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EMPIRICAL MODEL FOR TIME EVOLUTION THERMAL-DEPENDING PROPERTIES OF ALUMINIUM ALLOYS

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Summary. *In many forming processes the evolution of the material properties evolves with time and changes as temperature varies, forcing the use of a time-dependent thermomechanical computational model to simulate them. If the property under study could be described as a collectivity of microentities jumping over a certain distribution of energy barriers from one metastable state to another, then the whole behaviour of the material property follows a $T \cdot Ln(t/\tau_0)$ scaling. The use of $T \cdot Ln(t/\tau_0)$ as an integration variable could be employed to simplify the computational procedure. Also this scaling description allows one to extrapolate the time evolution behaviour at times (or speeds) that are experimentally completely inaccessible. From this scaling it is also possible to determine the attempt period τ_0, needed by the computational model. All the properties described by the Arrhenius Law could be scaled by this method. In the present work, for instance, the $T \cdot Ln(t/\tau_0)$ scalings are found for hardness and grain size of a 5,657 aluminium alloy with several annealing treatments.*

1 INTRODUCTION

There is a broad variety of physical systems that show a time-dependent behaviour of some of their physical properties because of the existence of energy barriers, which separate local minima corresponding to different equilibrium states of the system. In recent decades considerable effort has been devoted to understanding the relaxation phenomena in systems with different degrees of disorder, such as: spin glasses [1][2] where the distribution of energy barriers is due to the frustration of the competing magnetic interactions amongst the individual spins; high temperature superconductors [3][4] in which vortices are submitted to pinning by defects and dislocations, and where the application of a magnetic field creates metastable states in the vortex lattice; small magnetic particle systems [5][6]with a volume distribution and random orientation of easy axes, which show blocking phenomena depending on the experimental time windows; and, thin films, magnetic domain walls [7] and other magnetic materials for which the existence of energy barriers is a consequence of the competition between anisotropy and exchange energies. The search of a scaling hypothesis that allows one to bring all the relaxation data, obtained at different temperatures, in a unique master curve make possible to cover a large number of time decades, since in all thermally

activated problems, any change in the temperature of the system corresponds to a change in the time scale of the relaxation.

The simplest guess for the scaling law of a relaxing system governed by thermally activated processes is the so called $T \cdot Ln(t/\tau_0)$ master curve [8]. In this work, we want to discuss the validity of the $T \cdot Ln(t/\tau_0)$ scaling law for the study of the time evolution of some of the mechanical properties of 5,657 aluminium alloys.

2 RELAXATION CURVES

The variation of a property for the assembly of weak (or non) interacting entities with a distribution of energy barriers *f(E)*, which are overcomed by thermal fluctuations, according to the Arrhenius Law, is given by [5]:

$$\Delta P(t) = \Delta P_0^{\infty} \cdot \int_0^{\infty} dE \cdot p(t,E) \cdot f(E) \tag{1}$$

where *P* is the property under study, ΔP_0^{∞} is the total variation of the property between the initial and the equilibrium state, *E* is the energy barrier height and the function *p(t,E)* is given, according to Neel's theory [9], by:

$$p(t,E) = e^{-\frac{t}{\tau_0} \cdot \exp\left(-\frac{E}{k_B \cdot T}\right)} \tag{2}$$

where τ_0 is the attempting characteristic time and k_B the Boltzmann constant.

Taking into account that *p(t,E)*, for a given time *t* varies abruptly from 0 to 1, as the energy barrier *E* increases, is usual to simplify it by a step function with the discontinuity in $E_c(t)$, the inflexion point of *p(t,E)*, i.e.:

$$E_c(t) = k_B \cdot T \cdot Ln(t/\tau_0) \tag{3}$$

Then, equation (1) could be rewritten as follows:

$$\Delta P(t) = \Delta P_0^{\infty} \cdot \int_{E_c(t)}^{\infty} dE \cdot f(E) \tag{4}$$

where the only parameter of the evolution is the scaling variable $T \cdot Ln(t/\tau_0)$.

