Determination of Strain Rate Sensitivity (SRS) for Grain Size Variants on Nanocrystalline Material Produced by ARB and ECAP

P. B. Sob, A. A. Alugongo, T. B. Tengen

Abstract—Mechanical behavior of 6082T6 aluminum is investigated at different temperatures. The strain rate sensitivity is investigated at different temperatures on the grain size variants. The sensitivity of the measured grain size variants on 3-D grain is discussed. It is shown that the strain rate sensitivities are negative for the grain size variants during the deformation of nanostructured materials. It is also observed that the strain rate sensitivities vary in different ways with the equivalent radius, semi minor axis radius, semi major axis radius and major axis radius. From the obtained results, it is shown that the variation of strain rate sensitivity with temperature suggests that the strain rate sensitivity at the low and the high temperature ends of the 6082T6 aluminum range is different. The obtained results revealed transition at different temperature from negative strain rate sensitivity as temperature increased on the grain size variants.

Keywords—Nanostructured materials, grain size variants, temperature, yield stress, strain rate sensitivity.

I. INTRODUCTION

STRAIN RATE SENSITIVITY (SRS) is important in determining the deformation mechanisms of nanostructured materials [1]. Several studies on SRS have been carried out and this has contributed to the present controversies on nanomaterials mechanical properties. Most researchers have reported that SRS varied with the processing parameters and the microstructural variables [2]-[4]. The varying definition of model equations of SRS contributes greatly to the present controversies on nanomaterials mechanical properties. The different methods and techniques to compute SRS are explained in this section.

A. The Methods of Tensile Test

During this technique, a jump test was conducted using a universal testing machine by increasing and decreasing the strain rates by 10 % for every 100% increment of elongation [5]. The SRS values for various strains were computed using the expression [5].

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$$SRS = \frac{\log\left(\frac{\sigma_2}{\sigma_1}\right)}{\log\left(\frac{\dot{\varepsilon}_2}{\dot{\varepsilon}_1}\right)} = \frac{\log\frac{F_2(1+e)S_o}{F_1(1+e)S_o}}{\log\frac{V_2(1+e)L_o}{V_1(1+e)L_o}} = \frac{\log\frac{F_2}{F_1}}{\log\frac{V_2}{V_1}} \qquad (1)$$

where σ_1 and σ_2 are the flow stresses corresponding to instantaneous strain rates $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$. F_1 and F_2 are the forces and V_1 and V_2 are the cross-head speeds before and after the jump.

The SRS values at a single strain was calculated, at a fixed strain rate using the experimental data of the cross-head speeds V_1 and V_2 with the corresponding forces F_1 and F_2. A series of SRS values were computed from the jump test and plotted as a function of strain rates. The SRS was measured at different temperatures in the strain rate jump tensile test [1].

B. The Compression and Vishay Micro Measurement Techniques

Sabirov [6] studied the relationship between SRS of the flow stress and the operative deformation mechanisms in the UFG Al–Mg–Si (Al6082) alloy under compression. Their results of compression testing revealed that increased SRS due to grain boundary sliding and micro shear banding offers enhanced ductility at low strain rates. Another study on SRS by [7] revealed that, the SRS can be calculated by measuring the strain with a Vishay micro measurement group high-elongation uniaxial strain gauge affixed to the middle of the gauge section. The results revealed increase in yield strength when the material strain-rates are increased. It was however observed that at high deformation temperature the SRS increased with increasing deformation temperature [2]-[4]. Several studies have shown that nanomaterials are very sensitive to temperature [2]-[5]. Varying temperature during deformation of conventional materials to nanostructured materials affect the SRS of materials [2]-[7].

