SUPERPLASTIC DEFORMATION AND MATERIAL PARAMETERS OPTIMIZATION – A BRIEF REVIEW[1]

Paulo Guanabara Júnior[2]
Gilmar Ferreira Batalha[3]

Abstract

The aim of this review is to focus on aspects of superplasticity which are relevant to understanding the structure-property correlations and micro mechanisms related to specific material parameters used as superplastic material potential indicator. Since the main point of micro structural mechanisms and deformation conditions that control superplastic forming, among different test conditions, are related to tensile/creep test results and micro structural analysis. The parameters that are prerequisites for materials to exhibit superplasticity are reviewed, from deformation such as strain rate sensitivity index (m), temperature (T) and micro structural conditions related to grain (size, shape, stability), nature of grain boundary followed by mechanical and microstructural characteristics with several aspect of tensile behaviour under deformation conditions as nature of stress-strain rate curves, effect of strain rate sensitivity on ductility and parameters of the constitutive relationship and finely considering the mechanisms for superplastic deformation. The field of superplasticity has expanded dramatically including mechanically alloyed metals, super alloys, ceramics, intermetallics, and metal matrix and ceramic matrix composites. All have some specific material parameters closely related to micro structural mechanisms used as superplastic potential indicator. The main reason for reviewing the superplastic flow behaviour and micro structural evolution during deformation is the necessary knowledge of this process and related micro structural mechanism, whose superplastic forming parameters of control process are related to the test performed and micro structural analysis of results.

Key words: Superplasticity; Microstructural evolution; Superplastic deformation.

CONFORMAÇÃO SUPERPLÁSTICA E OTIMIZAÇÃO DOS PARÂMETROS DO MATERIAL- UMA BREVE REVISÃO

Resumo

O objetivo desta revisão é focar os aspectos do superplasticidade que são relevantes para a compreensão das correlações microestrutura e propriedade e micro mecanismos relacionados a parâmetros utilizados como potencial indicador de um comportamento superplástico Uma vez que os principais mecanismos microestruturais e de condições de deformação que controlam conformação superplástica, entre as diferentes condições de ensaio, estão relacionado com os ensaios de tração / fluência e análise micro estrutural. Os parâmetros que são pré-requisitos para os materiais a exibir superplasticidade revistos são: deformação, coeficiente de sensibilidade da taxa de deformação (m), temperatura (T) e características micro estruturais relacionadas com grão (tamanho, forma, estabilidade), a natureza do grão seguido pelos mecânicos e características microestruturas com vários aspectos do comportamento tensão deformação sob condições como a natureza de taxa de curvas tensão-deformação, efeito da taxa de deformação e ductilidade sensibilidade sobre os parâmetros da relação constitutiva e finamente considerando os mecanismos de deformação superplástica. Atualmente, o campo de superplasticidade se expandiu muito incluindo metais ligados mecanicamente, super ligas, cerâmicas, intermetalicos, compósitos de matriz metálica e de matriz cerâmica. Todos têm algum parâmetro material específico relacionado aos mecanismos micro estrutural utilizado como potencial indicador de superplasticidade. A principal razão para a revisão do comportamento superplástico e evolução micro estrutural durante a deformação é a necessidade de conhecer este processo e seus mecanismos microestruturais, cujos parâmetros de controle estão relacionados aos tipos de ensaios realizados e análise microestrutural dos resultados.

Palavras-chave: Superplasticidade; Microestrutura; Conformação superplástica.

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[2] *Pos-Doc research stay PRM/EPUSP, Dr. Mat. Eng°, S.Paulo (SP) E-mail: guanajr@gmail.com.*
[3] *Professor PRM/EPUSP, Dr.Mech. Eng°, S.Paulo (SP) E-mail: gilmar.batalha@poli.usp.br.*

1 INTRODUCTION

The parameters that characterize structural superplastic behavior are obtained from test used as potential superplasticity indicator. They have close relationship with its micro structural mechanisms. From these specific parameters, are used, for instance finite element carried out process of simulation at high temperatures forming operations. The outset interest has been demonstrated in use of such process in aerospace industry now starting to extend to automotive industry. The acceptance has been growing thanks to R&D efforts to overcome barriers that impede and restrict its use as: temperature, cycle of processing time and associated high cost to obtain superplastic alloy. These efforts let the opportunity of use different processing routes to obtain raw materials, and the development of prior preparation procedures before forming. So this process as a whole contributing to further streamline, improving superplastic characterization, as already known with aluminum alloys, thus also revealing and confirming potential of other materials, usually unskilled in this condition, i.e. austenitic steels of Fe-Mn-Al alloy system.(1) The superplastic forming process is usually held after the simulation study with use of finite element, to require a stricter parameters control during operation. The closest the characterization parameters are the actual forming conditions, more reliable is its use in the simulations, and less trouble is forming process control. According to Chandra,(2) in case of superplastic material is important to search a relationship that involve σ (stress), $\acute{\varepsilon}$ (strain rate) and ε (elongation), taking account: temperature, strain hardening / softening, grain growth (static and dynamic), cavitations (starting, growing and coalescing) and deterioration of thermo-mechanical properties after forming. Thus obtained model should be flexible enough to allow minimal changes in chemical composition of ingots, with small changes in primary and secondary thermo mechanic processing cast in form of product, variations in strain history of material (such as temporal and spatial variation of processing parameters), and simple enough to facilitate the development of experimental set parameters and model with the lowest test number, which should have high degree of accuracy and reliability.(2) Thus obtained parameters are not always exactly reproduced during the forming, where certain characteristics observed during tests are undesirable in forming process, i.e. cavitations.(3) Then the refinements of parameters become target to be achieved to obtain a better forming processed part, such as: lower forming time, temperature and uniform wall thickness.

