On the Physics of Super Plastic Flow in Spatially Extended Polycrystalline Systems

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ABSTRACT: The objective of this work is to describe the physics of super plastic flow in spatially extended polycrystalline systems. In recent contributions, the activation energy for super plastic flow in spatially extended polycrystalline systems has been obtained by applying the quantum mechanics and relativistic mathematical model proposed by Muñoz-Andrade. In this framework, in the present contribution the activation energy for super plastic flow in spatially extended polycrystalline systems dependence on strain rate and phase velocity de Broglie are obtained, as well, the nature determination of the wavelength of the cellular dislocations $\lambda_\perp$ wave associated with super plastic flow. Additionally, the main results of this work are analyzed in the context of the cosmic micromechanics connection during super plastic flow in spatially extended polycrystalline systems.

Key words: Super Plastic Flow, Activation Energy, Quantum Mechanics, Special Relativity Theory, Hyperbolic Flow, Dislocation Dynamics, Spatially Extended Polycrystalline Systems and Cosmic Micromechanics Connection.

1 INTRODUCTION

Super plastic flow (SPF) in spatially extended polycrystalline systems (SEPCS) obeys the fundamental principles of the physical meso-thermo-mechanics in a corresponding manner of the dislocation dynamics inside of spatially extended crystalline systems (SECS). Dislocations are linear crystalline disturbances, which can be considered as vibrating strings in the elastic field of crystals. Accordingly, with the physics of string theory to evaluate the dislocations dynamics as vibrating strings, it is necessary to know the energy and effective mass of a moving dislocation in the elastic field of a crystal during plastic flow or in the case of super plastic flow by cellular dislocations dynamics. In this framework, recently a work related with string theory and cosmic connection during super plastic flow was proposed as the unified theory of every thing, where electrons and quarks, which are the elementary particles of atoms, are actually tiny loops of vibrating string [1]. These are reasons for thinking in corresponding phenomenology at different scales for that the gravitational field around of the planetary orbits in the dark matter and dark energy of cosmic structure is equivalent with the elastic field around of dislocation loops in the metallic matrix of crystal lattice structure. In this way, phase field micro gravity theory to formulate the dislocation theory in terms of the phase transformation in the cosmic structure is analogous to the phase field micro elasticity theory of dislocations [2]. In sight of that, it is motivating to mention that the string theory has been resolved the incompatibility between quantum mechanics and general relativity [3]. This essential consideration allows obtain a mathematical model for the activation energy for SPF in SEPCS related with the cosmic micromechanics connection [1, 4-6]:

$$Q_\perp = -mkT\,\ln\left(\frac{\rho_\perp \upsilon_\perp \lambda_\perp^2}{c}\right) = -mkT\,\ln\left(\frac{\xi_\perp \lambda_\perp}{c}\right). \quad (1)$$

Where: $Q_\perp$ is the activation energy for glide cellular dislocations in SECS, m is the strain rate sensitive ($m = \ln(\sigma_2/\sigma_1)/\ln(\xi_{\perp 2}/\xi_{\perp 1})$., where σ_1 and σ_2 are the applied stresses, k is the Boltzmann constant (k = 8.617x10^{-5}eV/K = 1.38x10^{-23}J/K), T is the absolute temperature, $\xi_\perp$ is the strain rate for the irreversible deformation processes associated with the Orowan equation for plastic flow ($\xi_\perp = \rho_\perp\ \upsilon_\perp\ \lambda_\perp$.), $\lambda_\perp$ is the Burgers vector for dislocations, $\rho_\perp$ is the density of dislocations, $\upsilon_\perp$ is the average glide velocity of dislocations and c is the speed of light (c = 299792458 m/s). Therefore, by introducing the de Broglie phase velocity ($\upsilon_\perp ph = \xi_\perp\ \lambda_\perp$) into the equation (1), it is possible to rewrite such equation as follow

$$Q_\perp = -mkT\ln\left(\frac{\upsilon_{\perp ph}}{c}\right) = -mkT\ln\left(\frac{E_\perp}{p_\perp c}\right). \quad (2)$$