Temperature has a vital role to play during grain refinement since all severe plastic deformation (SPD) techniques involve thermomechanical processes. Kumar [8] reported that, the thermodynamic properties of nanomaterials depend on the size and shape of their vibration energy. Lee and Chiou [9]-[10] also observed that the SRS increased with decreasing grain size. Kumar [8] developed a theoretical model and studied the size and shape effect on strain and strain rate. The theoretical results were compared with experimental results in the

research and it was shown that the experimental data supports the theoretical developed model. Guisbiers [11] developed a model predicting the size dependence of melting and cohesive energy of nanocrystalline. From the studies, obtained results were compared with different models predicting the size dependence. Zhang [12] also demonstrated that, a simple model, free from any adjustable parameter can be developed for the melting enthalpy and melting entropy of nanocrystals. The idea was based on Mott's equation for melting enthalpy and melting entropy for non-semiconductor crystals model of size dependent melting temperature. The bulk properties of crystals depend on their structure but at nanoscales, in addition to the structure their size and shape are important factor which influences their properties. The most important characteristic of materials at nanoscales is their high surface to volume ratio which affects their thermodynamic properties and SRS [12]. It is now well known that the melting temperature of nanoparticles depends on their size [13]; thus size and temperature are important parameters when studying nanomaterials mechanical properties.

Although the size-dependent properties are so useful, a unique attempt to establish a quantitative model describing the size dependence of SRS, based on simple consideration of surface/volume ratio, cannot satisfactorily interpret the stochastic nature of grain size. Thus, it is necessary to model quantitatively SRS as function of grain size variants (3-D grain). *In this paper, the SRS is computed on grain size variants and the effect of processing temperature on SRS are discussed for a 3-D grain deformed by Accumulative Roll-Bonding (ARB) and Equal Channel Angular Pressing (ECAP).* The proposed models are tested with data from grain deformation in nanocrystalline aluminum samples.

II. METHODOLOGY

The most important mechanical characteristic of superplastic material is the high strain rate sensitivity of its flow of stress [12], [13]. The characteristic equation which describes material yield stress $(\sigma(r))$ and strain rate $(\dot{\varepsilon})$ can be related through a power law usually written as

$$\sigma(r) = K\dot{\varepsilon}^m \qquad (2)$$

where m is the temperature dependent strain rate sensitivity (SRS) factor. K is a proportionality constant that is being ignored by taking logarithm of both sides of the equation when the SRS is computed as

$$m = \frac{d\log(\sigma(r))}{d\log(\dot{\varepsilon})} \qquad (3)$$

By employing the different models of strain (ε) for 3-D grain during grain refinement, the corresponding strain rates $(\dot{\varepsilon})$ for r, r_1, r_2 and r_3 during grain refinement are defined as

$$d(\dot{\varepsilon}_1) = \frac{d\left[\dfrac{dr_1}{r_1}\right]}{dt} = \frac{d\left(M\left(\dfrac{1}{r_{1c}}\right)\left(\dfrac{1}{r_1}\right) - \dfrac{1}{r_1^2}\right)dt + \dfrac{CDdW(t)}{r_1} - \dfrac{ZV_1 r_1^2 d(t)}{r_1}}{dt} \qquad (4)$$

where r_{cl}=local critical grain size, Z and D are Constants, $dW(t)$=increment of the Wiener process, $V_1 = \tau_1 r_1^2$ define rate of grain breakage,

$$M = M_0\left(1 + \frac{CD}{r_1}\right),$$

CD = 4(Hm)(h$_0$)/((k)(T)), T_m = T{ln(m$_{01}$/m) and M_0 = M$_{01}$exp{-T$_m$(inf)/T}.

$$d(\dot{\varepsilon}_3) = \frac{d\left[\dfrac{dr_3}{r_3}\right]}{dt} = \frac{d\left(\dfrac{Ratio_1 dr_1}{r_3}\right)}{dt} \qquad (5)$$

$$d(\dot{\varepsilon}_r) = \frac{d\left[\dfrac{dr}{r}\right]}{dt} = \frac{d\left(\dfrac{-Ordt + IdW(t)}{r}\right)}{dt} \qquad (6)$$

where O and I are constants

$$d(\dot{\varepsilon}_2) = \frac{d\left[\dfrac{dr_2}{r_2}\right]}{dt} = \frac{d\left(\dfrac{Ratio_2 dr}{r_2}\right)}{dt} \qquad (7)$$

The material yield stress $\sigma(r)$ on nanomaterial's grain subjected to plastic deformation is given by [14].

$$\sigma(r) = \sigma_0' + A\left(r^{-\frac{1}{2}}\right) - B\left(r^{-1}\right) - C\left(r^{-\frac{3}{2}}\right) \qquad (8)$$

where $\sigma_0' = \sigma_0 + K_t$ is bulk yield stress, $A = K_d$ is HPR proportionality constant, $B = K_t[2hH_m/RT_r]$, $C = K_d[2hH_m/RT_r]$, K_t is a constant, h is atomic diameter in the case of metal, H_m is the bulk melting enthalpy, R is ideal gas constant, T_r is the room temperature, $K_d > 100K_t$ and $\sigma_0 > 10K_t$.