2 DISCUSSION OF SUPERPLASTIC DEFORMATION

2.1 Characterization of Superplastic Behavior

There are two main types of superplastic behavior: a) micrograin or microstructural superplasticity, and b) the transformation superplasticity (or environmental one), but the most studied and more useful to the purpose to improve superplastic forming process and related manufacturing techniques is the microstructural superplasticity. So this work dealing with the superplastic behavior and parameters characterization of such materials.

Characteristics of superplasticity as: small grain size ($d < 10$ µm) stable and equiaxial; test temperature $T \geq 0.5\ T_m$ (creep phenomenon characteristic), here T_m is melting point of material, remember $T \approx T_h$ (homologous temperature) with $T_h > 0.5$ considering metal at high temperature, in association with following relation, which define the basic condition of deformation flow, even before associated to tensile test, which parameters characterization are obtained through creep test. Such characteristic added to flow regime occurring by diffusion controlled process is characteristic of pure metal and simple solid solution alloy (incompatible with small grain growth retention at high temperature). It's due to superplastic flow of two phases alloy, which normally has self-diffusion process known grain boundary sliding (GBS) as the principal mechanism. Then followed research considering cooperative grain boundary sliding (CGBS) mechanism as dominant influence.[4,5] There were obtained both condition and parameter keeping close relation to microstructure of alloy, which define the basic deformation characteristic associated mainly through creep and hot tensile test results from relations as: a) stress (σ) x strain rate ($\acute{\varepsilon}$); b) strain rate ($\acute{\varepsilon}$) or stress (σ) x temperature (T); c) strain rate ($\acute{\varepsilon}$) or stress (σ) x grain size(d); d) contribution of deformation (ε) (to grain boundary sliding) x deformation until rupture (ε_r). The fundamental mechanism behavior that control the plasticity phenomenon at high temperature in polycrystalline material is related by known MBD Equation proposed by Mukherjee-Bird-Dorn,[6] among others, which has been used more than three decade showing good results with materials as: metallic alloy, intermetallics, ceramic and tectonic system, whose general form is written as:

$$\acute{\varepsilon} = C_1 D (b/d)^p (\sigma/G)^n \qquad (1)$$

here: $\acute{\varepsilon}$ – stationary strain rate; C_1 – non dimensional constant, which consider all other structural parameter, but grain size; G – shear module,(MPa); b – Burgers vector (µm); k – Boltzmann constant (1,381 x 10^{-23} J/K); T–absolute test temperature (K); d – medium grain size (µm); p –converse grain size exponent; σ – applied stress (N/mm^2); (MPa); n – stress exponent = $d\text{Log}\dot{\varepsilon}/d\text{Log}\sigma$, n = 1 / m ; and D – diffusion coefficient written as

$$D = D_o \exp(-Q_C/RT) \qquad (2)$$

here: D_o – diffusion frequency coefficient (m^2/s); Q_c – activation energy of creep process (kJ/ mol) e R – gas constant (8,314 J/mol x K).v .Equation MBD aggregate parameter obtained both tensile and creep test. Critical parameters to any material and creep test condition are: n (stress exponent); Q_c (activation energy) and p (converse grain size (d) exponent). Threshold stress (σ_0) value could be added to Equation 1, then modified to creep power law as:[7,8]

$$\acute{\varepsilon} = A.D\,(Gb/kT)\,((\sigma - \sigma_0)/G)^n \qquad (3)$$

here A – constant dependent mechanism; σ_0 – threshold stress; with same another component as defined at Equation 1. Constitutive model used to describe relation between flow stress σ, deformation ε and strain rate $\acute{\varepsilon}$ is the named power law or Ludwick equation, which could be obtained from MBD equation rewritten in form:

$$\sigma = K.\,\acute{\varepsilon}^{m.}\,\varepsilon^{n'} \qquad (4)$$

here: σ – effective flow stress; $\acute{\varepsilon}$ – effective strain rate; ε – effective deformation, m – strain rate sensitivity exponent; n´- strain hardening exponent; K–constant composed with data obtained of hot tensile test. At high temperature plastic regime the n´(strain hardening exponent) influence is very small and m (strain rate sensitivity of flow stress exponent) influence starting to be dominant let Ludwick Equation related to expression:

$$\sigma = C.\ \acute{\varepsilon}^{\ m} \qquad (5)$$

here C – constant function of temperature; m –strain rate sensitivity exponent, represents the slope of the logarithmic plot .The most important mechanical characteristic of superplastic material is m exponent, to strain rate ($\acute{\varepsilon}$) related through Equation 5, obtained with hot tensile test data, which tend to form a sigmoidal or three stages curve. Region I shows low $\acute{\varepsilon}$ and m values; at region II $\acute{\varepsilon}$ and m values are high (superplastic regime) and at region III $\acute{\varepsilon}$ and m are low. Where, in a Second procedure is obtained measured stable $\acute{\varepsilon}$ as function of σ with creep test data related through MBD Equation rewritten as

$$\acute{\varepsilon} = A.\ D.\ (b/d)^{\ p}\ (\sigma / E)^{\ n} \qquad (6)$$

here: A – material coefficient and E – elasticity module, with ( ) ≈ constant, related through equation:

$$\acute{\varepsilon} = C'.\sigma^{\ n} \qquad (7)$$

here: C´–constant = $(1/C)^{1/m}$; n –stress exponent = 1/m presented by slope of logarithmic plot. Thus obtained data also generate a sigmoidal curve with low n values at region II and high n values at region I and III. Evidently both procedures could use tensile test method, with change V_C, or with constant $\acute{\varepsilon}$, for instance. So neither creep test with constant load nor with constant stress, even with change stress or temperature. So everything is dependent of the desired parameter and control level.

