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EFFECT OF PARTICLE SIZE IN ANALYSIS OF CREEP IN AN ISOTROPIC UNIFORM COMPOSITE CYLINDER

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ABSTRACT

The following paper discusses the effect of particle size in analysis of creep in an isotropic uniform composite cylinder. The paper is a part of the series of papers published under the analysis of creep in an isotropic uniform composite cylinder.

INTRODUCTION

In applications such as pressure vessel for industrial gases or a media transportation of high-pressurized fluids and piping of nuclear reactors, the cylinder has to operate under severe mechanical and thermal loads, causing significant creep hence reduced service life (Gupta and Phatak, 2001; Tachibana and Iyoku, 2004; Hagihara and Miyazaki, 2008). As an example, in the high temperature engineering test reactor, the temperature reaches of the order of 900*oC* (Tachibana and Iyoku, 2004). The piping of reactor cooling system are subjected to high temperature and pressure and may be damaged due to high heat generated from the reactor core (Hagihara and Miyazaki, 2008). A number of studies pertaining to creep behaviour of the cylinder assume the cylinder to be made of monolithic material. However, under severe thermo mechanical loads cylinder made of monolithic materials may not perform well. The weight reduction achieved in engineering components, resulting from the use of aluminum/aluminum base alloys, is expected to save power and fuel due to a reduction in the payload of dynamic systems. However, the enhanced creep of aluminum and its alloys may be a big hindrance in such applications. Aluminum matrix composites offer a unique combination of properties, unlike many monolithic materials like metals and alloys, which can be tailored by modifying the content of reinforcement. Experimental studies on creep under uniaxial loading have demonstrated that steady state creep rate is reduced by several orders of magnitude in aluminum or its alloys reinforced with ceramic particles/whiskers like silicon carbide as compared to pure aluminum or its alloys (Nieh, 1984; Nieh *et al*, 1988). A significant improvement in specific strength and stiffness may also be attained in composites based on aluminum and aluminum alloys containing silicon carbide particles or whiskers. In addition, a suitable choice of variables such as reinforcement geometry, size and content of reinforcement in these composites can be used to make the cost-effective components with improved performance. With these forethoughts, it is decided to investigate the steady state creep in a cylinder made of Al-SiCp composite and subjected to high pressure and high temperature. A mathematical model has been developed to describe the steady state creep behaviour of the composite cylinder. The developed model is used to investigate the effect of material parameters viz particle size and particle content, and operating temperature on the steady state creep response of the composite cylinder.

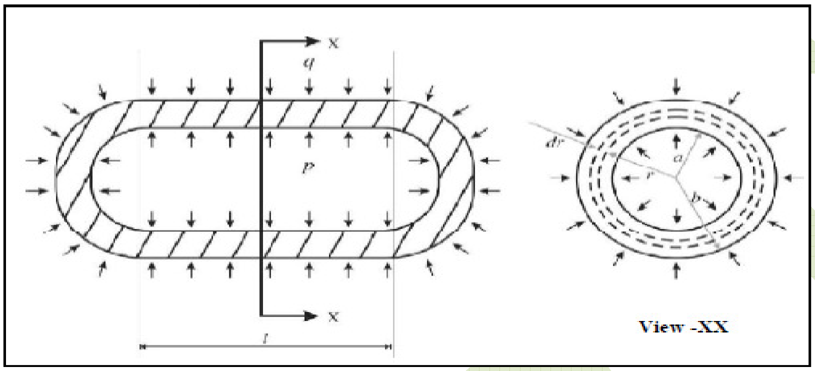

Fig. No.1 Schematic of closed end, thick-walled composite cylinder subjected to internal and external pressures.

