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Hybrid materials design to control creep in metallic pipes

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ABSTRACT

A hybrid material has been developed to improve creep performance in pressurized metallic pipes subjected to high-temperatures. Model materials were selected for an investigation of reinforcement design parameters in architectured materials. Brass pipes (65 wt.% Cu/35 wt.% Zn) with austenitic stainless steel reinforcement were pressurized and creep rupture tested at 673 K. Compared to unreinforced pipes of equal dimensions, a 47-times reduction in the effective strain rate was observed with a 50° reinforcement angle. A 'neutral angle' of 54.7 ± 1.5° was determined experimentally, where tangential (hoop) and longitudinal stresses on the pipe can be balanced and strains minimized. For initial angles below the neutral angle, creep strain was shown to facilitate a shift in orientation towards the neutral angle. For an initial angle of 42°, this shift towards the neutral angle resulted in instantaneous creep rate dropping from 170% of the mean creep rate to 60% of the mean creep rate over 820 h, when the final angle was measured to be 50°. A high-temperature prototype (tungsten braid oriented at 53° over a 253MA stainless steel pipe) was shown to give a creep life extension in excess of 300-times at 1313 K.

1. Introduction

There is constant demand for improved materials that can perform at higher temperatures to increase efficiency and reliability of systems such as gas turbine engines and petrochemical facilities [1,2]. Bulk materials have been continuously improved via alloying and manufacturing processes to obtain substantial gains in performance over the past few decades, e.g., in gas turbine engines [3,4] steam reformer and steam cracker furnace tubes [5]. However, improvements are made in relatively small steps and it may be argued that such materials are reaching the limit of their potential. The present research focuses on industrial applications, such as steam methane reformers, in which relatively large pipes (ca. 10 cm diameter and 13 m in length) operate under ~1–5 MPa internal pressure at approximately 1173 K. Since these pipes operate at temperatures greater than 1/3 the absolute melting temperature (T_M) of the alloys presently employed in these applications, the pipes are subject to failure by creep mechanisms, and cracks eventually develop along the longitudinal axis of the pipe due to tangential (hoop) stress.

The present work seeks insight into the design of "hybrid materials" as an alternative pathway to obtain substantial performance improvements over bulk materials and even composite materials in high temperature piping applications. Ashby [6] defined hybrid materials as "combinations of two or more materials or of materials and space, configured in such a way as to have attributes not offered by any one material alone". The simple hybrid design under consideration here involves externally reinforcing a pipe with an architectured layer of a material having substantially greater creep rupture life than the pipe material. This architectured reinforcement layer may be comprised of filament windings or a braided sleeve. Utilizing a hybrid layup allows the property space between rule of mixtures and 'greatest of both' scenarios to be exploited for a substantial life extension, utilizing the structural strength and chemical resistance of the pipe and the creep strength of the reinforcement layer.

A significant amount of work has been done in the area of fibre and braid-reinforced polymeric or elastomeric pipes [7] which operate at relatively low temperatures (less than 473 K). These reinforced composite materials have shown a great deal of success in improving both mechanical and creep strength. The cost-effectiveness of glass-fibre reinforced composites, coupled with their well-balanced combination of impact toughness and strength/stiffness properties makes them suitable for the development of aerospace components such as propeller shafts and turbine casings as well as automotive parts such as transmission drive shafts [7]. A polyethylene pipe containing aramid fibres can permit operating pressures of around ten-times the capability of conventional polyethylene pipe [8].

For fibre reinforcement oriented at an angle θ from the pipe axis, the theoretical angle at which stresses due to internal pressure are balanced by the reinforcement restorative force is known as the neutral angle (θ_N). This θ_N notation is used to refer to a general case, dependant on tube geometry and loading conditions (i.e. self weight or tension in addition to internal pressure). In a thin-walled pressure vessel where internal pressure is the only applied load, the tangential stress (σ_t) is twice the longitudinal stress (σ_z). It can be shown that when forces

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are in a state of equilibrium and the reinforcement is in tension, the theoretical neutral angle for thin-walled vessels (θ_N^*) is 54.7° [8,9].

$$\theta_N^* = tan^{-1}\left(\sqrt{\frac{\sigma_t}{\sigma_z}}\right) = tan^{-1}(\sqrt{2}) = 54.7°. \quad (1)$$

In composite systems where the reinforcement is embedded in a pipe matrix with low stiffness and/or strength, under applied internal pressure the reinforcement shifts to orient itself at the equilibrium position of θ_N. When $\theta > \theta_N$, the pipe will increase in length and its diameter will decrease. When $\theta < \theta_N$, the pipe will shorten in length and its diameter will increase [9]. This means of actuation for a given internal pressure is often utilized in pneumatic artificial muscles as well as muscular hydrostats in biological systems [10–12], where the deformation is elastic.

Refractory metals have been previously considered as good reinforcement candidates for achieving considerable gains in the creep rupture life of stainless steels and nickel-based super-alloys, materials commonly used in high temperature piping applications (1173 K and above) [13–18]. It must be noted that refractory metals themselves are limited by their poor oxidation resistance at service temperatures and can only be used in air when protected by suitable coating materials [15]. As a result, most creep tests on refractory composite and alloy systems have been performed under vacuum with the intended application being high temperature components for use in space [19]. For some applications with shorter life requirements, it may be practical to minimize the rate of oxidation by alloying or coating materials such that they form a stable, dense surface oxide [15]. However, in order to form an effective oxide layer, a critical Cr, Si or Al content is required in the alloy and such high levels of these alloying components cause brittle intermetallic phases to form with refractory metals [15,20].