2.2 Initial Study of Superplastic Behavior Evolution

Table 1 shows a brief summary of superplastic behavior evaluation based upon study initially performed in Western and continued in Eastern (Soviet Union) in forties. Thus were retaken on sixties with the review published by Underwood,(9) which help to expand rapidly the interest in Western with the realization that superplastic metals have a wide potential application in many industrial forming operation.(10)

Table 1. brief summary of superplastic behavior evolution based upon initially performed study.

Author	concept	constitutive relation
Bengough (1912) (11)	1º work of high ductility at tensile test before rupture.	
Jenkins (1928) (12)	Obtained 300% elongation with eutectic Cd-Zn and Pb-Sn alloy.	
Pearson (1934) (13)	1950% elongation with eutectic Bi-Sn alloy, proposed deformation mechanism through viscous grain boundary sliding.	
Bochvar & Presnyakov 1940(14)	Performed extended research in several that binary eutectics and eutectoids alloy studied by Pearson.	
Bochvar & Sviderskaia 1945 (15)	Introduced the term ¨sverhplastichnost¨ that is (ultra high plasticity) translated to English in 1947 as ¨superplasticity¨.	
Bochvar & Sviderskaia 1946 (16)	Continue study of binary eutectic and eutectoid alloy with metallic material in Russia.	
Bochvar (1946) (17)	Explained as a phenomenon which, at almost eutectoid alloy, the influence of treatment temperature in hardness properties and ductility of tensile tested material showed accented hardness loss and values below that one of constitutive phases.	
Presnyakov,Chernyakova 1960 (18)	Russian researchers believed that the system should be at steady-state equilibrium with deformation dependence of decomposition process.	
Presnyakov & Starikova1962 (19)	American researches disputed Russian position with an argument that eutectic solubilized alloy decompose expontaneously at room temperature, even after complete transformation show superplasticity	
Underwood (1962) (9)	Aroused interest on superplasticity in Western when published a review describing the detailed experimental work performed on superplastic materials in the Soviet Union.	
Backofen, Turner &Avery 1964 (20)	At this field with proposal and proved that behavior of superplastic alloy result of high strain rate sensitivity with flow stresses (m). K and m are constant, the equation is used at simple tensile state without effect of deformation (n=0). It was a first exhibition of potential SP use in simple forming operation	$\sigma = K \acute{\varepsilon}^{m}$ $m = (\log(P_{b'}/P_{a'}))/(\log(V_2/V_1))$
Avery & Backofen (1965) (21)	Exhibited that steady-state is not responsible for superplastic behavior of Sn-Pb and Sn-Bi alloy.	
Fields (1965) (22)	Exhibited that superplastic forming can be applied in manufacture through vacuums thermoforming.	
Gibbs (1966) (23)	showed an initial procedure of m calculation using load values to change V_C, immediately before (point d) and after (point e)	$m = (\log(P_e/P_d))/(\log(V_2/V_1))$
Rosserd (1966) (24)	added characteristic of strain rate strength and (n) strain hardening exponent to superplastic forming.	$\sigma = K \acute{\varepsilon}^{m} \varepsilon^{n}$
Hart (1967)(25) Duncombe (1972/74) Ghosh (1977)(26) et all	an important characteristic of superplastic straining is the difficulty of occur macroscopic necking or its slow expansion. These authors considered the beginning and neck development, however there were controversy related to their models with respect threshold instability. Hart & Duncombe criterion describe only different stage in superplastic instability development.	$I = (1 - m - n/\varepsilon)/m$ I - instability parameter to describe whole necking process
Schwartz, Mitchell, Dorn1967(27)	At showed study the strain rate x stress curve was obtained through double-shear experiment in creep condition.	
Morrison (1968) (28)	Initial procedure for m (strain rate sensitivity) here true stress and strain rate at point *a* and *b* presents maximum load.	$m = (\log(\sigma_b/\sigma_a))/(\log(V_2/V_1))$
Bird, Muhkerjee, Dorn (1969)(29)	Showed work about relation between strain rate (έ) & temperature (t) correlation creep behavior and structure of superplastic material.	
Woodford (1969)(30)	Showed study of strain rate sensitivity with flow stress (m) with a ductility measure.	
Ball,Hutchison1969(31)	Grain boundary sliding (GBS) process through dislocation climb.	$\acute{\varepsilon} = K_1 (b/d)^2 D_{gb} (\sigma / E)^2$
Hayden et al. (1969)(32)	Have a credit of first classification of superplasticity divided in two types: isothermic and phase transformation. Afterwards restructured and extended to: structural SP, by phase transformation and thermal cycling SP. Such classifications are more description of refine grain process or technique to decrease grain size.	
Hart (1970)(33)	procedure of m calculation which the crosshead speed is interrupted at S point, then true stress values are estimated in different points alongside relaxation curve, m is determined through slope plot of log σ with log dσ/dt.	$m = \partial \ln\sigma / \partial \ln(d\sigma/dt)$
Al-Naib,Duncan1970(34) Cornfield,Johnson1970(35)	Showed that could be possible to produce parts with complex shape at very low stress level.	
Langdon (1970) (36)	Dislocation of climb and glide.	$\acute{\varepsilon} = K_4 (b/d) D_L (\sigma / E)^2$

