INVESTIGATION OF SMALL PUNCH CREEP OF A 2124Al ALLOY REINFORCED BY SiC PARTICULATES

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Creep behaviour of the alloy 2124Al reinforced with 20 vol.% silicon carbide particulates was studied at temperatures from 623 to 773 K by small punch testing with a constant force. The time dependence of the central deflection was registered and the minimum deflection rate was determined. The dependence of this quantity on applied force is interpreted in terms of the threshold force. Novel procedure for comparison of force in small punch testing and stress in conventional creep testing is given.

Key words: small punch test, creep rate, stress exponent, activation energy, threshold stress

1. Introduction

The development of aluminium-based alloys resulted in a great variety of materials with promising elevated temperature properties. The high temperature creep of such materials was for more than three decades a theme that attracted J. Čadek to many valuable studies. His contributions towards this topic range from SAP [1] materials through NOVAMET [2], Al-C-O mechanically alloyed materials [3] to 2xxx (according to Aluminum Association classification) [4], 6xxx [5] and 8xxx alloys [6, 7] reinforced with particles and fibres. The metal matrix composite of 2124 reinforced by 20 vol.% of SiC particulates was one of these materials [8]. The analysis of the data obtained on this composite has shown that a true threshold is measured, which indicates the absence of additional strengthening due to load transfer and substructure. This fact can facilitate an interpretation of data obtained by non-conventional testing methods. Therefore, we will use this composite to demonstrate the possibilities of one of miniaturized testing techniques, namely the small punch testing for a study of materials prepared by powder metallurgy.

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2. Experimental

The 2124Al-20SiC$_\mathrm{P}$ composite was received (see [9, 10]) in the form of a plate, 12.75 mm in thickness. The composite was manufactured by DWA Composite Specialities by powder metallurgy techniques. The typical chemical composition of the matrix of the composite is 3.8–4.9 % Cu, 1.2–1.8 % Mg, 0.3–0.9 % Mn, max. 0.2 % Si, max. 0.5 % Fe, max. 0.25 % Zn, bal. Al, by weight percent. Silicon carbides particulates of mean diameter 4.5 μm were homogeneously distributed in the matrix. Their nominal content was 20 volume percent. The composite was obtained after extrusion and heat treatment to T4 condition.

For small punch testing, a constant load cantilever creep machine was adapted. During the test, a precise ceramic ball made of FRIALIT® F99.7, 2.5 mm in diameter, is pushed with a constant force against a specimen supported by a 4-mm diameter receiving die (lower die) (*cf.* Fig. 1). The disc specimen of diameter 8 mm and thickness 0.5 mm is clamped by an upper die. Central deflection is measured as the difference in the positions of the punch and lower die, using a linear variable differential transformer W2K from Hottinger-Baldwin Co. (Germany) and is continuously recorded with a PC. The technique is described in more detail elsewhere [11].

The specimens for small punch testing were prepared by machining cylinders 8 mm in diameter. The cylinders were subsequently cut to slices 1.2 mm thick using spark erosion. The slices were ground carefully from both sides equally and finally polished to 1200 grit. The final thickness of 0.500 ± 0.002 mm was measured by using a micrometer with a resolution of 1 μm.

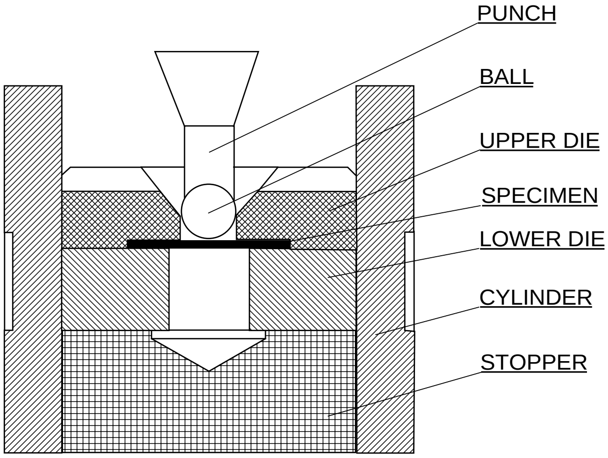

Fig. 1. Schematic diagram of test arrangement.

3. Experimental results

Examples of the dependence of central deflection *vs.* time obtained in the small punch arrangement are given in Fig. 2. It can be seen that the same general features of the curves can be observed as in conventional creep tests. The detected curves have a very pronounced stage of the primary creep in which the deflection rate decreases by several orders of magnitude. The steady state creep is apparently missing but the minimum deflection rate can be evaluated. After reaching the minimum, the deflection rate is steadily increasing till an instant of rupture can be detected.