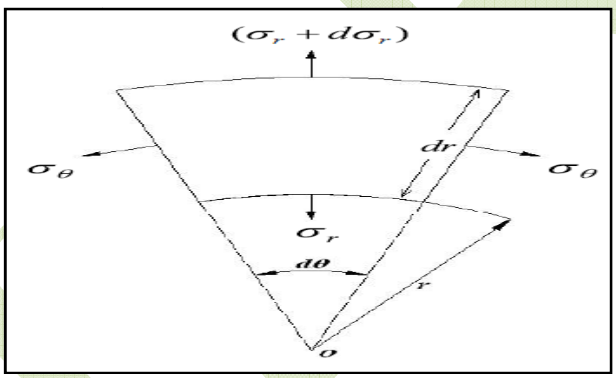

Fig. No. 2 Free body diagram of an element of the composite cylinder

EFFECT OF PARTICLE SIZE

Figure 3 shows the distribution of radial, tangential, axial and effective stresses in the composite cylinder for varying size of SiCp reinforcement from 1.7 μm to 45.9 μm. The radial stress remains compressive over the entire radius, with maximum and minimum values respectively at the inner and outer radii, under the imposed boundary conditions given in Eqs. Below

(i) At $r = a,\ \sigma_r = -p$

(ii) At $r = b,\ \sigma_r = -q$

The tangential stress varies from maximum compressive value at the inner radius to reach a maximum tensile value at the outer radius of the cylinder. The axial stress, which is the average of radial and tangential, stresses, Eqn. below

$$\sigma_z = \frac{\sigma_r + \sigma_\theta}{2}$$

Exhibits a variation similar to that observed for tangential stress. The variation in size of reinforcement (SiCp) does not exhibit a sizable effect on the values of stresses in the cylinder, except for some marginal variation observed in tangential stress near the inner and outer radii. The maximum variation observed for tangential stress is about 4% at the inner as well as at the outer radius whereas for axial stress the variation observed is less than 1% at the inner radius and about 2% at the outer radius of the cylinder having coarser SiCp of size 45.9 *μm* as compared to those observed for cylinder having finer SiCp of size 1.7 *μm*. The tangential stresses, both compressive (near the inner radius) as well as tensile (near the outer radius), in the cylinder having finer sized SiCp (1.7 *μm*) are marginally higher than those observed in cylinders with relatively coarser SiCp (*i.e.* 14.5 *μm* and 45.9 *μm*). The effective stress decreases on moving from the inner to the outer radius of the cylinder. With the increase in SiCp size from 1.7 *μm* to 45.9 *μm*, the effective stress exhibits a marginal increase near the inner radius but it decreases marginally towards the outer radius.

The strain rates, given by Eqs below

$$\dot{\varepsilon}_r = \frac{\dot{\varepsilon}_e}{2\sigma_e}[2\sigma_r - \sigma_\theta - \sigma_z]$$

$$\dot{\varepsilon}_\theta = \frac{\dot{\varepsilon}_e}{2\sigma_e}[2\sigma_\theta - \sigma_z - \sigma_r]$$

$$\dot{\varepsilon}_z = \frac{\dot{\varepsilon}_e}{2\sigma_e}[2\sigma_z - \sigma_r - \sigma_\theta]$$

Are dependent on the effective strain rate $\dot{\varepsilon}_e$ which ultimately depends upon (σ_e-σ_0). The difference of effective stress σ_e and threshold stress σ_0 as evident from creep law given by Eqn. below

$$\dot{\varepsilon}_e = [M(\sigma_e - \sigma_o)]^n$$

where $M = \frac{1}{E}\left(A' \exp\frac{-Q}{RT}\right)^{1/n}$ and the stress exponent $n = 5$.

Therefore, to investigate the effect of reinforcement (SiCp) size on the creep rates, the variation of stress difference (σ_e-σ_0).
Is plotted with radial distance in Fig below

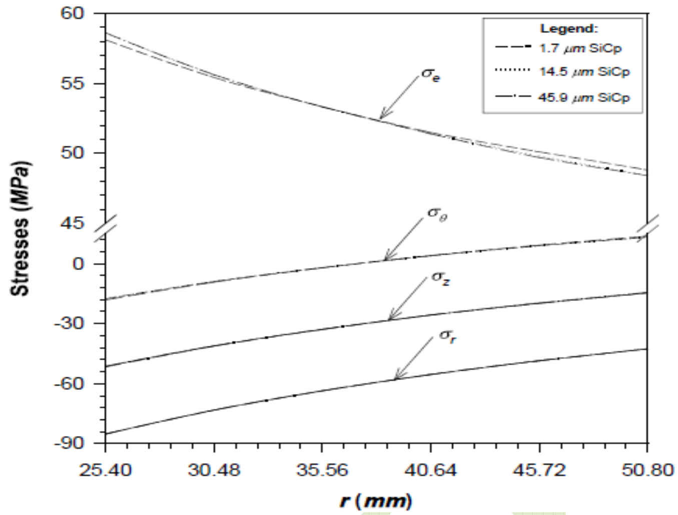

Fig 3 Variation of creep stresses for varying particle size of SiC (*V* = 10 *vol%*, *T* = 350 °*C*).