Hedworth, Stowell1971 [37]	m calculation which (c) point is above change point (d) of V_1 curve after change of V_2 curve of point (c).	$m = (\log(P_c/P_d))/(\log(V_2/V_1))$
Raj & Ashby (1971) [38]	consequence of GBS and diffusion creep.	
Muhkerjee (1971) [39]	controlled rate of sliding by dislocation climb GBs.	$\acute{\varepsilon} = K_2\,(b/d)^2\,D_{gb}\,(\sigma / E)^2$
Langdon (1972) [40]	showed a study of effect of superficial configure at GBS.	
Johnson (1972) [41] Davies et al. (1972)[42]	Johnson indicated that SP occur beyond requested stress, by torsion or compression that exceed conventional behavior. Publishing review of superplastic work indicated that SP behavior could be obtained of two different ways - *superplasticity by micrograin* - great tensile elongation and fine grain, - *superplasticity by transformation* - elongation > 100 % by thermal cycling, with simultaneous application tensile deformation and phase transformation temperature.	
Yorder, Weiss 1972[43]	tried to relate two ways of SP behavior in C steel with almost eutectoid composition, resulting in micrograin related to hardness capability through strain rate, while transformation are related to deformation hardness.	
Murty, Mohamed, Dorn 1972 [44]	use of double-shear in deformation study.	
Burke, Nix (1975)[45] Joslin,Mcharque1993[46] Langdon (1994)[47, 48]	these authors showed that superplasticity occurs not only at imposed straining, as initially indicated, but as a deformation characterized by ductility under creep.	
Hayden et al. (1972)[49]	GBS controlled by intragranular dislocation of creep rate.	$\acute{\varepsilon} = K_{11}\,(b/d)^3\,D_p\,(\sigma / E)^2$
Ashby, Verall (1973)[50]	rate controlled by diffusional accommodation.	$\acute{\varepsilon} = K_{14}\,(b/d)^2 D_{eff}\,(\sigma - \sigma_0 /E)$
Hart et al.1973/1976[51]	authors developed a detailed method to determine m, which avoid change in material structure during stress relaxation test, in wide range $\acute{\varepsilon}$, without add plastic deformation and without necessity of long test period.	
Mohamed, Langdon 1975[52]	analyzed creep under low stress level in SP eutectoid Zn-22Al alloy	
Mohamed, Shei, Langdon 1975 [53]	Author associate superplastic flow with activation energy (Q), that act as a type of movement trend.	
Muhkerjee (1975) [54]	change of original rate controlled by GBS /dislocation climb/glide model	$\acute{\varepsilon} = K_3\,(b/d)^2\,D_{gb}(\sigma/G)^2$
Mohamed, Langdon 1976 [55]	showed procedure to determine (Q) to superplastic flow.	
Arieli & Rosen (1976) [56]	Procedure to m calculation which true σ and $\acute{\varepsilon}$ values are calculated in several points alongside load x time curve thus is plot log σ with dε / dt.	$m = \partial \ln\sigma / \partial \ln (d\varepsilon/dt)$
Gifkins (1976) [57]	pile-up sliding at GB.	$\acute{\varepsilon} = K_5\,(b/d)^2\,D_{gb}\,(\sigma / E)^2$
Padmanabhan (1977) [58]	proposition of a theory of *structural superplasticity* based upon data experimental which adopted approach consider stress, controlled diffusion and viscous boundary, prevent correct kinetic and variable interdependence, associate *activation energy* (Q) in a model, here (n) is *stress exponent* with experimental data.	$\acute{\varepsilon} = (\sigma^n/L^{b^*})\exp(-Q/kT)$
Ghosh (1977)/(1979) [59]	a particular method to determine m , perform change structure with very small but measurable constant $\acute{\varepsilon}$ and temperature, to measure change corresponding *flow stress*(σ), avoiding change in deformation history from a sample to another eliminating strain hardening and change of temperature /sample.	
Gittus (1977) [60]	Theory of dislocation climb at interphase boundary (IPB).	$\acute{\varepsilon} = K_8\,(b/d)^2\,D_{IPB}(\sigma - \sigma_0/E)^2$
Vastava,Langdon1979 [61]	intercrystaline and interphase boundary sliding in eutectic Pb-Sn /SP.	
Taplin,Dunlop,Langdon (1979) [62]	Review of study up to date, of mechanical behavior of superplastic material in terms of failure and characteristic of flow stress.	
Spingarn & Nix (1979) [63]	Deformation through intragranular sliding alongside dislocation bands.	$\acute{\varepsilon} = K_{12}\,(b/d)^3\,D_{gb}(\sigma/G)^2$
Ghosh,Hamilton 1979 [64]	Showed work about mechanical behavior and hardness characteristics of superplastic Ti-6Al-4V alloy.	
Arieli, Yu & Mukherjee (1980) [65]	Showed work about superplastic creep behavior and low stress in Zn-Al eutectoid alloy.	

source: [1,2,10,65-68] adapted and complemented.

