CONSTITUVE MODELLING FOR CREEP OF DRAWN COPPER WIRE

Zakaria Boumerzoug[1)]*, Salim Gareh* [2)*]
[1)] *Laboratoire des Matériaux Semi-conducteurset Métalliques (LMSM), Université de Biskra, 07000 Biskra, Algérie*
[2)] *Department of Mechanical Engineering, Faculty of Technology, University of Biskra, Biskra 07000, Algeria*

Received: 23.10.2014
Accepted: 14.11.2014

* Corresponding author: *e-mail: garehsalim@gmail.com, Tel: +213796651689, Department of Mechanical Engineering, Faculty of Technology, University of Biskra, Biskra 07000, Algeria*

Abstract
The high-temperature creep behaviour of drawn copper wire was studied by different constant stresses 98,108 and 118 MPa and under the temperatures of 250, 290 and 340°C. This study deals with the creep based prediction modelling of an industrial copper wire. The proposed unified creep damage constitutive equations were determined using experimental data achieved for materials at applied stress. The comparison of experimental and predicted effective creep strain curves is carried out for all applied stresses applied on the drawn copper wire. The evaluated stress exponent n = 9.21, 10 and 14 and the activation energy Q = 22.25, 31.75 and 50.75 indicated that the creep deformation of the drawn copper wire is controlled by the dislocation creep. The evaluated of the mean relative error from 5.18 % to 10.11 confirmed the creep strain predicted by the proposed model well agree with experimental data.

Keywords: creep deformation, drawn copper wire, creep constitutive model

1 Introduction

Copper in particular has attracted attention due to its good properties such as low resistivity. Due to its high ductility which is the ability to be easily drawn into wires, copper dawning is very attractive manufacturing process. The wire drawing is a process that is used for the manufacturing of metal wires. Copper wire has long been the preferred conductor material. The demands of electrical technology require copper to have higher mechanical properties and to be capable of using at elevated operating temperatures while still retaining the good conductivity for which it is selected in the first place [1].

Creep is the process by which plastic flow occurs when a constant stress is applied to a metal for a prolonged period of time. After the initial strain $\varepsilon 0$ which follows the application of the load, creep usually exhibits a rapid transient period of flow before is settles down to the linear steady-stage, which eventually gives way to tertiary creep and fracture [2].

However, creep phenomena development is still not sufficiently recognized, especially under uniaxial stress conditions. However, further complex microscopic creep investigations are required to achieve a better understanding of the nature of the process. In a uniaxial creep curve tertiary creep is observed as the increase of the creep rate. The shape of the final part of the creep curve and the duration of the tertiary creep stage depend on the material composition, the stress and the temperature [3]. The origins of tertiary creep are progressive damage processes

DOI 10.12776/ams.v20i4.411 p-ISSN 1335-1532
e-ISSN 1338-1156

including the formation, growth and coalescence of voids on grain boundaries, coarsening of precipitates and environmental effects [4-10].

In order to describe the creep behaviours of metals and alloys, many researchers have tried to establish constitutive models, such as continuum damage equation and Andrade's equation [11-17]. For example Authors [11] performed a review on the development and the use of internal state variable theory based on the Coleman and Gurtin thermodynamics formulations for dislocations, creep, and continuum damage mechanics. Authors [12] proposed a model which integrated the power-law creep, diffusional creep and a simple damage term for simulating the creep-failure behaviour of the inter-critical heat affected zone. Authors [13] developed a new anisotropic tertiary creep damage constitutive model based on crystal plasticity theory for anisotropic materials. Results indicated that creep deformation was modelled accurately. Author [14] compiled the results of experiments in different experimental conditions on different materials: steel, concrete, nylon, graphite, etc.; in all cases the agreement is excellent with the Andrade's equation.

In this investigation, we have modified Andrade's equation by the relationship of the state damage. The comparison of experimental and predicted effective creep strain curves is carried out for all applied stresses on the copper wire.

2 Material and experimental methods

The material used in this investigation is an industrial copper wire of composition 99.9 Cu, 0.001 Bi, 0.002 Sb, 0.002 As, 0.005 Fe, 0.002 Fe, 0.002 Ni, 005 Pb, 0.002 Sn, 0.004S, 0.004 Zn and 0.073 (wt. %), others elements. Samples having gauge length of 100 mm and diameter of 1.8 mm obtained after cold wire-drawing process were annealed at 500°C for 2 hours. The creep specimens were tested at temperature 250, 290 and 340 °C and under stress 98, 108, and 118 MPa.

