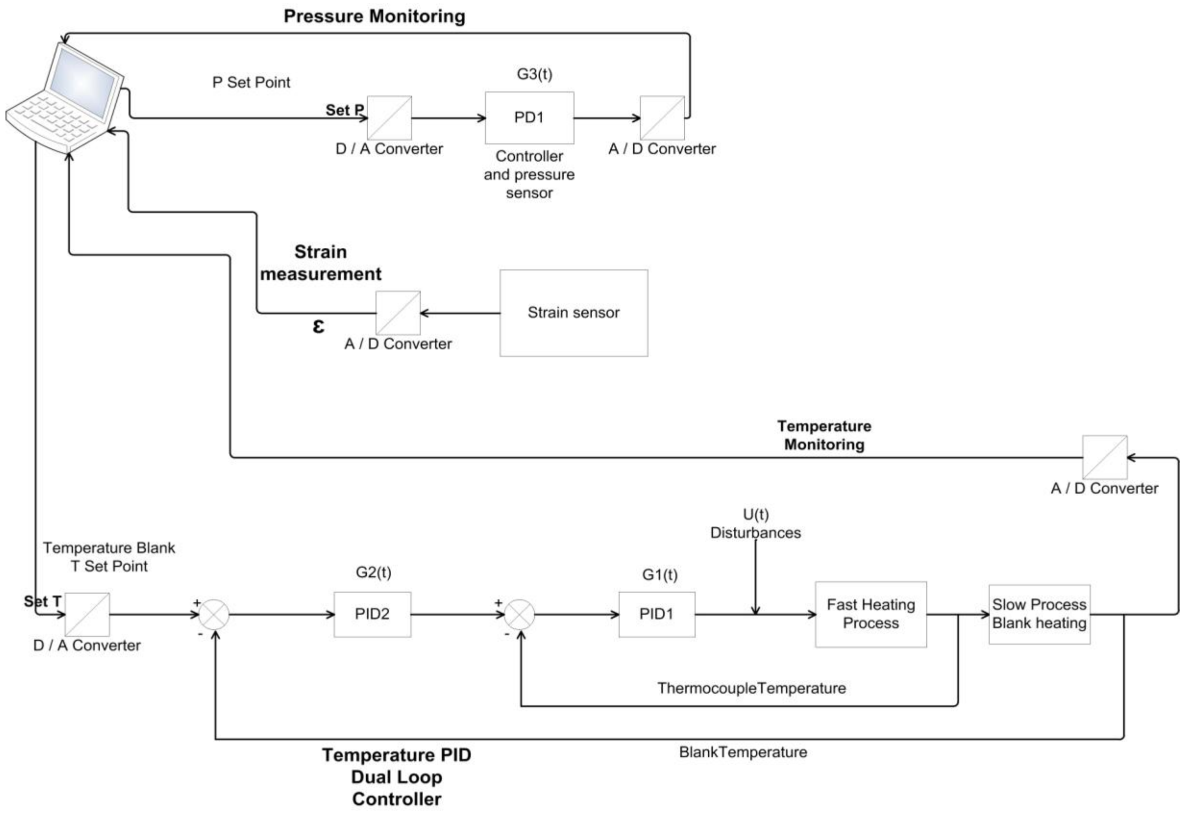

Fig. 10- Independent Control System (Temperature, Pressure and Strain) (Marinho et al., 2011)

6. RHEOLOGICAL MODEL

In summary, this rheological model (Fig. 11) is divided into two stages: The first step is to heat the Blank, without overshoot, up to the optimum superplastic forming temperature. The second stage refers to the forming itself. Through the acquisition of thickness versus time and the equivalent stress versus time, the cycle of pressure imposed by the pressure control system follows equation (7).