2.3 Parameter of Superplastic Deformation on GBS and Accommodation Processes for Traditional Material

Micro structural characteristic of superplasticity are very different of another inelastic process, i.e. plasticity due elastic-plastic or creep process at high temperature. This shows a highly sensible m value; with strain hardening as secondary effect at inelastic behavior, as primary deformation with decrease mechanism in material texture, grain rotation and boundary sliding coupled with diffusion and dislocation. The deformation reduces initial anisotropy and collapse of material due to onset, coalescing of cavitation and finally geometric instability. One of essentials requirement is a fine grain structure in superplasticity. Which is a low flow stress (σ) and m value are generally high with major straining elongation.[64]There are available separation/phase transformation and mechanical work with recrystallization as refining methods. This could be obtained in principle, only with heat treatment, however occur mechanical work in such process step, so this processing route (thermo-mechanical treatment) use, with refine grain in less processing steps. Fine grain structure, however should be stable with equiaxial grain during forming process. At stress/deformation behavior considered in rule as despicable strain hardening occurrence during test, however were observed induced grain growth, in some cases meaningful, by strain hardening.[66] Study of static and dynamic grain growth; function of time and $\acute{\varepsilon}$ showed that dynamic growth rate is rapidly and sensibly great than static for higher $\acute{\varepsilon}$. At high temperature fine grain process let high deformation in forming part (from strip), at low stress and flow stress, there are strong $\acute{\varepsilon}$ and temperature influence in cavitation.[67] During superplastic flow impurity level of material neither have notable effect at grain boundary sliding contribution nor at stress exponent (n) values or even at activation energy $Q_c = Q_{cg}$ values, but impurity segregation at grain boundary interface could let to several different phenomenon, which involves a reduction of values following parameters of material as: superficial energy, diffusion through grain boundary, and strength to boundary cohesion [7]. These impurities adversely influence ductility, and even let to cavity nucleation (whose coalescing during deformation cause premature break of material) or to weaken through grain boundary.[8] Both strain rate ($\acute{\varepsilon}$) and temperature (T) seem to obey strain rate control mechanism, also as invariable form with microcrystalline material, following relation of MBD Equation.[6] Table1 in preview section showed a partially brief summary of early proposed equations, but is observed at all of those equations that it was fixed m = 0.5, and grain size conversely proportional to flow stress σ ($p < 0$), but in none was clearly considered non-homogeneity at deformation in such grain structure level, due to grain size distribution, orientation, particle, different type of grain boundary structure, energy or misorientation.[2]

Tables that follow shows many constitutive relation form of superplastic deformation from the developed basic principles proposed during initial SP study period on grain boundary sliding (GBS) and its accommodation processes, which considered the involved materials parameter as: σ_0 , T, d, b, Q_c, k, D in their several forms. This second sequence or set of basic principle which considers the proposed models for superplastic deformation on grain boundary sliding (GBS) and its accommodation processes as shown in Table 2 with 1. Dislocation pile-ups within the grains as Part A - Slip accommodation (rate controlling) according to authors as Ball-Hutchison 1969, Raj & Ashby 1971, Mukherjee 1971, etc. [68]

Table 2. Brief summary of proposed models for superplastic deformation Part1.dislocation pile-ups within the grains of: Section A. slip accommodation (rate controlling), 2009.

Author	concept	Constitutive relation
Ball & Hutchson (1969) [69]	Showed that grain groups slip as unity, and unfavorably oriented grains obstruct the process. The stress concentration is relieved by dislocation motion in the blocking grains. These dislocations pile-up against the	$\acute{\varepsilon} = K_1 (b/d)^2 D_{gb} (\sigma / E)^2$
	Opposite GB. The leading dislocation in pile-ups can climb into GB and get annihilated. GBS through dislocation climb.	
Raj , Ashby (1971)[38]	Show consequence of grain boundary sliding process and diffusion creep.	
Muhkerjee (1971) [39]	Grain slide individually. Dislocations are generated by ledges and protrusions in GBs, traverse the grain, and are held up in pile-ups at opposite GBs. The rate of sliding is controlled by the climb of the leading dislocation into GBs.	$\acute{\varepsilon} = K_2 (b/d)^2 D_{gb} (\sigma / E)^2$
Murty,Mohamed, Dorn (1972)[70]	Use double-shear creep test to study Newtonian viscous deformation mechanism, viscous slide and dislocation climb.	
Astanin,Kaibyshev, Pshenichnyuk1997[71]	among cooperative processes of SPD one can mention the interaction of intragranular slip with GBS, cooperative GBS (CGBS) and coherent grain group movement. Investigation of cooperative processes provides better understanding of the mechanisms of microstructure transformation and cavitation, the effect of a scale factor, allows to generalize contradictory SPD models into a universal one	

Source: [68] adapted and complemented.

Table 3. shows the sequence of Section A. :Slip accommodation (rate controlling), with Part 2. Pile-ups in the interfaces (grain and / or phase boundaries). Such table shows the presentation of GBS on superplastic deformation and its accommodation processes proposed by following authors: Langdon (1970), Gifkins (1976), Gittus (1977), Kaibyshev et al. (1985), Fukuyo et al (1990), Perevezentsev et al (1992), Nazarov (1997),among others.[72]

Table 3. brief summary with sequence of section A and Part 2. Pile-ups in the interfaces (grain and / or phase boundaries), 2009.

