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RELATIONSHIP BETWEEN INTERNAL FRICTION AND SHEAR MODULUS FOR Fe-0.2 Ti ALLOY WITH OIL LAYER

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Résumé. Le maximum du frottement intérieur d'un composite métal-huile et le défaut du module de cisaillement apparaissent à la température de solidification de l'huile. Nous avons testé trois modèles pour analyser la relation entre le frottement intérieur et le module de cisaillement. Nous avons également obtenu la variation du temps de relaxation avec la température.

Abstract - Internal friction maximum which appears at temperature of solidification of oil is followed by a shear modulus defect. The three models were applied to analyse the relationship between the oil internal friction and the shear modulus spectra. The temperature dependence of relaxation time was obtained.

INTRODUCTION

Low temperature internal friction peaks and shear modulus defects observed for oil coated samples are connected with the solidification process of oil layer [1,2,3]. There are some problems to solve. The first concerns the structure of damping spectrum. Internal friction appears as single peak only when specimen is annealed. It is evident that internal friction should be attributed to the layer properties and to properties of sample surface. The second problem is with an analytical description of the measured damping. Internal friction of lubricated sample gives us information about dynamic properties of oil at low temperature. Several methods of internal friction division into the bulk and the surface layer damping are developed [4,5]. They assume that defined surface layer is linked to the sample.

This paper reports the result of analogous treatment for an oil - layer which leads to the damping division and to temperature dependence of relaxation time. Three the simplest models are tested: at first the Nowick and Berry model when composite is treated as standard solid with any relaxation process, then two models which describe the viscous and viscoelastic properties of oil layer deposited on an elastic base.

EXPERIMENTAL RESULTS

Measurements of internal friction were performed with a torsional pendulum oscillating at 1 Hz [6] with constant value of vibration amplitude $\gamma = 2 \cdot 10^{-5}$. The energy loss due to damping was automatically recorded. Temperature was changed from 80 to 300 K with constant heating rate 0.2 K/min.

Samples of Fe-0.2Ti alloy were of technical purity and in the form of wires 1 mm in diameter and 50 mm in length. In the initial state the alloy was cold worked during producing. Before the measurements the samples were annealed at the temperature

973 K for 4 hours.

Thin mineral oil layer was put on the metal surface by greasing.

The typical results of internal friction and shear modulus measurements performed during heating are shown in Fig. 1. Internal friction of uncoated sample increases weakly with temperature and shear modulus decreases linearly as can be seen from curves 1a and 1b, respectively. After coating an asymmetric internal friction peak appears $/Q^{-1} = 2.6 \cdot 10^{-3} /$ at the temperature $T = 205 \pm 1$ K /curve 2a, Fig. 1/. The shear modulus defect is correlated with the damping maximum /curve 2b, Fig. 1/. At high temperature the shape of the internal friction spectrum /curve 2a, Fig. 1/ seems to be due to the existence of a second damping maximum at temperature near by 230 K. This process leads also to the small step on the modulus data /curve 2b, Fig. 1/.

DISCUSSION

Let us at first calculate the oil layer internal friction. Next, internal friction will be analysed in terms of the adopted models. The measured internal friction of the composite, Q_x^{-1} , can be divided into two parts: internal friction of uncoated sample, Q_0^{-1} , and an unknown internal friction of oil, Q_x^{-1} . We use for this the standard formula [4,5]:

$$Q_x^{-1} = \frac{Q_0^{-1} - (f_0/f)^2 \cdot Q_0^{-1}}{1 - (f_0/f)^2} \quad /1/$$

where: f_0 and f - the vibration frequencies of uncoated and coated sample, respectively. Division was made twice for two sets of initial results. At first, the calculations were performed without the subtraction of the second damping process. We assume that this process should be due to the interaction of oil with deformed metal surface [7]. The values were used as illustrated by curves 2a for Q^{-1} and 1b for f_0^2 /Fig. 1/. In the next step, the internal friction spectrum was arbitrarily separated at higher temperature, leading to the results which are shown by the curve 3a /Fig. 1/. The data for the f_0^2 function of the uncoated sample were as that represented by curve 3b, which is parallel to the previous curve 1b /Fig. 1/.