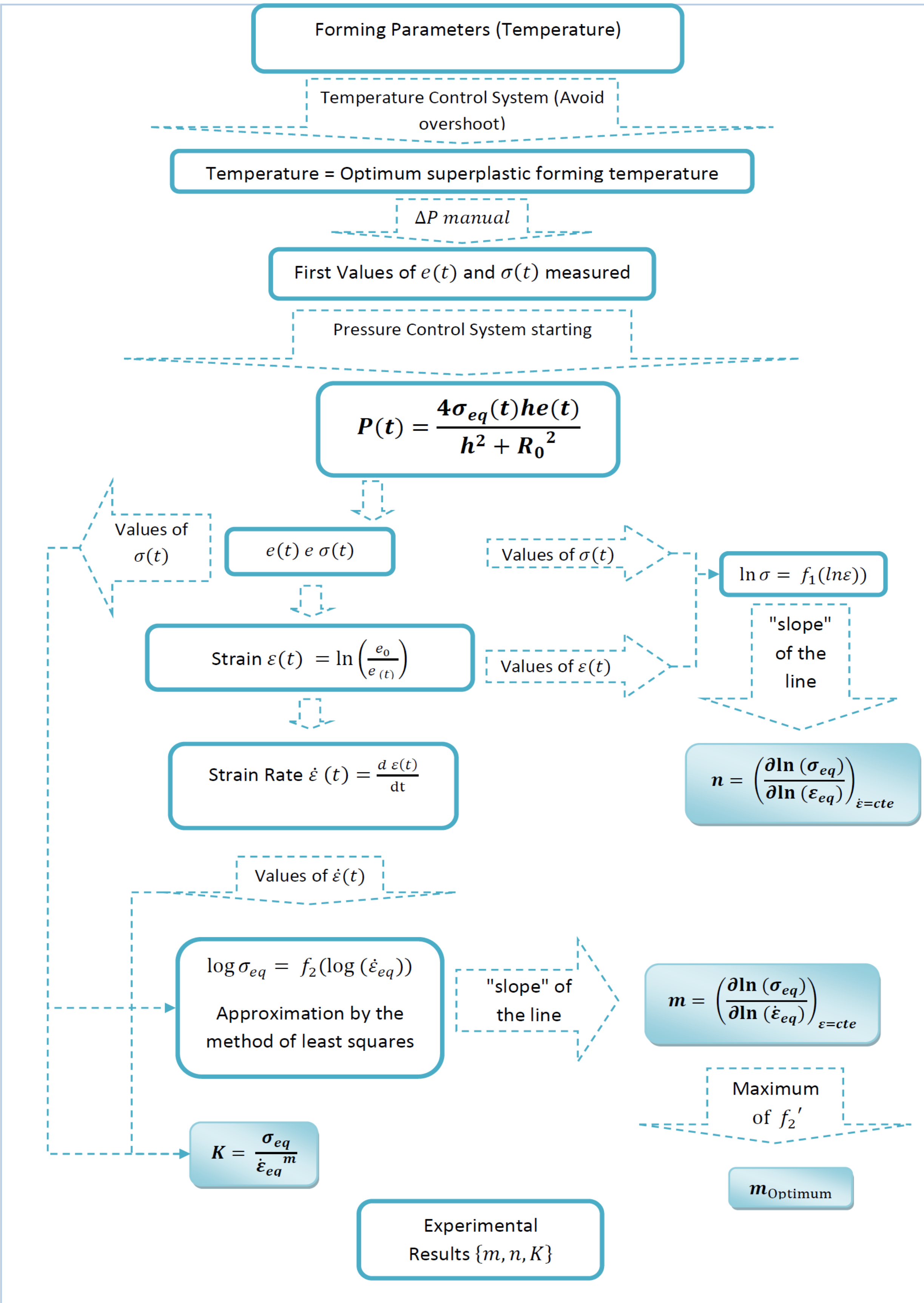

Fig. 11 - Surrogated superplastic rheological model (Marinho et al., 2011)

7. CONCLUSIONS

About the proposed control, the proposed temperature control using two cascaded PIDs (Fig. 10), which can better control the process and lead with flooding time, is able to improve the heating system operation. There are two parallel processes - the fast one, which consists in heating the oven and the temperature measurement by the thermocouple at the furnace, and the slow one, which is about real blank heating (after the flood time) and the temperature measurement is an infrared thermal camera. (Marinho et al., 2011)