It is noticed that the stress difference (σ_e-σ_0) decreases significantly over the entire radius with decreasing SiCp size from 45.9 *μm* to 1.7 *μm*. The decrease observed may be attributed to the increase in threshold stress with decrease in particle size as evident from Table below

Table.No.1 Creep parameters for Al-SiCp composites (Pandey et al, 1992)

P (*μm*)	*T* (°*C*)	*V* (*vol %*)	*M* ($s^{-1/5}$/*MPa*)	σ_0 (*MPa*)	Coefficient of correlation
1.7			4.35×10^{-3}	19.83	0.945
14.5	350	10	8.72×10^{-3}	16.50	0.999
45.9			9.39×10^{-3}	16.29	0.998
		10	4.35×10^{-3}	19.83	0.945
1.7	350	20	2.63×10^{-3}	32.02	0.995
		30	2.27×10^{-3}	42.56	0.945
	350		2.63×10^{-3}	32.02	0.995
1.7	400	20	4.14×10^{-3}	29.79	0.974
	450		5.92×10^{-3}	29.18	0.916

As consequence, the effective strain rate $\acute{\varepsilon}_e$ also reduces significantly over the entire radius with decreasing particle (SiCp) size, Fig. given below

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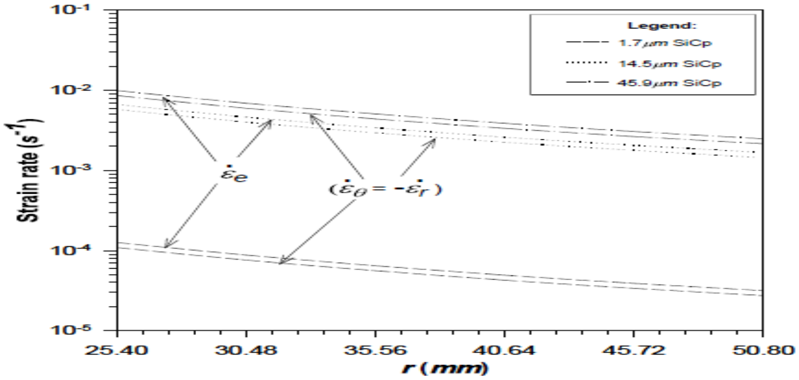

Fig no. 4 Variation of strain rates for varying particle size of SiCp (*V* = 10*vol%*, *T* = 350 °*C*).

The decrease observed is about two orders of magnitude with decrease in SiCp size from 45.9 *μm* to 1.7*μm*. It is quite evident from Eqn. given above that the decrease observed in effective strain rate is due to decrease in parameter *M* and increase in threshold stress σ_0 with decreasing size of SiCp, as revealed from Table 3.1. The radial and tangential strain rates are equal in magnitude but have opposite nature due to the incompressibility condition, Eqn. we obtained, and the assumption of plane strain condition $\acute{\varepsilon}_Z$=0 The radial (compressive) and tangential (tensile) strain rates in the cylinder for a given size of SiCp reinforcement are 13% lower than the corresponding effective strain rates, Eqn. below

$$\dot{\varepsilon}_\theta = -\dot{\varepsilon}_r = 0.87\,\dot{\varepsilon}_e$$

As is also evident from Fig no. 4 the effect of particle size on strain rates is similar to that observed for effective strain rate. Therefore, it may be concluded that the steady state creep rates in the composite cylinder could be significantly reduced by employing finer size of SiCp reinforcement in aluminum matrix. For the same volume fraction of reinforcement, the smaller size particles will be larger in number, and therefore lead to more load transfer to the reinforcement with a corresponding reduction in the level of effective stress shared by the matrix material, which enhances the substructure strength (Li and Langdon, 1993; Peng *et al*, 1998; 1999; Han and Langdon, 2002) and ultimately helps in restraining the creep flow of composite cylinder.