Equations (2)-(8) are solved simultaneously using Engineering Equation Solver software (F-Chart Software, Madson, W153744, USA) and also employing the fact that, grain size distribution evolve as lognormal distribution [15].

III. RESULTS AND DISCUSSION

To test the models proposed in this report, the data from (nanocrystalline) aluminum sample (some of which are found in other reports, [16]) are used, which are *M$_0$'=0.01nm^{2}s^{-1}, m=4, CC=12, a=0.90, D=10^{-4}, h$_0$=0.25nm, T$_m$(∞)=933.47K, CV$_0$=0.3, Ratio$_1$=0.81, Ratio$_2$=1.071, H$_m$(∞)=10.71KJMol^1, σ$_0$'=16.7MPa, K$_t$=1.3, σ$_0$=15.40MPa,*

$Kd=1301.77MPa\_nm^{1/2}$, $R=8.31JK^{-1}mol^{-1}$, $T_r=300K$. The additional data obtained from this work are $O=0.0035$, $I=1.1$, $r_{cl}=1.95r$, $r_0=100nm$, $Z=0.4$ and $\tau_1=0.000008$. The additional data were obtained through curve fitting of the empirical data from the different measures of the sizes. The obtained results are presented in the plots below.
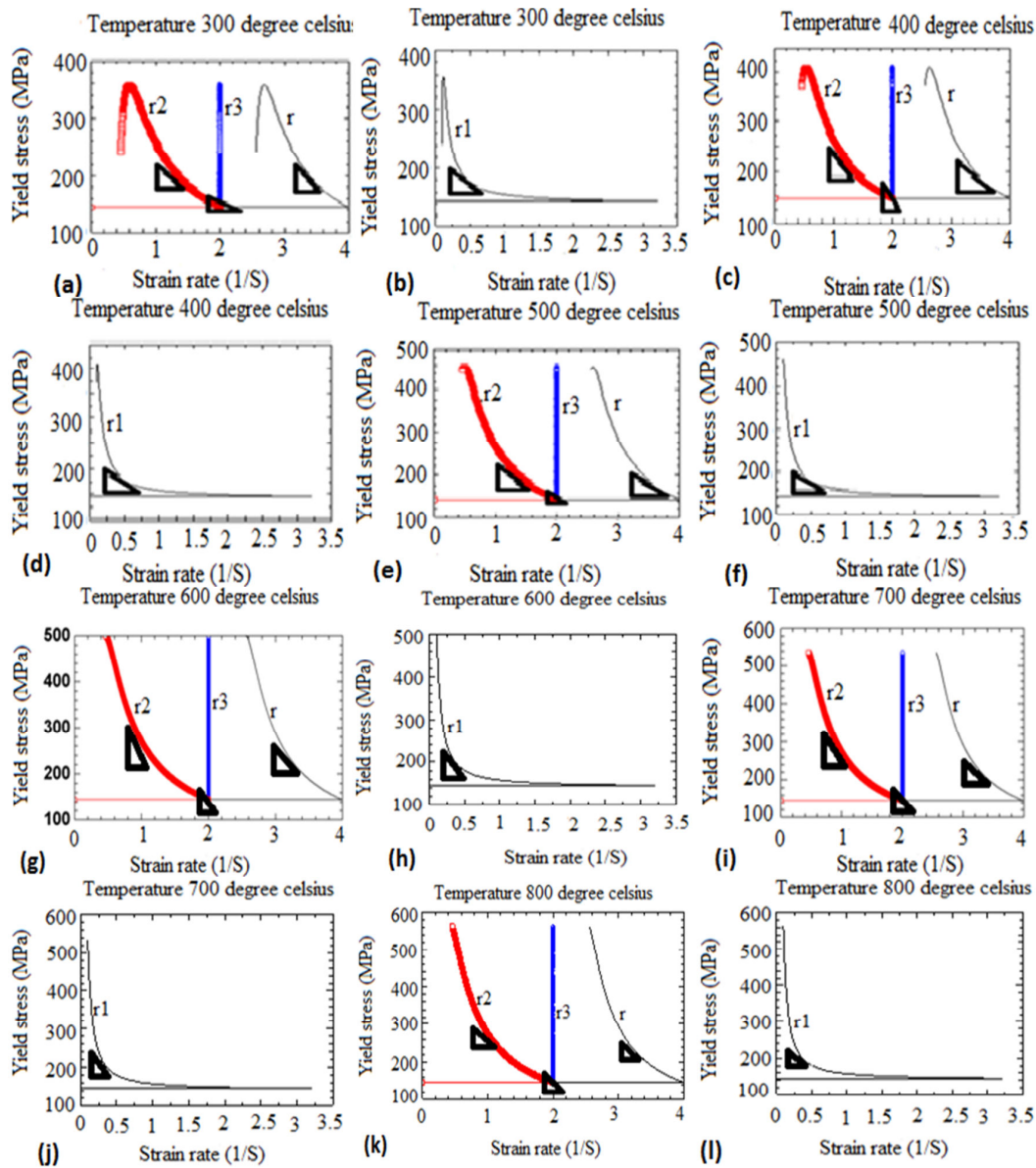