The validity of the scaling is determined by de validity of the step approximation, which is acceptable as long as the width of *p(t,E)* is small compared to the width of the energy barrier distribution, *f(E)*[8]. This assumption is usually certain when the time evolution of the system is clear under experimental conditions.

3 EXPERIMENTAL RESULTS

Several samples of 2×5 cm were cut from a 0.90 mm-thick sheet of 5657H25 aluminium alloy and annealed at temperatures from 180 ºC up to 400 ºC for a time period ranging from 5 min. to 55.2 h.

A piece of original sheet was cold laminated up to 0.33 mm (additional 63% of cold work), then several samples of 2×5 cm were cut and annealed at temperatures from 180 ºC up to 400 ºC for a time period ranging from 5 min. to 12.6 days.

The measurements of each annealing was plotted versus $T \cdot Ln(t/\tau_0)$, selecting a trial value for τ_0 (typically 10^{-8} s). Choosing τ_0 value one could lead to all the curves bringing in one master curve only. The selected value is the right one for the attempting period (τ_0) of the current measured property.

3.1 Hardness

Nine Vickers indentations HV0.5 (ISO 6507-1) were carried out in all the samples and the average value taken as the hardness value.

As received and laminated, samples converge in their master curve when $\tau_0 = 3 \cdot 10^{-13}$ s. Results and fitted curves are shown in Figure 1.

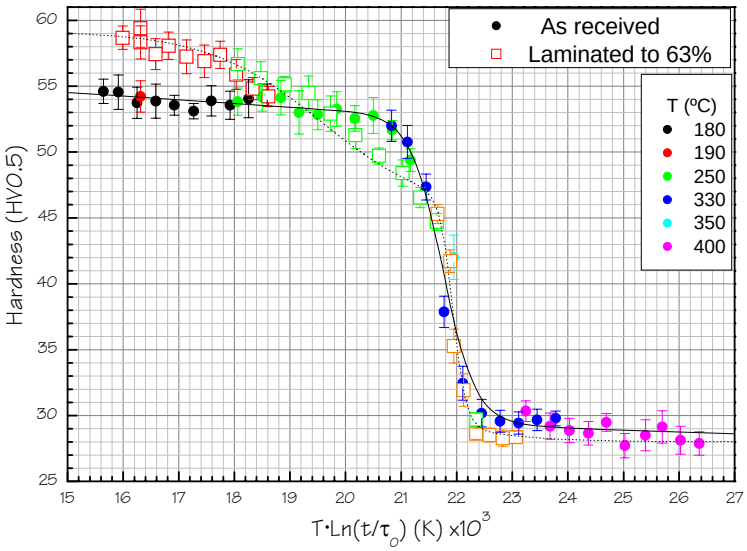

Figure 1: Hardness versus $T \cdot Ln(t/\tau_0)$ for $\tau_0 = 3 \cdot 10^{-13}$ s

The fact that laminated and as received material have the same attempting period, implies that the same microentities are involved in the time-evolution of the hardness, and the more provable ones are dislocations.

3.2 Grain size

Some selected samples of laminated aluminium were prepared for microscopic measurement of their grain size under polarized light [10]. The grain size was measured in lamination and perpendicular direction following the Heyn method (UNE 7-280-72).