2.1 Approach Modelling

A relationship for describing high-temperature plastic deformation within the structural phenomenological model of the Andrade [18] is based on the plastic deformation ε, arising from a constant stress σ, is expressed in the Eq. 1:

$$\varepsilon = \varepsilon_0 + B t^m + \dot{\varepsilon}_m t \tag{1.}$$

$$\dot{\varepsilon}_m = A\left(\frac{\sigma}{1-w}\right)^n \tag{2.}$$

whereε_0 is the instantaneous plastic deformation, *B* and *m* are material constants. The term tm models the primary creep and is the creep rate.

We know that the Andrade's equation plot only first and second stage of the creep curve, but not plot third stage. For that reason we have to substitute Eq. 2 (relationship of Kachanov [19] and Rabotnov [20]) into Eq. (1).

$$\varepsilon(t) = \varepsilon_0 + B t^m + A\left(\frac{\sigma}{1-w(t)}\right)^n t \tag{3.}$$

DOI 10.12776/ams.v20i4.411 p-ISSN 1335-1532 e-ISSN 1338-1156

A variable w (0<w<1) was introduced by [21] to present the state of damage of material.

$$w(t) = 1 - \left(1 - \frac{t}{t_r}\right)^{\frac{1}{l+1}} \tag{4.}$$

The material constants A, n, and l can be then determined from the stationary creep. Let $\dot{\varepsilon}_{m1}$ and $\dot{\varepsilon}_{m2}$ be minimum creep rates for constant stresses σ_1 and σ_2, respectively. Then the material constants n and A can be estimated from:

$$n = \frac{\log\left(\dot{\varepsilon}_{m1} / \dot{\varepsilon}_{m2}\right)}{\log\left(\sigma_1/\sigma_2\right)} \tag{5.}$$

$$A = \frac{\dot{\varepsilon}_{m1}}{\sigma_1^n} = \frac{\dot{\varepsilon}_{m2}}{\sigma_2^n} \tag{6.}$$

within the temperature ranges considered in this work, increasing temperature caused an increase in the parameters A and B, for that the material constants A and B should be replaced by the functions of temperature. Assuming the Arrhenius type temperature dependence the following relations can be utilized (Eq. (7) and Eq. (8)).

$$B = B_0 e^{-(Qtr/RT)} \tag{7.}$$

$$A = A_0 e^{-(Q/RT)} \tag{8.}$$

where Q_{tr} and Q are the activation energies of creep and transient creep, respectively.

$$Q_{tr} = \left[\frac{\partial \ln B}{\partial(-1/RT)}\right]_\sigma \tag{9.}$$

$$Q = \left[\frac{\partial \ln \dot{\varepsilon}_m}{\partial(-1/RT)}\right]_\sigma \tag{10.}$$

Substituting Eq. (7) and Eq. (8) into Eq. (3) yields the creep model Eq. (11):

$$\varepsilon = \varepsilon_0 + \left[B_0 e^{-(Q_{tr}/RT)}\right] t^m + \left[\left(A_0 e^{-(Q/RT)}\right)\left(\frac{\sigma}{1-w}\right)^n\right].t \tag{11.}$$

3 Results and Discussion

Fig. 1 present the curves of creep strain versus time of copper draw wire, obtained at different applied stress (118, 108 and 98 MPa) at temperature 250, 290 and 340°C. Generally, the time dependent elevated temperature creep deformation can be represented by the creep strain time curve which is usually distinguished by the primary, secondary and tertiary stages. Following the initial strain on loading, the creep rate gradually decreases during the primary stage. The creep rate continues to decrease and reach a minimum or secondary value during the secondary

DOI 10.12776/ams.v20i4.411 p-ISSN 1335-1532
e-ISSN 1338-1156

stage. During the tertiary stage, due to the increase of cavitations and cracks in the specimens, the creep rate rapidly increases, which lead to the final fracture.