Where $E_\perp$ is the energy associated with a dislocation and $p_\perp$ is the moment of the entity (dislocation). Consequently, the phenomenology and mechanics of SPF in SEPCS associated with quantum mechanics and the especial relativity theory is that by analogy with the energy of a photon E = hν, where the radiant energy of a photon of a given frequency (ν) only be emitted and absorbed in "quanta" of energy given by E = hν, where h is the Planck constant (h = 6.6260755 x 10^{-34} J sec = 6.626 x 10^{-27} erg sec), in this manner the relationship between deformation or disturbance of the elastic field in a crystal lattice of a given frequency ($\xi_\perp$) could only be emitted and absorbed in "quanta" of given by $E_\perp = h\xi_\perp$, and the typical thermal energy for an oscillator is given by kT, where, T is the absolute temperature. In an equivalent way of the equation (1) and equation (2), the activation energy associated with dislocation dynamics for plastic flow or cellular dislocation dynamics for SPF, as follow:

$$Q_\perp = -mkT\ln\left(\frac{h\xi_\perp}{kT}\right). \quad (3)$$

At the present, it is important to mentioned that the main results obtained until now, tell us that there is a correspondence law between the expansion process of the universe at Max Planck scale, Edwing Hubble scale and plastic flow in SECS and polycrystalline systems at atomic scale and SPF in SEPCS at mesoscopic scale [1-2].

2 ACTIVATION ENERGY FOR SUPER PLASTIC FLOW

2.1 *Ti-Alloys*

In consideration that Ti alloys are widely used in aviation or aerospace industries let us to analyze some experimental data reported in the past for the Ti alloys in order to find out the activation energy for SPF dependence on strain rate sensitive m by applying the quantum mechanics and relativistic mathematical model proposed by Muñoz-Andrade through the equation (3). The superplastic deformation behaviour for the Ti-6.5Al-3.3Mo-1.8Zr alloy with submicron grain size was investigated with the next experimental conditions:

Table1. Superplasticity Observations in Ti-6.5Al-3.3Mo-1.8Zr alloy [8]

Grain Size (μm)	Strain Rate (s^{-1})	Temperature (°C)	Strain Rate Sensitivity, m
0.88	5.4x10^{-4}	900	0.5
0.74	3.6x10^{-2}	800	0.35

The activation energy obtained in this work for the higher temperature of 900°C, $Q_\perp$=186.958 KJ/mol which is close with the result obtained in the reference [8] by applying the traditional techniques ($Q_\perp$=183.7KJ/mol). This result is similar to the activation energy value for volume diffusion of Ti (169KJ/mol for α-Ti) [8]. Also, for the lower temperature of 800°C, $Q_\perp$=106.326 KJ/mol which is close to the activation energy value for grain boundary diffusion of Ti (101KJ/mol for α-Ti) [8].

Let us to obtained the phase velocity de Broglie ($\upsilon_\perp ph$) and the nature determination of the wavelength of the cellular dislocations $\lambda_\perp$ wave associated with super plastic flow for the experimental investigation of for the Ti-6.5Al-3.3Mo-1.8Zr alloy mentioned above by using the equations (1) and (2). For the higher temperature of 900°C, the phase velocity de Broglie, $\upsilon_\perp ph$ = 6.962x10^{-9}m/s and $\lambda_\perp$ = 12.89 μm. As well, for the lower temperature of 800°C, $\upsilon_\perp ph$ = 4.8258x10^{-7}m/s and $\lambda_\perp$ = 13.4 μm. As a result, in both experimental conditions the deformation mechanics could be assisted in couple way by cellular dislocation dynamics.