Author	**concept**	**constitutive relation**
Muhkerjee (1975) [(73)]	This is a modification of his original model. GBS is rate controlled by dislocation motion in GB by climb glide process. The compatibility between the adjacent Grain is achieved by diffusion controlled climb of lattice dislocations along the GBs. Thus repeated accommodation is possible for the operation of GBS as a unit process.	$\acute{\varepsilon} = K_3\,(b/d)^{2}\,D_{gb}\,(\sigma/G)^2$
Langdon ,1970 [(36)]	GBS occurs by the movement of dislocations along, or adjacent to, the boundary by combination of climb and glide. The strain rate due to sliding is proportional to σ^2/d. The various deformation mechanisms, including sliding, operate independently at lower stresses and/or smaller grain sizes. At constant but high stresses, the contribution of GBS to total strain increases with decrease in grain size, but this trend is reversed at lower stress levels.	$\acute{\varepsilon} = K_4\,(b/d)\,D_L\,(\sigma/E)^2$
Mohamed,Shei, Langdon(1975[(53)]	authors associated superplastic flow with activation energy (Q), that act as trend of movement type.	
Gifkins (1976)[(57)]	Sliding takes place by the motion of GB dislocations that pile up at triple points. The stress concentration is relaxed by the dissociation of the leading GB dislocation. The dissociated dislocations move along the adjoining GBs at triple point, or/and lattice in vicinity of GB. The split dislocations climb and glide until they meet each other and get annihilated.	$\acute{\varepsilon} = K_5\,(b/d)^2\,D_{gb}(\sigma/E)^2$
Gittus (1977)[(60)]	This is a theory for SPD in two phase materials. Pile-up GB *dislocations climb* away into adjacent disordered segment of the *interphase boundary* (IPB). Sources in the IPB introduce new dislocations to replace those that have climbed away from the head of pile-up. Sliding occurs at the IPBs as the dislocations in the pile-up glide toward the head of the pile-up. A threshold stress due to the pinning interaction between IPB super dislocations and boundary ledges, are incorporated.	$\acute{\varepsilon} = K_8\,(b/d)^2 D_{IPB}\,(\sigma - \sigma_0/E)^2$
Vastava,Langdon (1979)[(61)]	Showed an analysis of intercrystaline boundary sliding and at interphase in eutectic Pb-Sn alloy in superplastic condition.	
Watanabe1983 [(74)]	due a review to show the close relation between creep intergranular fracture and stress concentration through GBS.	
Mohamed (1983)[(75)]	due a interpretation of superplastic flow in terms of threshold stress (σ_0) suggesting that σ_0 is dependent of temperature be resultant of segregation of impurities in boundary and interaction with dislocations of (GB).	
Kaibyshev (1985) [(76)]	hardening and recovery of dislocation GB. Importance of changes in structure and properties of GBs at interaction with lattice defects is emphasized. Superplastic flow begins with the generation and motion of GB dislocations. Stress concentration due to pile-ups of GB dislocations These dislocations enter the GBs after traversing through the grain interior. Such absorption of dislocations by GBs result in the activation of GBS and diffusion. The application of the concepts of strain hardening and recovery describes the microscopic pattern of flow.	$\acute{\varepsilon} = K_7(b/d)^{2}(\sigma - \sigma_0/E)^2$ $K_7 = K_6/kT\ D_0\ \exp(-Q/kT)$
Fukuyo et al 1990 [(77)]	The slipe accommodation process for GBS involves the sequential steps of climb and glide. When the climb is the rate controlling step, the stress concentration at the lead of the pile-ups results in superplasticity (m = 0.5). When glide is the rate controlling step, however, m is equal to unity because there is no pile-up stress.	$\acute{\varepsilon} = K_6(b/d)^2(D_{ch}/b^2)(\sigma/E)^2$
Perevezentsev et al(1992) [(78)]	Superplastic behavior results from the transition of a grain boundary into a special high-excited state, by destabilization of the atomic structure by fluxes of lattice dislocations. Such a state facilitates the occurrence of GBS. GBS is accommodated through cooperative local GB migration, emittance of lattice dislocations from bends and boundary junctions, and diffusion mass transfer	$\acute{\varepsilon} = K_{10}(b/d)^{2}D_{gb}\,(\sigma/G)^2$
Nazarov 1997[(79)]	Kinetics of relaxation of various non equilibrium dislocation ensembles formed in GBs was analyzed to develop models for superplastic flow. This involves series of mechanisms which are effective and operate at different levels of the applied stresses, different geometry of triple junctions and grain sizes. The common feature of these Mechanisms is the back stress from accommodating GB dislocation arrays which impedes the main deformation process and determines the similar rate equations.	$\acute{\varepsilon} = K_9(V_a D_{gb}\partial/d^2)(\sigma/G)^2$ here V_a is the atomic volume, ∂ is the width of GB.
Watanabe (1997)[(80)]	The possibility of GB engineering for superplasticity based on structural effects on GBS migration, fracture and cavitation which involved in high temperature deformation in polycrystals. The importance and the need of a systematic study of GB character distribution (GBCD), GB connectivity is pointed out in order to achieve GB engineering for superplasticity in advanced materials.	
Mohamed (2001) [(81)]	shows through experimental observation the effects of impurity level and type on the sigmoidal relationship reported for superplastic alloys reviewing with particular emphasis on creep behavior, boundary sliding and cavitation.	

Source: [(72)] adapted and complemented.