Fig. 1 Yield stress and strain rates at different temperatures and SRS calculated at the slops of the grain size variants

TABLE I
THE RESULTS OF SRS MEASUREMENT AT SIX TEMPERATURES ON GRAIN SIZE VARIANTS

Temperature (°C)	SRS) r_1	(SRS) r_2	(SRS) r_3	(SRS) r4
300	-5.66	-5.67	-5.91	-8.65
400	-5.74	-6.33	-4.54	-12.12
500	-6.13	-19.07	-2.83	-11.61
600	-3.40	-5.03	-4.64	-4.78
700	-4.47	-5.03	-4.47	-18.35
800	-4.03	-4.03	-4.67	-4.67

The SRS values for the grain size variants were calculated from the slopes of the plots at different temperature using $d(\log(\sigma(r)))$ and $d(\log(\dot{\varepsilon}))$; these values are presented in Table I.

IV. THE SENSITIVITY OF NANOMATERIALS

The variation of SRS with temperature is shown in Fig. 2 for six temperatures. It is observed that, at a temperature range from room-temperature up to 400°C, no pronounced SRS is

found for r_1. By increasing the testing temperature further, the SRS also increased and decreased for grain size variants. The different results of SRS for grain size variants are due to different grain curvatures during grain refinement. The higher amount of high angle grain curvatures is the main reason for the enhanced SRS and the lower amount of low angle grain curvatures is the main reason for a lower SRS for grain size variants. The results obtained indicate a change in the deformation mechanism of the ultra-fine grain regime due to different grain curvatures during grain refinement. The thermal activated recovery processes taking place at the grain curvatures are the dominating deformation mechanisms. Studying the effect of curvature on SRS it is observed from Fig. 2 that, at a temperature of 400°C different SRS are revealed for the grain size variants. From the different SRS revealed at a temperature of 400°C the material SRS is high for radius measured along r_3 since the grain curvature for r_3 is higher when compared with the curvatures of r_2, r_1 and r. When the temperature increased from 400°C to 500°C the SRS increased along r_3 and decreased along r_1, r and r_2 since the grain curvature of r_3 is higher when compared with the curvatures of r_1, r and r_2. The SRS decreases more along r_2 when compared to r_1 while r and r_3 increased at a temperature of 400°C to 500°C since the grain curvature of r_2 is $_{lower}$ than the curvature of r_1, r and r_3. *The variation of SRS with temperature in grain size variants suggests that, the SRS for 6082T6 aluminum at the low and the high temperature ends are different*. This suggests that, different dynamic strain aging (DSA) mechanisms dominate the behavior of r_1, r_2, r_3 and r at different temperature ranges since at extremely low temperature the SRS is small and at high temperature the SRS increase and results to material hardening. The high temperature behavior does not appear to be due to structural changes such as precipitation, which could change the nature of the rate controlling obstacles to dislocation motion. From this study, it has been revealed that nanomaterials are very sensitive to temperature during manufacturing.