Additionally, the activation energy for SPF of nanocrystalline Ti-6Al-3.2Mo alloy could be obtained by same procedure, with the follow experimental conditions:

Table2. Superplasticity Observations in Ti-6Al-3.2Mo alloy [9]

Grain Size (nm)	Strain Rate (s^{-1})	Temperature (°C)	Strain Rate Sensitivity, m
60	$5.4x10^{-4}$	600	0.5

The activation energy obtained in this work, $Q_\perp$=138.350 KJ/mol, which is similar to the activation energy value for volume diffusion of Ti ($Q_\perp$=131.7KJ/mol for β-Ti) [8]. The phase velocity de Broglie, $\upsilon_\perp ph = 1.83x10^{-8}$m/s and $\lambda_\perp$ = 36.61 μm. Furthermore, the activation energy for super plastic flow of nanocrystalline Ti-6Al-4V alloy is obtained under the next experimental conditions:

Table3. Superplasticity Observations in Ti-6Al-4V alloy [9]

Grain Size (nm)	Strain Rate (s^{-1})	Temperature (°C)	Strain Rate Sensitivity, m
70	$1.0x10^{-3}$	575	0.5

The activation energy obtained in this contribution, $Q_\perp$=131.843 KJ/mol, which is similar to the activation energy value for volume diffusion of Ti ($Q_\perp$=131.7KJ/mol for β-Ti) [8]. The phase velocity de Broglie, $\upsilon_\perp ph = 1.69x10^{-8}$m/s and $\lambda_\perp$ = 16.98 μm.

2.2 Al-4.9Cu-0.3Zr Alloy

In order to find out the activation energy for SPF dependence on the strain rate sensitivity m, let us to analyze the experimental data reported in the past for the Al-4.9Cu-0.3Zr alloy at 673K [10].

In figure 1, the dependence of strain rate sensitivity on strain rate at 673K, it is shown. From that information and by the application of the equation (3) the activation energy at different values of strain rate sensitive has been obtained in order to established their dependence, as it is shown in figure. 2. Additionally, the dependence of the activation energy for SPF on the phase velocity de Broglie ($\upsilon_\perp ph = \xi_\perp \lambda_\perp$), these results are shown in figure 3. Also, a cellular dislocation $\lambda_\perp$ wave was obtained, this value for the different experimental condition, practically is close to average value, $\lambda_{\perp average}$ = 21.46μm.

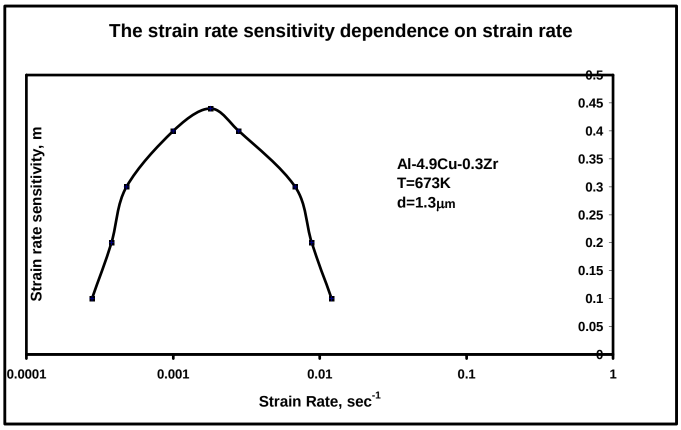

Fig. 1, Dependence of strain rate sensitivity (m) on strain rate $\xi_\perp$ of Al-4.9Cu-0.3Zr alloy at 673 K, with grain size d = 1.3μm. Information obtained from reference [10].