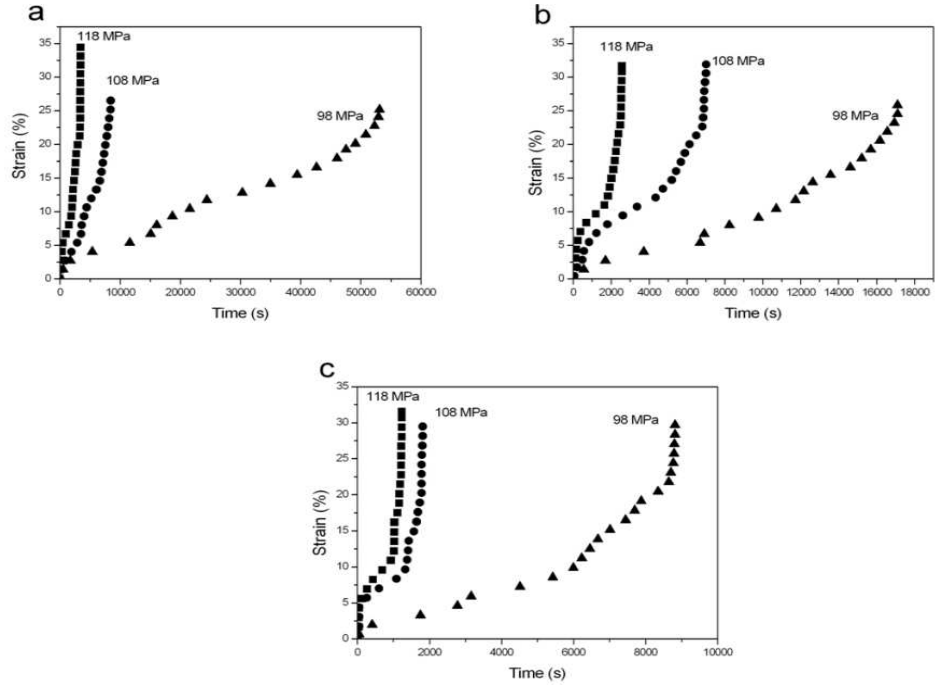

Fig.1 Experimental creep curves for copper wire at temperature of (a): 250°C, (b): 290°C and (c): 340 °C

The minimum creep rate of the copper wire has the applied stress dependence as shown in Fig. 2a. The stress exponent, n is about 14, 9.21 and 10 respectively for copper wire at temperature 250, 290 and 340°C. These n values indicate the dominance of dislocations glide and climb as the rate controlling deformation mechanisms [21].

The activation energy of transient creep Q_{tr}[22], as calculated from the slopes of the straight lines of **Fig. 2b** has values ranging between 18.5 and 20 kJ/mol. To determine the activation energy for creep *Q*, the minimum creep rates were measured in the temperature between 250,290 and 340°C and at the applied stress 98,108 and 118 MPa. The values of the activation energy *Q* are equal to 22.25, 31.75 and 50.75 kJ/mol for copper wire under stress 98,108 and 118 MPa respectively (**Fig. 2c**).

The transient creep in Ref [22], is represented the second part in Eq. (3); this means that it can be written the following Eq. (12).

$$\varepsilon_{tr} = Bt^{m} \qquad (12.)$$

We can calculate the transient creep time exponent m with the Eq. (13) (**Fig.3**). The values of the *m* are changing with temperature and stress, for example in **Fig. 4a**, *m* = 0.415, 0.56 and 0.60 under stress 98,108 and 118 MPa, respectively at temperature 250°C. In Ref [3], they calculated the parameter *m* = 0.55 for copper.