V. The Strain Rate Sensitivity and Grain Size Variants

The primary reasons for increased and decreased in SRS is due to different grain curvatures, grain curvature diffusion, grain curvatures sliding mediated by dislocation activity and controlled plasticity on the grain size variants during grain refinement. It is observed from Fig. 3 that the SRS vary with grain size variants due to different grain curvatures. It is observed from Fig. 3 that at a grain size of 20nm different SRS are revealed for the grain size variants. From the different SRS revealed at a grain size of 20nm the material SRS is high for radius measured along r_3 and low for radius measured along r, r_1 and r_2 since the grain curvature of r is higher than the curvatures of r, r_1 and r_2. It is observed at a grain size of 40nm that SRS increased when measured along r, r_1, r_2 and decreased along r_3 due to higher grain curvatures of r, r_1, r_2 and lower grain curvature of r_3. It is also observed at a grain size of 60nm to 80nm that, the SRS increased along r_3, r_1, r_2

and decreased along r. It is further observed at a grain size of 100nm that, the SRS increased more along r when compared to r_1, r_2 and r_3 due to higher grain curvature of r.
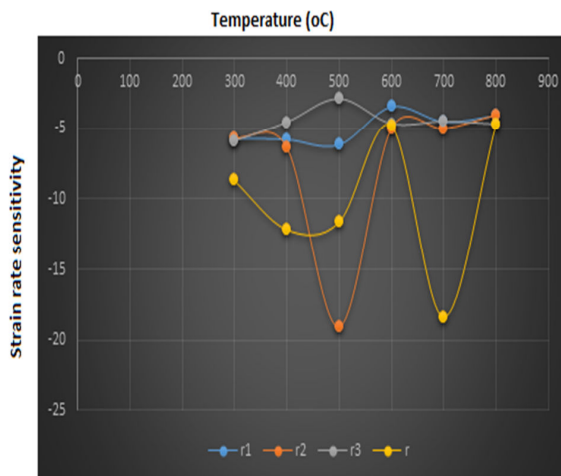

Fig. 2 Variation of (SRS) with Temperature at six temperatures within the negative SRS range for grain size variants
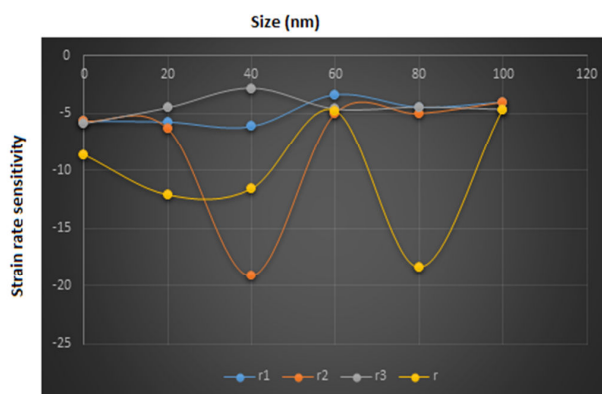

Fig. 3 Variation of the strain rate sensitivity (m) with size (nm) at six temperatures within the negative SRS range

The results in Fig. 3 show a clear fashion that, the SRS continuously increased and decreased at different temperatures on grain size variants. The increased in SRS is directly related to a change in the rate controlling mechanism for plastic deformation. There have been reports of both increased and decreased SRS with decreasing grain size in metals [2], [17] similar to the result obtained in this research.

VI. Conclusions

The current work was aimed at determining the effect of SRS on grain size variants. To achieve that the characteristic equation which describes material yield stress $(\sigma(r))$ and strain rate $(\dot{\varepsilon})$ was modified to be applicable to 3-D grains. The models of strain for 3-D grain were also transformed into

a model of strain rate. Furthermore, the stochastic natures of the grain size variants were also taken into consideration

It can be concluded that the effect of deformation temperature led to different SRS due to different grain curvatures of the grain size variants. It was also observed that, the SRS of the grain size variants decreased and increased with increasing temperature. The increased and decreased in SRS with temperature for the grain size variants suggests that, the SRS for 6082T6 aluminum at the low and the high temperature ends are different. This indicates that, different dynamic strain aging (DSA) mechanisms dominate the behavior of the grain size variants at different temperature ranges since at extremely low temperature, the SRS is small and at high temperature; the SRS increased and results to material hardening. It can be concluded that increased in temperature impact the SRS of nanostructured during grain refinement.