Table 4 shows the sequence of section A. Slip accommodation (rate controlling) as with Part 3. Accommodation by the motion of individual dislocations. Such table follows that previous Tables above, according to the authors: Arieli, Mukherjee1980; Hayden et al 1972; Spingarn, Nix 1979.

Table 4. Brief summary of proposed superplastic deformation models on sequence of section A. Slip accommodation (rate controlling), with Part 3. Accommodation by the motion of individual dislocations of 2009.

Author	concept	constitutive relation
Hayden et al. (1972)(49)	GBS is controlled by the rate of intergranular dislocation creep. Dislocations are nucleated at Gb triple points and ledges, traverse individually in the grain by glide and climb and then finally climb to annhilation site in the opposite GBs. Proposed two constitutive relation for the relatively lower and higher temperature ranges.	$\acute{\varepsilon} = K_{11} (b/d)^3 D_p(\sigma /E)^2$
Spingarn & Nix (1979)(63)	Deformation occurs by intergranular slipe along slip bands which are blocked by GBs. The strain at the boundaries is accommodated by diffusional flow. The slip band spacing decreases as the strain rate is increased. At very large stresses, the slip band spacing is taken to be equal to the subgrain size.	$\acute{\varepsilon} = K_{12}(b/d)^3 D_{gb}(\sigma/G)^2$
Arieli,Mukherjee (1980)(65)	The individual lattice dislocations in a narrow region near the interfaces climb directly into and/or along the interfaces. Multiplication of dislocations takes place during climb for making the process self-regenerative. At high stresses more dislocation arrive at the interfaces from the grain interior, the critical step then being the overcoming of the obstacles to their motion inside the grains. This involves glide and climb processes controlled by lattice diffusion.	$\acute{\varepsilon} = K_{13} (b/d)^2 D_{gb}(\sigma/G)^2$

Source: (72) adapted and complemented.

Table 5 shows Section B. Diffusional accommodation of this second sequence of the proposed models for GBS on superplastic deformation and its accommodation processes according to authors as: Ashby-Verrall (1973), Padmanabhan (1980) and Kaibyshev (2000), (2001).

Table 5.Brief summary of some concepts for SP deformation: Section B. Diffusional accommodation, 2009.

Author	concept	constitutive relation
Ashby & Verall (1973)(50)	Superplasticity is treated as a transition region between diffusion accommodated flow, operative at low έ, and diffusion-controlled dislocation climb at high έ. Units of four grains must deform cooperatively in order to achieve a unit strain 0.55. During this process, while the two adjacent neighboring grains are separated apart the other two grains come closer to each other. This involves a transient stage where two triple points of the four grains are replaced by quadruple by diffusional process, finally the grain switching turns the original grain configuration in the tensile axis direction. At low έ, the specimen elongation is accomplished by grain rearrangement which in turn takes place by GBS. There arises (σ_0) due to transient increase in GB area during grain rearrangement process. At high έ, the specimen elongation is achieved by the change of the shape of individual grains.	$\acute{\varepsilon} = K_{14} (b/d)^2 D_{eff} (\sigma - \sigma_0/E)$ $D_{eff} = D_L[1 + (3.3w/d)(D_{gb}/D_L)]$
Padmanabhan (1980)(82)	superplasticity can be shown by pure GBS without any accommodation process. Inittialy, atom- vacancy interchanges lead to GBS until the flow is blocked at an obstacle, e.g. ledges, triple points etc. The resistance to flow offered by the obstacle leads to the development of an elastic back stress. When this significantly exceeds the mean boundary shear stress, stress enhanced local diffusion results in atomic rearrangement. This process continues until the obstacles become more conducive to easy and continuous sliding. Finally, the steady state superplastic flow is attained when all the obstacles are smoothed out and GBS can take place without being accompanied by other process.	$\acute{\varepsilon} = K_{15} (b/d)^2 D (\sigma / E)^2$ here D could differs from DL and Dgb
Kashyap,Arieli, Mukherjee1985(83)	its a review of microstructural aspects of SP phenomenon in terms of shape, grain size and growth; GBS and migration, rotation and grain rearrangement; and diffusion and dislocation activities.	
Kaibsyshev, Faizova, Hairullina(2000)(84)	experimental observations of morphological and chemical changes in SP deformed samples shown that the SP deformation exerts a strong influence on the process of diffusional mass transfer. A conclusion has been made that the specific feature of the superplastic deformation- development of bands of the CGBS may explain the mechanism of such an influence.	
Kaibsyshev(2001)(85)	show the possible mechanisms of formation of CGBS bands, which difference in SP behavior of metallic and ceramic materials connected with occurrence of liquid and amorphous phases at grain boundaries during deformation.	

Source: (72) adapted and complemented.

2.4 Deformation Induced Continuous Recrystallization Material (DICR)

The overall deformation mechanism in superplasticity of many alloys generally include, as integrated part, its accommodation processes and the grain boundary sliding (GBS), which needs extensive material transport to maintain compatibility between the grains(66) to occurs. The several models have been developed to explain the topological features and constitutive relationship observed during SP deformation. They are based on motion of dislocation and diffusional accommodation. Then trying to overcome the limitations of proceeding models, but none of these theory and constitutive models is able to account for whole phenomenon. The traditional SP materials have equiaxed grain structure in a microstructure of a recrystallized material, a first group of SP materials.