Concerning the rheological model, the proposed instrumentation architecture led to a new rheological model for materials characterization by superplastic bulge test. Acting directly under a law of pressure, equation (7), and using the thickness data from the top of the conformed dome, along with the biaxial stress field value, it is possible to study the material rheology with a single forming step. Regarding sensors, in short, there are two pressure valves, the ARAMIS, an infrared pyrometer and a thermocouple. The pressure valves were dimensioned based on pressure limits necessary to the forming process - the first one to apply pressure for deformation and the second one to control the cavitation through the application of counter pressure. The ARAMIS will allow a new method for rheological characterization; usually the biaxial stress field value is considered constant, but ARAMIS can measure it. For last the infrared radiation pyrometer (no-contact, data acquisition possibility, infrared band chosen possibility) the thermal solution was chosen..

Finally, concerning the tool, it was possible to develop a tool which fits the first requirements of the project, and simultaneously being flexible for future amendments with unforeseen project boundary conditions.

8. ACKNOWLEDGEMENTS

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REFERENCES

Abu-Farha, K. (2007). *Integrated approach to the superplastic forming of magnesium alloys.* University of Kentucky. Dissertation, 2007.

Aoura, Y. (2004). *Contribution a la modélisation du comportement superplástique des alliages métalliques pour les procédés de mise em forme.*

Backofen, W. A., Turner, I. R., & Avery, D. H. (1964). *Superplasticity in an Al-Zn Alloy* (Vol. 57). Transaction of the ASM, pp 980-989.

Barnes, A. J. (2007). *Superplastic Forming 40 Years and Still Growing.* @ASM International.

Bengough, G. D. (1912). J. Inst. Metals. Apud Langdon, T. G. (2009*). Seventy-five years of superplasticity: historic developments and new opportunities* (Vol. 44). Journal of Materials Science.

Bochvar, A. A., & Sviderskaya, Z. A. (1946). Izvest. Akad. Nauk SSSR, Odtel. Tekh. Nauk.

Chokshi, A. H., Mukherjee, A. K., & Langdon, T. G. (1993). Superplasticity in Advanced Materiais. *Materials Science and Engineering R , 6*, pp. 237-274.

Dobrzański L A, T. T. (2009). Selection of heat treatment condition of the Mg-Al-Zn alloys (Volume 32/ Issue 2). Journal of Achievements in Materials and Manufacturing Engineering.

Fields, D. S., & Stewart, T. J. (1971). *Strain effects in the superplastic deformation of 78Zn-22Al* (Vol. 13). Great Britain: Pergamon Press.

GOM. (2000). Retrieved from http://www.gom.com/industries/sheet-metal-forming/fileadmin/user_upload/industries/yield_stress_EN.pdf

Majak J, P. M. (2007). *A simple algorithm for formability analysis* (Vol. 1/22). Journal of Achievements in Materials and Manufacturing Engineering.

Marinho, E. P. (2011). *Instrumentação e Controle do processo de fabricação de componentes aeronáuticos por conformação superplástica.* São Paulo.

Pearson, C. E. (1934). J. Inst. Metals. 54:111 Apud Langdon, T. G. (2009). *Seventy-five years of superplasticity: historic developments and new opportunities* (Vol. 44). Journal of Materials Science.

Robert, C. (2009). *Contrinution a la Simulation des procedes de mise en forme, Application au Formage Incremental et au Formage Superplastique.* Laboratoire Arts et Métiers ParisTech d'Angers: l'École Nationale Supérieure d'Arts et Métiers.

Samekto, H. (2005). *Finite Elemente Simulation des superplastischen Umformprozesses für Aluminiumlegierung 5083.* Stuttgart: DGM informationsgesellschaft mbH.

Sieger, K., & Werle, T. (1994). *Manufacturing Examples and Fundamentals.* (U. S. Institut für Umformtechnik, Ed.)

Underwood, E. E. (1962). *A Rewiew of superplasticity and Related Phenomena* (Vol. 14). Journal of Metals.

Vulcan, M. (2006). *Der pneumatische Tiefungsversuch und seine Anwendug in der superplastischen Aluminium-Blechumformung.* Universidade de Stuttgart.

Xu, C. (2009). Superplastic flow in a nanostructured aluminum alloy produced using high-pressure torsion. *Materials Science Engineering A , 500*, pp. 170-175.

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