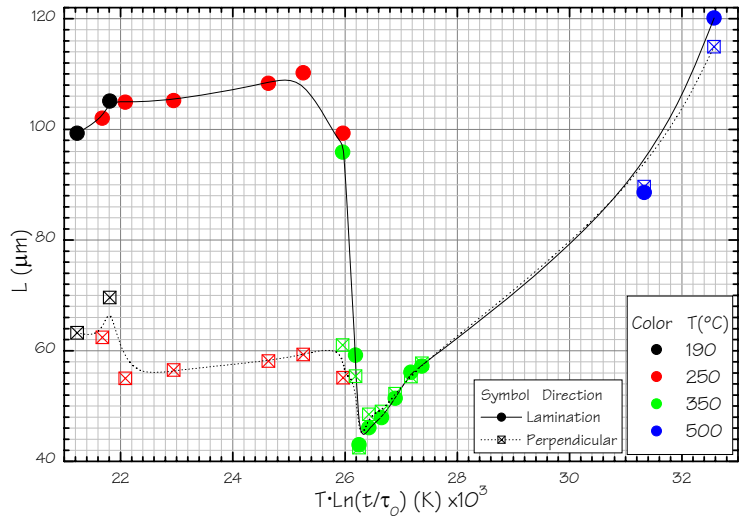

Figure 2: Grain size versus $T \cdot Ln(t/\tau_0)$ for $\tau_0 = 3 \cdot 10^{-16}$ s

The grain size in lamination and perpendicular directions converge in their master curve when $\tau_0 = 3 \cdot 10^{-16}$ s. Results and eye guidelines are shown in Figure 2.

The value of τ_0 is compatible with the fact that atoms are the microentities involved in the

grain growth, by diffusion through the grain wall.

4 CONCLUSIONS

- The $T{\cdot}Ln(t/\tau_0)$ scaling could reduce the cost of mechanical characterization of materials by the reduction of experimental points required to be measured.
- The $T{\cdot}Ln(t/\tau_0)$ scaling could reduce the computational effort of simulations by the reduction of variables involved in calculus of mechanical properties.
- The $T{\cdot}Ln(t/\tau_0)$ scaling could extrapolate results to time (or speed) experimentally unreachable, by a single change in the temperature of the experimental device.
- The $T{\cdot}Ln(t/\tau_0)$ scaling could properly describe the evolution of hardness and grain size of 5,657 aluminium alloy in several annealing treatments.

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REFERENCES

[1] M. Mézard, G. Parisi and M.A. Virasoro, *Spig-Glass Theory and Beyond*, Lecture Notes in Physics Vol. 9, World Scientific (1987)

[2] R.V. Chamberlin and F. Holtzberg, "Remanent magnetization of a simple ferromagnet", *Phys. Rev. Lett.*, 67 (12), 1606-1609 (1991)

[3] C.W. Hagen and R. Griessen, "Distribution of activation-energies for thermally activated flux motion in high-Tc superconductors - an inversion scheme", *Phys. Rev. Lett.*, 62, 2857-2860 (1989)

[4] Y. Yeshurun and A.P. Malozemoff, "Giant Flux Creep and Irreversibility in an Y-Ba-Cu-O Crystal: An Alternative to the Superconducting-Glass Model", *Phys. Rev. Lett.*, 60, 2202-2205 (1988)

[5] H. Pfeiffer, "Relaxation behavior of magnetic particle assemblies due to thermal fluctuations", *Phys. Status Solidi A*, 120, 233-245 (1990)

[6] R.W. Chantrell, "Magnetic viscosity of recording media", *J. Magn. Magn. Mater.*, 95 (3), 365-378 (1991)

[7] EB. Krotenko, X.X. Zhang and J. Tejada, "Self-heating in magnetic-relaxation experiments in $TbFeO_2$ single crystal and Fe_3Tb metallic alloy", *J. Magn. Magn. Mater.*, 150 (1), 119-123 (1995)

[8] A. Labarta, O. Iglesias, Ll. Balcells and F. Badia, "Magnetic relaxation in small-particle systems: $T{\cdot}Ln(t/\tau_0)$ scaling" *Phys. Rev. B*, 48 (14),10240-10246 (1993).

[9] L. Néel, "Théorie du trainage magnètique des ferromagnétiques en grains fins avec applications aux terres cuites" *Ann. Geophys.*, 5, 99-136 (1949)

[10] ASM International. Handbook Committee, *ASM Handbook: Vol. 9 Metallography and Microstructures*, ASM International (1990-).