DOI 10.12776/ams.v20i4.411 p-ISSN 1335-1532
e-ISSN 1338-1156

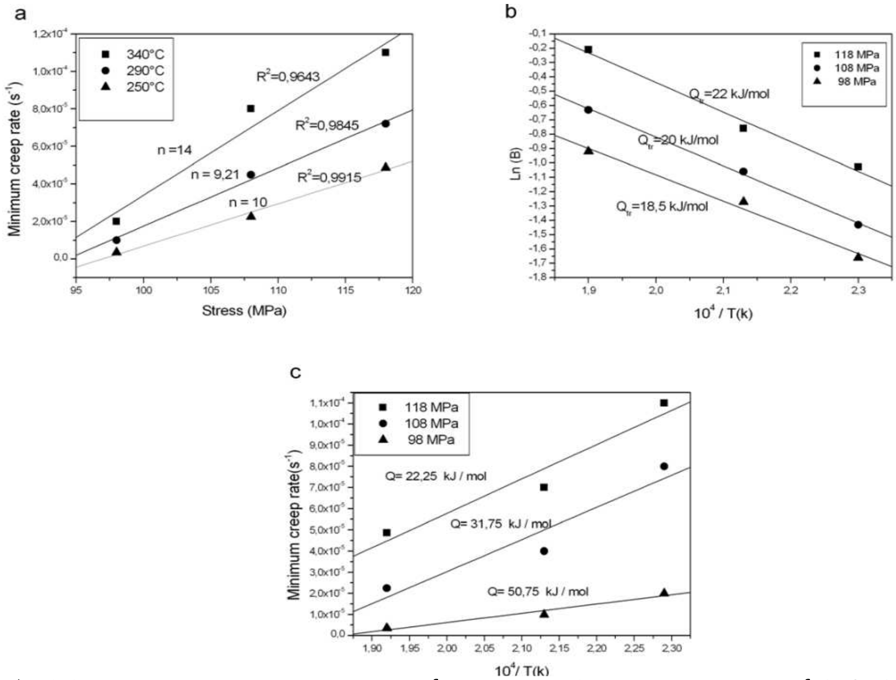

Fig.2 a)Minimum creep rates versus stress for copper wire at temperature of 250, 290 and 340°C, b) Relation between transient creep strain and temperature for copper wire under different stress 98,108 and 118 MPa. c) Relation between minimum creep rate and temperature for copper wire under different stress 98,108 and 118 MPa

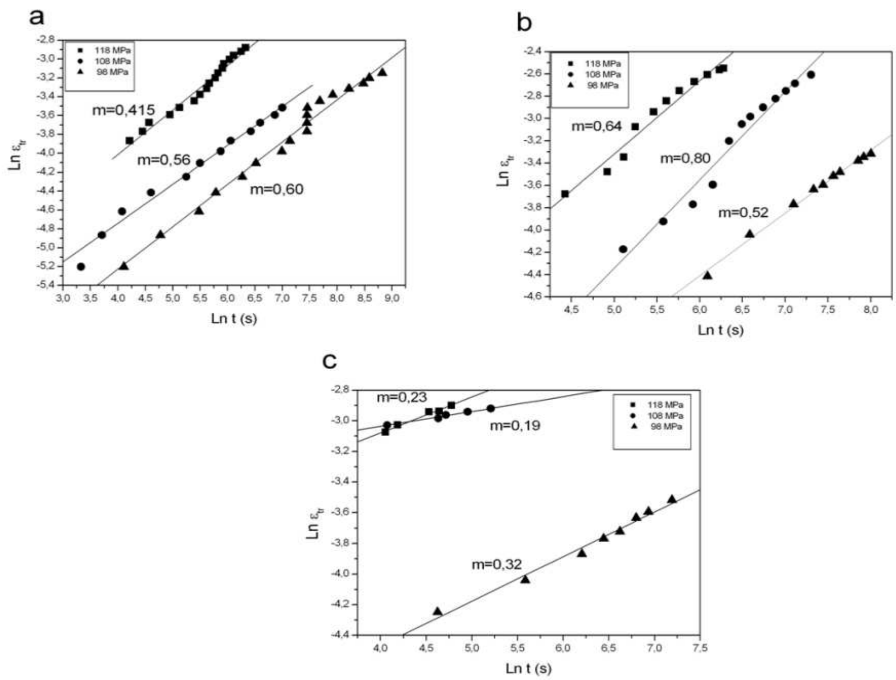

Fig.3 Representation graphical for calculate the transient creep time exponent m at temperature of a) 250 °C, b) 290°C and 340°C

DOI 10.12776/ams.v20i4.411 p-ISSN 1335-1532
e-ISSN 1338-1156

$$m = \left[\frac{\partial \ln \varepsilon_{tr}}{\ln t} \right] \tag{13.}$$

These curves are predicted data by using the determined material constants, listed in **Table 1**. **Fig. 4** show that the comparisons of the measured and predicted creep strains by Eq. (11). Obviously, an agreement between measured and calculated values is satisfactory under the creep temperature of 250, 290 and 340°C, which indicates that the proposed constitutive models can give a good estimate of the first, secondary and tertiary stages creep deformation for drawn copper wire.