There are a second group of SP materials with texture and nonequiaxed grain structure. Such materials are obtained through unrecrystallized state rolled sheet condition. Since it's difficult, after a tensile test for instance to observe difference between the micro structural evolution on both materials, because this second group changes initial characteristics, with different grain shape distribution from the surface to the center and probably with non uniform texture in cross section. The grain growth (phenomenon associated to recovery, change of subgrain, dislocation structure and precipitates) become equiaxed with weaker texture and developing a recrystallized characteristic during SP deformation. The initial unrecrystallized structure is described as non-equiaxed grain shape with strong texture, while the recrystallized structure has equiaxed grain shape and weakened texture.(73) Because the recrystallized structure is reached through superplastic deformation. So according to Watts;(86) Nes;(87) Fan(72) and others, the process of micro structural evolution during SP deformation from an unrecrystallized rolled sheet aluminum alloy has been attributed to: a) texture weakening; b) increase in grain misorientation; and c) increase in high angle GB. The term to describe such process is *deformation induced continuous recrystallization* (DICR).

Table 6 shows this third set of constitutive mechanism, which considering to describe that important feature of micro structural evolution during superplastic deformation in rolled sheet materials, the named DICR (deformation induced continuous recrystallization), with micro structural changes from the initial unrecrystallized to the recrystallized structure. Thus according to authors as: Ghosh & Gandhi;(88) Amichi & Ridley;(89) Blackwell & Bate;(90) Liu et al.(91) among others, using two stage of SP deformation mode to obtain larger elongation than constant $\dot{\varepsilon}$ mode. Which proposed typical deformation mechanisms were subgrain: a) coalescence; b) boundary sliding; c) boundary migration; d) rotation, GBS and subgrain switching; e) superplasticity and through f) dislocation activity.

Table 6. brief summary of some mechanisms for DICR of superplatic deformation, 2009.

Author	concept	DICR Mechanism
Watts et al 1976 [86] Brichnell,Edington 1979 [92]	the process may occurs either by the coalescence of adjacent boundaries or by slip/climb of dislocations to the opposite boundaries.	a) subgrain coalescence
McNelley at al 1986 [93] Hales & McNelley 1988 [94]	sliding of low angle GB takes place at initial stage of SP deformation, also with trend of random microstructure, they believed that grain rotation occur during SPD associated with GBS. The absorption of dislocations within the grain by boundaries had the effect of increase misorientation between adjacent grains during SP deformation.	b)subgrain boundary sliding
Nes 1978 [87] Nes 1978 [95]	this subgrain has a rapid grain growth due to straining, which allows the formation of high angle GB, where subgrain growth during static annealing would be too low to develop high angle GB. Its is considered that a high angle GB could evolve from subgrain boundaries.	c) subgrain boundary migration
Gudmundsson et al 1991 [96]	consider the sliding of preexisting high angle GB might have led to an increase in misorientation through subgrain rotation.	d) subgrain rotation / GBS
Ashby & Verrall 1973 [50] Gudmundsson et al1991[96] Lyttle & Wert 1994 [97]	suggested that the overall mechanism consiste of the previous model plus subgrain switching and GBS, based upon Ashby & Verrall model.	e) subgrain rotation/ GBS+subgrain switching
Gandhi & Raj 1991 [98]	predicted that the subgrain structure would be stable within a certain range of έ. However, if έ was too slow the arrival dislocations rate would exceed the emission rate, and the subgrain boundaries would gradually grow into high angle boundaries. If έ was too high, then the emission rate would be faster and the low angle boundaries would annihilate into the crystal grains.	f) subgrain superplasticity
Edington et al 1976 [99] Hales & McNelley 1988 [94] Blackwell,Bate 1993 [90]	they observe that a great deal of dislocation interactions occurred in larger grains, the multiple dislocation slip systems were active, and these dislocations originated from different sources. They also suggested that dislocation creep was involved in the deformation process and dislocation played an important role in the accommodation of GBS.	g) dislocation activities as an accommodation of GBS.
Q.Liu et al 1992 [91] Z.Liu et al 1992 [100] Higashi et al 1991 [101] Mukherjee 1971 [39] Liu,Chakrabarti 1996 [102]	they suggested that DICR could be separated in two stage: the first one subgrain boundaries migration was thought to be easier , and coalescence to have made a large contribution to the increase in grain misorientation. The second stage the generation and absorption of dislocations at GB were considered to result in a rapid increase in misorientation. That dislocation glide within the grains can occur continuously to account for strain during deformation, and higher the έ the faster the increase in misorientation.	h) dislocation activities contributing to deformation

Source: [72] adapted and complemented.

3 CONCLUSIONS

This work tried to discuss, through brief reviews, only the initial or classic structural superplasticity approach, since the superplastic deformation and its material parameters optimization are useful as a tool to improve the superplastic forming of components (SPF). This is applied with high έ, both high and low temperature showing application in metal and nanocrystaline alloy, among others materials as: ceramics, composites, intermetallics, metallic glass. These materials follow general trend of constitutive relation of such equation, but with important difference at stress level and strain hardening rate (n´).[6] So proposed models and others developments for superplastic deformation of these later materials were not considered here, as those obtained from severe plastic deformation (SPD) techniques, or even nanocrystaline or metallic glass materials. Its because such models should be better approached in manufacturing study of superplastic forming of engineering structures, combining numerical simulation as finite element (FEM) and others auxiliary methods, coupled with optimization techniques to obtain characterization parameters of superplastic behavior as a more wide-ranging for constitutive relation models.[103]

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