The dependence of the minimum deflection rate on the applied force for three temperature levels is given in Fig. 3 in bilogarithmic coordinates. In agreement with the early report of the same composite crept using a double shear configuration [9], the dependence can be described by the power-law relationship of the form

$$\dot{\delta}_{\mathrm{M}} = A \cdot F^{n_{\mathrm{S}}}, \qquad (1)$$

where $\dot{\delta}_{\mathrm{M}}$ is the minimum deflection rate, F is the acting force and A is a constant which incorporates the dependence on temperature. The value of the exponent n_{S} is only slightly dependent on temperature and it ranges from 5.87 at 623 K to 4.72 at 723 K.

The dependence of the time to fracture on the applied force is given in Fig. 4. The dependence can also be described by a power law of the type of Eq. (1) with negative values of power ranging from $n_{\mathrm{F}} = -5.67$ at 623 K to $n_{\mathrm{F}} = -4.58$ at 723 K.

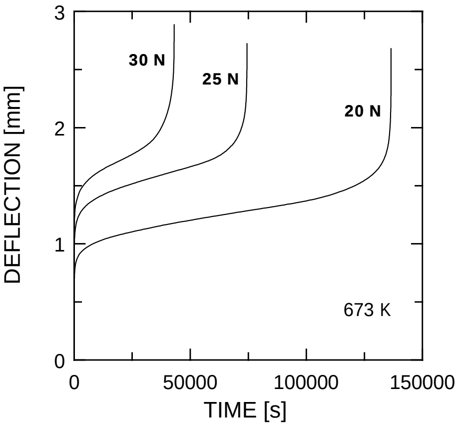

Fig. 2. Examples of time dependence of measured central deflection.

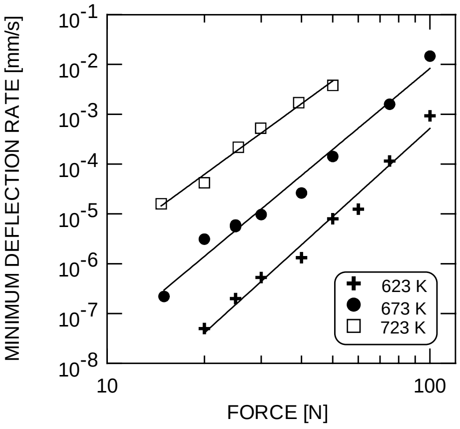

Fig. 3. Dependence of minimum deflection rate on applied force.

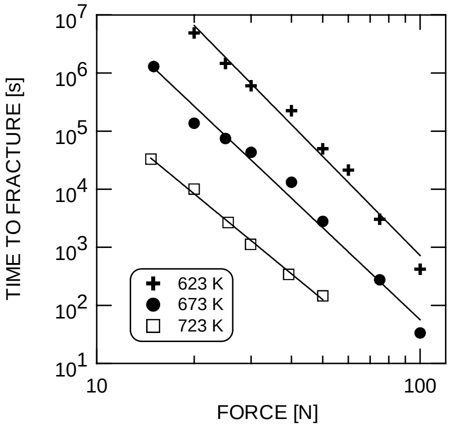

Fig. 4. Dependence of time to fracture on applied force.

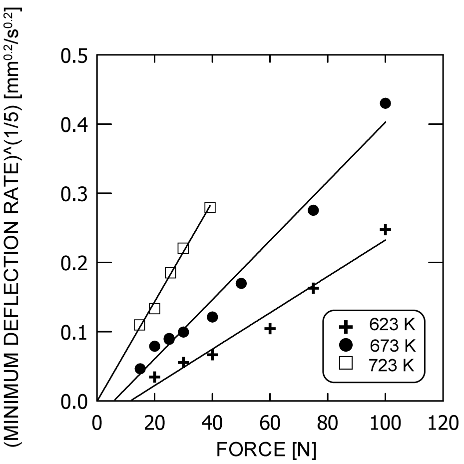

Fig. 5. Determination of the threshold force by linear extrapolation of plots of $\left(\dot{\delta}_{\mathrm{M}}\right)^{1/q}$ vs. the applied force.

4. Discussion

During the last decade, the creep of aluminium composite was successfully interpreted by means of the threshold stress concept (for the most recent review see [12]). As can be recognized by a detailed inspection of Fig. 3, the presence of a threshold at temperatures 623 and 673 K can be admitted even in the present small punch tests. The threshold force can be found by the usual method as in conventional creep, i.e. by plotting $\left(\dot{\delta}_{\mathrm{M}}\right)^{1/q}$ vs. the applied force in linear coordinates and determining the force for which $\left(\dot{\delta}_{\mathrm{M}}\right)^{1/q} = 0$ (*cf.* Fig. 5). The power q for this procedure was taken as $q = 5$ in agreement with usual application of the method to elevated creep data [4, 13]. The temperature dependence of the threshold force estimated by this method is given in Fig. 6 together with the results of the threshold stress reported by Čadek et al. [4] on the identical composite and by Kim et al. [13] on the nominally same material. The temperature at which the threshold force in small punch tests equals zero is in an excellent agreement with the corresponding temperature given by Čadek et al. [4]. It is less than the temperature reported by Kim et al. [13]. Reasons of this discrepancy were discussed by Kim: The difference probably originates from the microstructural difference induced by a different processing.