SELECTION OF MATERIAL PARAMETERS

It is evident from the above discussion that the creep stresses in a thick composite cylinder do not vary significantly by varying size and content of reinforcement (SiCp) as compared to the variation observed in strain rates. From The point of view of designing composite pressure vessel, operating under elevated temperature, the strain rates are considered to be primary design parameters. In order to reduce the steady state creep rates in the composite Cylinder, working under a given set of operating conditions (*i.e.* operating pressure and temperature) any of the following three options could be employed: (i) using finer size of reinforcement (SiCp) without varying its content, (ii) incorporating higher amount of dispersoids (SiCp) without altering its size, and (iii) simultaneously decreasing the size and increasing the amount of SiCp reinforcement. The selection of optimum size and content of the reinforcement in a composite pressure vessel, working under a given set of operating conditions, can be decided by simultaneously optimizing the cost of composite and the value of maximum strain rate in the composite cylinder for different combinations of particle size and particle content within the specified range.

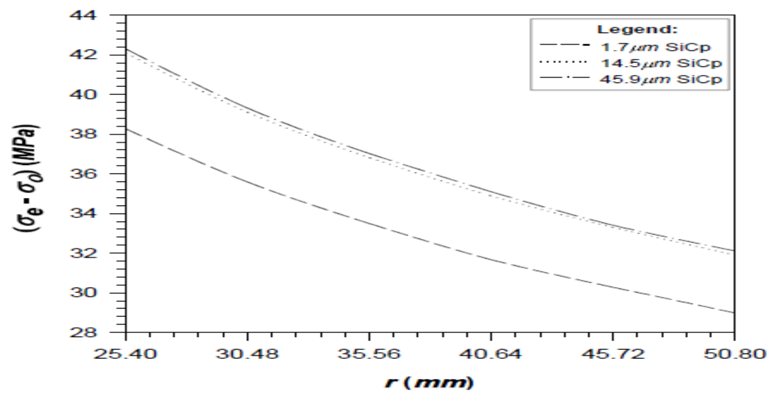

Fig No. 5 Variation of stress difference for varying particle size of SiC (V = 10 *vol%*, T = 350 °C).

RESULTS AND DISCUSSION

Numerical calculations have been carried out to obtain the steady state creep response of the composite cylinder for different particle size, particle content and operating temperature.

VALIDATION

Before discussing the results obtained, it is necessary to check the accuracy of analysis carried out and the computer program developed. To accomplish this task, the tangential, radial and axial stresses have been computed from the current analysis for a copper cylinder, the results for which are available in literature (Johnson *et al*, 1961). The dimensions of the cylinder, operating pressure and temperature, and the values of creep parameters used for the purpose of validation are summarized in Table 3.2.

Table no.2 Summary of data used for validation (Johnson et al)

Cylinder Material : Copper
Cylinder dimensions: $a = 25.4\ mm$, $b = 50.8\ mm$.
Internal Pressure = 23.25 MPa, External Pressure = 0
Operating Temperature = 250 ^oC
Creep parameters estimated: $M = 3.271\times10^{-4}\ s^{-1/5}/MPa$, σ_o = 11.32 MPa

To estimate the values of parameters *M* and o for copper cylinder, firstly σ_e have been calculated at the inner and outer radii of the cylinder by substituting the values of σ_e σ_r σ_θ σ_z in Eqn. we obtained at these locations, as reported in The study of Johnson *et al* (1961). The values of stresses σ_r σ_θ and σ_z and the tangential strain rate $\acute{\varepsilon}_\theta$ reported by Johnson *et al* (1961) at the inner and outer radii are substituted in Eqn. we know to estimate the effective strain rates at the corresponding radial locations. The effective stresses and effective strain rates thus estimated at the inner radius σ_e = 189.83MPa and $\acute{\varepsilon}_e = 2.168\text{x}10^{-8}$ s^{-1} and at the outer radius σ_e = 116 MPa $\acute{\varepsilon}_e = 1.128\text{x}10^{-9}$ s^{-1} of the copper cylinder are substituted in creep law, Eqn. obtained above, to obtain the creep parameters *M* and o for copper cylinder as given in Table 2. These creep parameters have been used in the developed software to compute the distribution of tangential strain rate in the copper cylinder. The tangential strain rates, thus obtained, have been compared with those reported by Johnson *et al* (1961). A nice agreement is observed in Figures above verifies the accuracy of analysis presented and software developed in the current study.

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