REFERENCE

[1] Kreitcberg, A. & Prokoshkin, S. & Brailovski, V. & Gunderov, D. & Khomutov, M. 2014. Influence of the strain rate and deformation temperature of the deformability of Ti – Ni SMAs: A preliminary study. *Material Science and Engineering 63(2014)012109*

[2] Picu, R. C. & Vincze, G. & Ozturka, F. & Gracio, J. J. & Barlat, F. & Maniatty, A. M. 2004. Strain rate sensitivity of the commercial aluminum alloy AA5182-O. *Materials Science and Engineering A 390 (2005) 334-343.*

[3] May, J. & Hoppel, H. W. & Goken, M. 2005. Strain rate sensitivity of ultrafine-grained aluminium processed by severe plastic deformation. *ScriptaMaterialia 53(2005)189-194*

[4] Lee, W. S. & Lin, C. F. &Chen, T. H. & Hwang, H. H. 2008. Effects of strain rate and temperature onmechanical behavior of Ti–15Mo–5Zr–3Al alloy. *J Mech Behav Biomed Mater 2008;1 (4):336–44.*

[5] Anton, S. & Brane, S. & Mateyz, F. 2009. Determination of the strain-rate sensitivity and the activation energy of deformation in the superplastic aluminium alloy Al-Mg-Mn-Sc. *RMZ – Materials and Geoenvironment, Vol. 56, No. 4, pp. 389–399, 2009*

[6] Sabirov, I. & Barnett, M. R. & Estrin, Y. & Hodgson, P. D. 2009. The effect of strain rate on the deformation mechanisms and the strain rate sensitivity of an ultra-fine-grained Al alloy. *Scripta Materialia 61 (2009) 181–184*

[7] Brad, L. B. &Thomas, B. C. &Morris, F. D. 2007. The Strain-Rate Sensitivity of High-Strength High-Toughness Steels. *Sanddia Report Sand 2007-0036*

[8] Kumar, R. & Sharma, G. & Kumar, M. 2013. Effect of size and shape on the vibrational and thermodynamics properties of nanomaterials. *Journal of thermodynamics Vol. pp 5*

[9] Lee, W. S. & Lin, C. F. &Chen, T. H. & Hwang, H. H. 2008. Effects of strain rate and temperature onmechanical behavior of Ti–15Mo–5Zr–3Al alloy. *J Mech Behav Biomed Mater 2008;1(4):336–44.*

[10] Chiou, S. T. & Tsai, H. L. & Lee, W. S. 2009. Impact mechanical response and microstructural evolution of Ti alloy under various temperatures. *J Mater Process Technol2009;209 (5):2282–94.*

[11] Guisbiers, G. 2010. Size dependent materials properties towards a universal equation. *Nanoscale Research Letters, Vol. 5, No.7, pp. 1132-1136*

[12] Zhang, Z. & Lii, X. X. & Jiang, Q. 1999. Finite size effect on melting enthalpy and melting entropy of nanocrystals. *Physical B Vol. 270, No. 3-4, pp. 249-254*

[13] Xiong, S. & Qi, W. & Cheng, Y. & Huang, B. & Wang, W. & Li, Y. 2011. Universal relation for size dependent thermodynamic properties of metallic nanoparticles. *Physical Chemistry Chemical Physics, Vol. 13, No. 22, pp. 10652-10660*

[14] Zhao, M. & Jiang, Q. 2006. Reverse hall-petch relationship of metals in nanometer size. *Emerging Technologies-Nanoelectronics, IEEE Conference on Vol. pp 472-474, (10-13 Jan. 2006)*

[15] Tengen, T. B. & Iwankiewicz, R. 2009. Modelling of the grain size probability distribution in polycrystalline. Composite Structures 91(2009) 461-466

[16] Tengen, T. B. 2008.*Analysis of Characteristic of Random Microstructures of Nanomaterials.* PhD. Thesis. Witwatersrand Johannesburg.

[17] Meyers, M. A. & Mishra, A. & Benson, d. J. 2005. Mechanical properties of nanocrystalline materials. *Progress in Materials Science 51(2006)427-556*