Such two procedures give the different $Q_x^{-1}(T^{-1})$ functions which are presented in Fig. 2 by curves 1 and 2, respectively. The remarkable divergence appears at higher temperature, above T_m . In the first case internal friction decreases at high temperature. The course of the corrected results /curve 2, Fig. 2/ depends strongly on an assumed temperature character of shear modulus /curve 3b, Fig. 1/. The two curves 1 and 2, presented in Fig. 2, limit the area of the estimated values of the oil internal friction.

Let us assume that the oil layer has thickness h and is deposited on the wire sample with radius R . The real and imaginary parts of complex modulus of such composite can be determined from the following formulae [7]:

$$G' = \alpha \cdot G_1 + (1 - \alpha) G_\infty \operatorname{Re}(x) \quad /2a/$$

$$G'' = (1 - \alpha) G_\infty \operatorname{Im}(x) \quad /2b/$$

where: $\alpha = (R / (R + h))^4$ - geometric factor; G_1 - shear modulus of rigid, uncoated sample; G_∞ - oil shear modulus, determined for very high frequency; $\text{Re}(x)$ and $\text{Im}(x)$ - real and imaginary parts of the oil complex shear modulus; x - a parametr equal to $\omega \cdot \tau$ product, with τ as relaxation time. The composite internal friction Q^{-1} and the layer internal friction Q_x^{-1} are estimated as follows:

$$Q^{-1} \approx \text{tg } \varphi = \frac{G''}{G'} \quad /3a/$$

$$Q_x^{-1} \approx \text{tg } \varphi_x = \frac{\text{Im}(x)}{\text{Re}(x)} \quad /3b/$$

We want to compare the experimental values of Q^{-1} with the values of the shear modulus defect and in this way to determine wheather the physical effects can be calssified under the general heading of relaxation effect or not. We introduce at first the normalized modulus defect function $G/T/$ and the normalized internal friction function $F/T/$. They are calculated from experimental results and on the other hand they can be defied by the formulae /2/ and /3/. This functions are described, as follows:

$$G(T) = \frac{f^2(T) - f_0^2(T)}{f^2(T_0) - f_0^2(T_0)} = \frac{S}{S_0} \text{Re}(x) \quad /4a/$$

$$F(T) = \frac{Q^{-1}(T)}{Q_m^{-1}} = \frac{1}{k \left(S_0 + \frac{1}{G(T)} \right)} \frac{\text{Im}(x)}{\text{Re}(x)} \quad /4b/$$

$$\text{where: } S = \frac{1 - \alpha}{\alpha} \frac{G_\infty}{G_1} \quad /5a/$$

and $S_0 = (f^2/f_0^2 - 1)$ - the maximal value of shear modulus calculated at temperature T_0 , / $T_0 < T_m$ /; k - is the experimental parameter defined by following relation:

$$Q_m^{-1} = k \cdot S_0 \quad /5b/$$

From the formulae /4a/ and /4b/ one can determine the x values when the rheological function $I/x/$ and $\text{Re } x/$ are assumed. The S_0 and k parameters were estimated from the results shown in Fig.1. For the results without the correction on the second internal friction process, case /a/, these two parameters have values:

$S_0 \cdot 10^3 = 15 \pm 0.5$, $k \cdot 10^3 = 163 \pm 10$. For the corrected results, case /b/, is found that $S_0 \cdot 10^3 = 16.5 \pm 0.5$ and $k \cdot 10^3 = 148 \pm 10$. The low value of k parametr suggests that measured damping can by phenomenologically described as the result of relaxation process with broad distribution function of relaxation times. Assuming that S parameter, /5a/, is independant on temperature

we can easily utilize the Nowick and Berry model by introducing the following relations:

$$\operatorname{Re}(x) = F_1(x, \beta); \quad \operatorname{Im}(x) = F_2(x, \beta) \quad /6/$$