Table 1 List of determined material constants for Eq (11)

T (°C)	σ (MPa)	ε_0 (%)	A	B	n	t_{rupture} (s)	l	m	Q_{tr}	Q
250	98	0,12	65.10^{-34}	0.32	14	3479	16	0.415	18.5	50.75
	108	0,23		0.27		8422		0.56	20	31.75
	118	0,19		0.18		53083		0.60	22	22.25
290	98	0,55	24.10^{-28}	0.33	9.21	18000	11.21	0.64	18.5	50.75
	108	0,76		0.66		7500		0.80	20	31.75
	118	0,66		0.72		2750		0.52	22	22.25
340	98	1,25	48.10^{-26}	0.39	10	9000	12	0.23	18.5	50.75
	108	0,74		0.74		1900		0.19	20	31.75
	118	2,50		0.88		1300		0.30	22	22.25

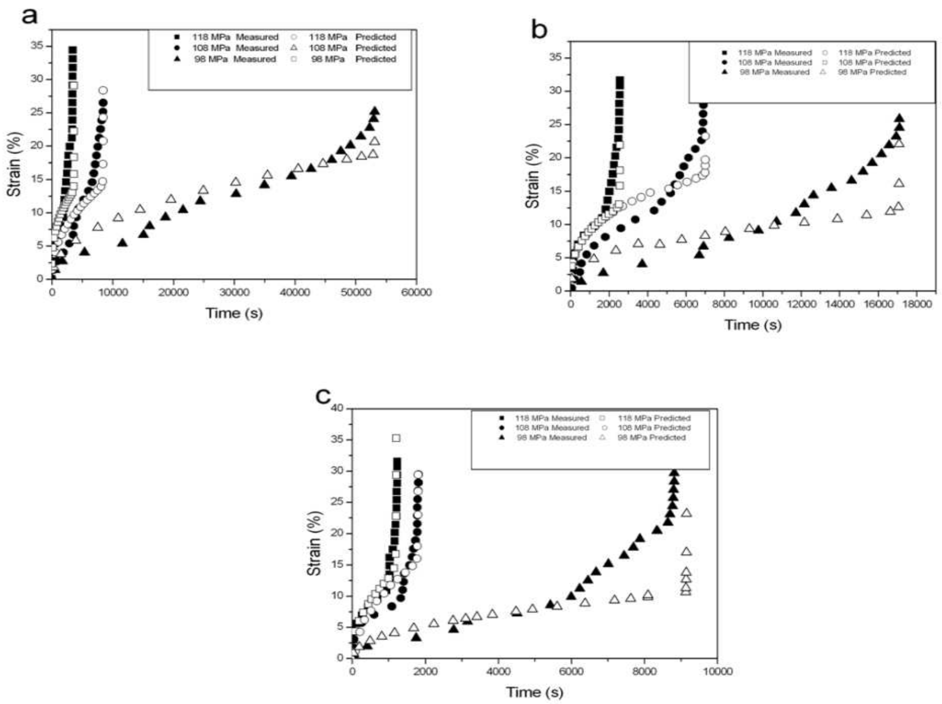

Fig.4 Comparison of experimental and predicted effective strain creep curves for copper wire at temperature of a) 250°C, b) 290°C and 340°C

DOI 10.12776/ams.v20i4.411
p-ISSN 1335-1532
e-ISSN 1338-1156

Where and are the experimental strain and prediction strain, respectively. We have calculated the mean relative error ($Error_M$) for all creep testes as in **Table 2**, using Eq. (15). We observed that the values of the $Error_M$ are between 5.18 and 10.11 %, which is less than 10 %.

$$Error(\%) = \left|\frac{\varepsilon_E - \varepsilon_P}{\varepsilon_E}\right|.100 \quad (\%) \tag{14.}$$

$$Error_M = \frac{\sum_{i=1}^{N} Error(\%)}{N} \tag{15.}$$

N presents the number of data points on each creep curve (between curve experimental and prediction), which we calculated the relative error.

Table 2 The value of the mean relative error ($Error_M$).

Relative error moy (ErrorM)	T=250°C	T=290°C	T=340°C
σ = 98 MPa	5.18	6.76	7.28
σ = 108 MPa	9.21	8.84	8.42
σ = 118 MPa	8.87	10.11	7.22

4 Conclusion

Constitutive model to describe the high temperature creep behaviour of drawn copper wire based on the modification of the Andrade's equation. The creep curves of drawn copper wire predicted by proposed model well agree with experimental results, which confirm that the developed creep constitutive model can give an accurate and precise estimate of the high temperature creep behaviour for drawn copper wire.