An important prerequisite for practical application of small punch test is the existence of a reliable procedure for comparison of basic quantities of this test

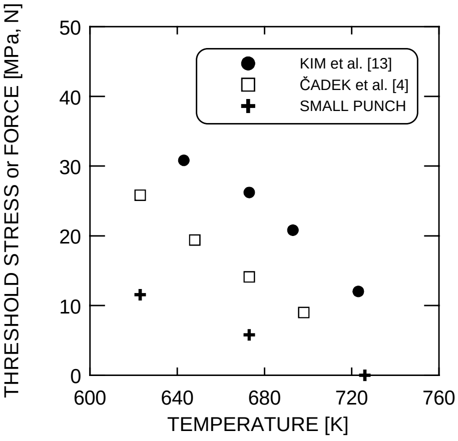

Fig. 6. Temperature dependence of threshold stress in conventional creep tests and threshold force in small punch tests, respectively.

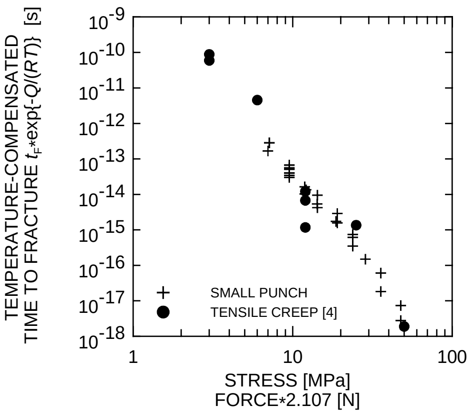

Fig. 7. Dependence of temperature-compensated time to fracture on applied stress and on force, respectively.

and corresponding quantities of conventional creep tests – i.e. force F in small punch tests vs. stress σ in creep test. We will address this problem by following phenomenological approach: Let us assume that the stress (and the force, respectively) and the temperature dependence of the time to fracture is in both types of the test described by a combination of Norton and Arrhenius law

$$t_{\mathrm{F}} = A_{\mathrm{C}} \exp\left(\frac{Q}{RT}\right) \sigma^{n}, \tag{2a}$$

$$t_{\mathrm{F}} = A_{\mathrm{S}} \exp\left(\frac{Q}{RT}\right) F^{n}, \tag{2b}$$

where the activation energy Q and the power n have the same value in both conventional creep and the small punch testing, A_{C} and A_{S} are constants, R is the universal gas constant and T is the absolute temperature. Using the least square method, the optimized values of parameters in Eqs. (2a, b) can be found that give a minimum sum

$$S = \sum_i \left(\ln t_{\mathrm{F}i} - \ln A_{\mathrm{C}} - n \ln \sigma_i - \frac{Q}{RT_i}\right)^2 + \sum_j \left(\ln t_{\mathrm{F}j} - \ln A_{\mathrm{S}} - n \ln(F_j) - \frac{Q}{RT_j}\right)^2 \tag{3}$$

(i represents conditions of conventional tests and j those of small punch tests). This is performed by partial differentiation of Eq. (3) with respect to A_{C}, A_{S}, Q and n

and equalling the derivatives to zero. The resulting set of four equations is then solved for A_{C}, etc.

The ratio of force to stress that gives the same time to fracture is

$$\frac{F}{\sigma} = \left[\frac{A_{\mathrm{C}}}{A_{\mathrm{S}}}\right]^{1/n}. \tag{4}$$

The results of calculations are as follows: $n = -5.7$, $Q = 240$ kJ/mol, $\ln A_{\mathrm{C}} = -17.59$, $\ln A_{\mathrm{S}} = -13.34$. The ratio of force (in Newton) in small punch test to stress in conventional creep test (in MPa) in the composite under consideration is

$$\frac{F}{\sigma} = 2.107.$$

The quality of fit is demonstrated in Fig. 7 where the dependence of the temperature-compensated time to rupture on stress or recalculated force, respectively, is given.

5. Conclusions

1. The force dependence of the minimum deflection rate can be described in terms of the threshold stress/threshold force concept.

2. The estimated threshold force is close to zero at a temperature of 723 K. This is in agreement with the reported threshold stress behaviour in conventional creep tests.

3. Procedure for conversion of stress in uniaxial creep test and force in small punch test is presented. This is based on phenomenological comparison of tests of the same duration.

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