where F_1 and F_2 are the Nowick and Berry functions [8] and β is the Gaussian distribution parameter. The β value was estimated basing on k parameter value on the relationship $k = f / \beta$ calculated by Nowick and Berry [8]: $\beta = 5 \pm 0.2$ for $k = 0.15 \pm 0.01$. In order to determine the x vs temperature dependence the following expressions were accepted: $G/T/ = F/x/$, from /5a/, and $F/T/ = S_0 \cdot F_2$, from /4b/, with neglecting the G function in denominator /4b/. It leads to independent estimation of the x parameter from F and G functions. The results as obtained with both /a/ and /b/ conditions are plotted in Fig. 2. The three functions of $\ln(x)$ vs T dependence are represented by curves 3, 4 and 5, respectively. There appears a discrepancy between curves 3 and 4. It indicates that the Nowick and Berry model can not be adopted for uncorrected data. In the second case /b/ both G and F functions give the same values of x parameter as show by curve 5 in Fig. 2. From the mean slope of this curve one can deduce the activation enthalpy value: $H = 2.4 \pm 0.2$ eV and the τ_0 parameter value: $\lg \tau_0 = -55 \pm 5$. That last value proves that tested model describes our results only phenomenologically.

In the next step of the approximation procedure we assume that the S parameter value depend on temperature. The temperature dependence of G_∞ is unknown. This parameter should decrease continuously from the initial value $G_\infty / T_0 /$ to the very small value at higher than T temperature.

Two rheological models of liquid were verified. At first the simplest Maxwell model for oil dynamical properties was assumed. The following expressions are assumed:

$$\operatorname{Re}(x) = \frac{x}{1 + x^2} \quad /7a/$$

$$\operatorname{Im}(x) = \frac{x^2}{1 + x^2} \quad /7b/$$

where: $x = \omega \tau$; $\tau = \eta / G_\infty$; η - static viscosity of oil. The x parameter value and S/S_0 ratio value was deduced from F and G function. The temperature dependence of shear modulus $G(T)$, related to $G_\infty(T_0)$ was estimated. These new values of x and S/S_0 parameters are presented by curve 2 in Fig. 3 and curve 2 in Fig. 4, respectively. Now the $\ln \omega \tau$ vs T^{-1} dependence /curve 2, Fig. 3/ is more realistic /curve 2, Fig. 3/ but G_∞ shear modulus decreases strongly, as shown by curve 2 in Fig. 4. The second rheological model was as proposed by Barlow [9]. The viscoelastic properties of liquid are represented by real and imaginary parts of liquid shear modulus, as follows:

$$\operatorname{Re}(z) = \frac{4z^{3/2}(1+\sqrt{z})}{((1+\sqrt{z})^2 + z)^2} \quad /8a/$$

$$\operatorname{Im}(z) = \frac{2 \cdot z^2(1+\sqrt{z})}{((1+\sqrt{z})^2 + z)^2} \quad /8b/$$

where: $z = \frac{1}{2} \cdot x$.

The calculations, as mentioned above, give x and S/S_0 values which are plotted as curve 3, in Fig. 3 and curve 3 in Fig. 4, respectively. For this model the S/S_0 ratio value /curve 3, Fig. 4/ does not change as much as previously, /curve 2, Fig. 4/. It influences the temperature dependence of x parameter as shown by curve 3 in Fig. 3.

It must be underlined that the three presented above models give the same relationship for Q_x^{-1}/T function.

We can not distinguish between two last models without the supplementary information on the temperature dependence of G_∞ and α parameters. Such measurements should help us to determine the physical model of internal friction phenomenon which is observed for such composite as metal with oil layer.

CONCLUSIONS

1. The composite internal friction maximum can be described phenomenologically by three models: Nowick and Berry, Maxwell and Barlow, respectively.
2. The temperature dependence of relaxation time is determined satisfactory only when visco- or viscoplastic behaviour of liquid oil is assumed. The temperature dependence of G_∞ and α parameter must be tested too.

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Fig.1. Internal friction /a/ and modulus /b/ spectra: 1 - uncoated, 2 - coated, 3 - with correction.

Fig.2. Oil damping and $\omega\tau$ on temperature dependence: 1,3,4 - uncorrected data, 5 - Nowick-Berry model.

Fig.3. Arrhenius plots from the models of: 1 - Nowick-Berry, 2-Maxwell, 3 - Barlow.

Fig.4. Oil shear modulus on temperature dependence from the models of: 1 - Nowick-Berry, 2 - Maxwell, 3 - Barlow, 4 - modulus defect.