References

[1] V. Callcut: *High Copper Alloys-High Strength Coppers for Demanding Electrical Applications*, 2006 http://www.copper.org/publications/newsletters/innovations/2006/09/high_cu_alloys.html

[2] R.E. Smallman, A.H.W. Ngan: *Physical metallurgy and advanced materials*, Elsevier, 2007

[3] J. Lin, Z.L. Kowalewski, J. Cao: International Journal of Mechanical Sciences, Vol. 47, 2005, No. 7, p. 1038–1058, DOI:10.1016/j.ijmecsci.2005.02.010

[4] I. Dlouhy, B. Strnadel: Engineering Fracture Mechanics, Vol. 78, 2008, No. 3-4, p. 726-738, DOI:10.1016/j.engfracmech.2007.03.038

[5] M.W. Decker, J.R. Groza, J.C. Gibeling: Materials Science & Engineering A, Vol. 369, 2004, No. 1-2, p. 101–111, DOI:10.1016/j.msea.2003.10.306

[6] S. Spigarelli: International Journal of Pressure Vessels Piping, Vol. 101, 2013, p. 64-71, DOI:10.016/j.ijpvp.2012.10.2005

[7] B. Wilshire, A.J. Battenbough:Materials Science & Engineering A, Vol. 443, 2007, No. 1-2, p. 156–166, DOI:10.1016/j.msea.2006.08.094

[8] Z. Boumerzoug, S. Gareh, A. Berribeche: Word Journal of Condensed Matter Physics, Vol. 2, 2012, No. 4, p. 241-245, DOI:10.4236/wjcmp2012

[9] A. Beribeche, Z. Boumerzoug, V. Ji: Advanced Materials Research, Vol. 811, 2013, p. 9-13, DOI: 10.4028/www.scientific.net/AMR.811.9

[10] A. Diha, Z. Boumerzoug: Advanced Materials Research, Vol. 629, 2013, p. 90-94, DOI: 10.4028/www.scientific.net/AMR.629.90

DOI 10.12776/ams.v20i4.411 p-ISSN 1335-1532
e-ISSN 1338-1156

[11] M.F. Horstemeyer, D.J. Bammann: International Journal of Plasticity, Vol. 26, 2010, No. 9, p. 1310–1334, DOI:10.1016/j.ijplas.2010.06.005
[12] J. Besson, S. Leclercq, V. Gaffard, A.F. Gourgues-Lorenzon: Engineering Fracture Mechanic, Vol. 76, 2009, No.10, p.1460–1473, DOI:10.1016/j.engfracmech.2008.12.007
[13] C.M. Stewart, A.P. Gordon, Y.W. Ma, R.W. Neu: International Journal of Pressure Vessels Piping, Vol. 88, 2011, No. 8-9, p. 356–364, DOI:10.1016/j.ijpvp.2011.66.010
[14] A.J. Kennedy: Processes of creep and fatigue in metals, Oliver and Boyd, London, 1962.
[15] W.F. Budd, T.H. Jacka: Cold Regions Science and Technology, Vol. 16, 1989, No. 2 , p.107- 144,DOI:10.1016/0165-232x(89)90014-1
[16] T. A. Venkatesh, D. C. Dunand: Acta Materialia, Vol. 47, 1999, No. 17, p. 4275 – 4282, DOI:10.1016/s1359-6454(99)00308-0
[17] J. C. Dandrea, R. Lakes: Mechanics Time-Depend Materials, Vol. 13, 2009, No. 3, p. 303–315,DOI:10.1007/s11043-009-9089
[18] L.M. Kachanov: *The theory of creep*, Boston Spa, National Lending Library, 1958
[19] Y.N. Rabotnov: *Creep problems in structural members*, Amsterdam, North Holland Publishing Company, 1969
[20] J. Lemaitre, J.L. Chaboche: *Mechanics of Solid Materials*. Cambridge University Press, Cambridge 192, Levinson, M, 1981
[21] J.Y. Kim et al.: Acta Mechanica Solida Sinica, Vol. 21, 2008, No. 4, p. 308-311, DOI:10.1007/s10338-008-0835-0
[22] G.S. Al-Ganainy, A. Fawzy, F. Abd El-Salam: Physica B, Vol. 344, 2004, No.1-4 , p. 443-450,DOI:10.1016/j.phsb.2003.10.028

Acknowledgments
We would like to thank Dr. S. Benramache, Mr. A. Heciniand, Mr. H. Bentrah for their help.