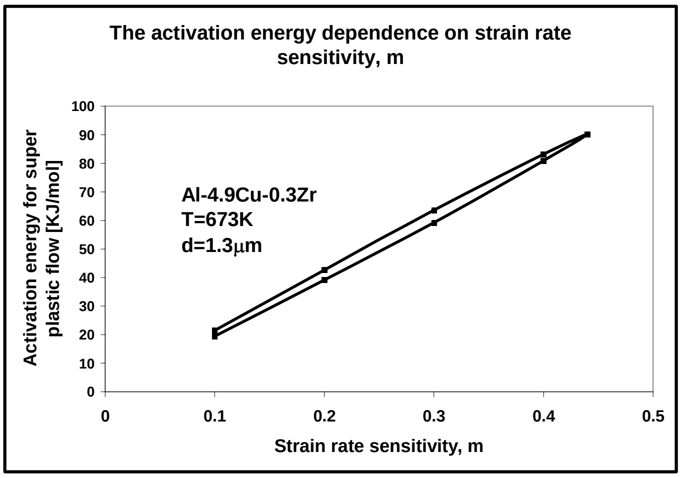

Fig. 2, Dependence of activation energy for super plastic flow of thermo mechanical worked Al-4.9Cu-0.3Zr alloy on strain rate sensitivity at 673 K, with grain size d = 1.3μm.

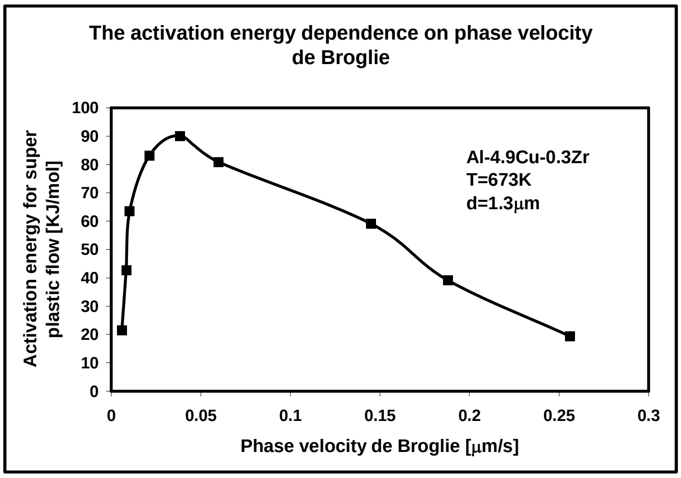

Fig. 3, Dependence of activation energy for super plastic flow of thermo mechanical worked Al-4.9Cu-0.3Zr alloy on velocity of phase de Broglie at 673 K, with grain size d = 1.3μm.

2.3 Al-Cu Alloy

Moreover, the activation energy for super plastic flow of nanocrystalline Al-Cu alloy could be obtained with the same procedure, through the follow experimental conditions:

Table4. Superplasticity Observations in Al-Cu alloy [9]

Grain Size (nm)	Strain Rate (s^{-1})	Temperature (°C)	Strain Rate Sensitivity, m
100	$1.0x10^{-3}$	350	0.5

The activation energy obtained in this contribution work, $Q_\perp$=96 KJ/mol which is very close to the activation energy value for optimum super plastic flow of Al-4.9Cu-0.3Zr ($Q_\perp$=90.19KJ/mol) that has been previously obtained. The phase velocity de Broglie, $\upsilon_\perp ph = 2.3x10^{-8}$m/s and $\lambda_\perp$ = 23.10 μm.

3 DISCUSSION

The main results of this investigation allow suggests us that the physics of super plastic flow in spatially extended polycrystalline systems could be a couple deformation mechanisms in an ultra fine grains as well in nanocrystalline materials, because the micro mechanisms connecting lattice dislocations with grain boundary dislocations and grain boundary sliding could be couple or assisted by cellular dislocations dynamics. This point of view is related with the determination of the phase velocity de Broglie $\upsilon_\perp ph$ and the cellular dislocation $\lambda_\perp$ wave, which has been obtained by means of the validation of the quantum mechanics and relativistic mathematical model proposed by Muñoz-Andrade through the equation (3).

4 CONCLUSIONS

The validation of the quantum mechanics and relativistic mathematical model using in this work allows obtain in a practical technique the activation energy for SPF of several advanced materials dependence on strain rate sensitivity and phase velocity de Broglie. On top, the nature determination of the wavelength of the cellular dislocations $\lambda_\perp$ wave associated with SPF. Therefore, it is feasible to mention that the physics of SPF could be associated with cooperative grain boundary sliding and self-accommodation process in a couple nature manners with the cellular dislocations dynamics as consequence of the physical meso-thermo-mechanics.

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