Prior to the present work, a proof-of-concept 43-mm diameter, schedule 160 alloy 800H pipe was reinforced using helically wound 0.38 mm diameter tungsten wires, and creep tested at 1303 K and 3.5 MPa internal pressure (analytical grade argon). To combat oxidation, the reinforced pipe was coated with a plasma sprayed 79E nickel-based alloy. This proof-of-concept test showed at least a 4-times life extension over a monolithic pipe of equal dimensions tested simultaneously under the same conditions. Although the prototype pipe did not rupture, there were signs of oxidation in the tungsten reinforcement, which was considered the life-limiting factor [21].

The main purpose of the present work was to optimize the architecture of the reinforcement. A model materials system of brass pipes reinforced with austenitic stainless steel was selected for study, which was convenient to avoid oxidation of refractory metal, facilitate fabrication, improve availability of materials and lower test temperatures. A series of model materials prototypes, having systematically altered reinforcement architecture, were built and creep tested under internal pressure until failure. Post-test assessment and periodically interrupted tests revealed the strains that were obtained during the tests. While a similar approach to creep testing has been used for polymeric composites at low temperature [22,23], the use of pressurized pipe tests to assess the creep rupture performance of metals at high temperature has only been considered in a few select cases [24–26] and never, to the authors' knowledge, for metallic composites or hybrids.

2. Methodology

Structural pipes are widely used in fluid and gas transportation in the petrochemical industry, where they often contend with aggressive environments, high temperatures and elevated pressures, and are prone to failure via creep. The multiaxial mechanical properties of the pipe become extremely important when the material or structure is anisotropic or orthotropic, as is the case for composites and hybrids [27].

2.1. Life prediction of unreinforced materials

Shigley [28] states that a pressure vessel can be assumed to be thin-walled when the ratio of the wall thickness to inner radius (t/r_i) is < 0.05. For typical test pipe dimensions, 25.4 mm outer diameter and $t = 1.22$ mm, this assumption is invalid as $t/r_i = 0.106$. Therefore, Lamé's equations for stresses in a thick-walled pressure vessel were reduced for zero external pressure (Eqs. (2)–(4)). Von Mises equation (Eq. (5)) was used to resolve these multiaxial stresses into an equivalent stress, σ_{VM}. Principal stresses in a cylindrical coordinate system σ_r, σ_t and σ_z are functions of radial distance at a given point (r), internal pressure (p_i) and outer and inner radii (r_o and r_i) of the cylinder. Tangential and von Mises stresses are largest at the inner wall of the pipe.

$$\sigma_r = \frac{p_i r_i^2}{r_o^2 - r_i^2}\left[1 - \frac{r_o^2}{r^2}\right] \quad (2)$$

$$\sigma_t = \frac{p_i r_i^2}{r_o^2 - r_i^2}\left[1 + \frac{r_o^2}{r^2}\right] \quad (3)$$

$$\sigma_z = \frac{p_i r_i^2}{r_o^2 - r_i^2} \quad (4)$$

$$\sigma_{VM} = \sqrt{\frac{\left[(\sigma_r - \sigma_t)^2 + (\sigma_t - \sigma_z)^2 + (\sigma_r - \sigma_z)^2\right]}{2}} \quad (5)$$

Eqs. (2)–(5) were then solved for typical test piece dimensions and 2 MPa of internal pressure, to find an equivalent stress, σ_{VM}, of 18.9 MPa at the inner wall. This value was used for the life prediction of an unreinforced control pipe.

2.2. Model pipe material selection

The brass used in this study has a nominal composition of 65 wt.% Cu/35 wt.% Zn, with a copper composition typically in the range of 64–68.5% [29]. While some β' may exist in this composition at room temperature, it is in solution at 673 K and the alloy may be considered single phase α-brass during creep testing [30]. For a 673 K test temperature and $\sigma_{VM} = 18.9$ MPa, interpolating from the creep curve provided for 70–30 α-brass by Evans and Wilshire [31] gives an estimated creep rupture life of 83.5 h for the unreinforced pipe.

2.3. Reinforcement architecture

The 304 and 316 L stainless steel reinforcement configurations tested were defined by parameters relating to their architecture. These include surface area coverage, braid/wrap angle, wire packing fraction, longitudinal stiffness, wire size, number of yarns and number of wires per yarn. Modelling [32] reveals that overall braid stiffness is a function of braid angle, wire diameter, packing fraction, yarn sectional area and length and angle of undulation (crimp angle) through the thickness of the braid.

These reinforcement configurations and their characteristics prior to testing are summarized in Table 1. Reinforcement angle, θ, was measured relative to the pipe axis (0°) and defined from 0° ≤ θ ≤ 90°. At least six measurements of θ were taken for each reinforcement type, with the mean and standard deviation reported in Table 1. Braid naming convention was selected based on the wire coarseness (C or F to denote 'coarse' and 'fine' wires, respectively) and nominal reinforcement angle.

'C-65°' (Fig. 1b) refers to a braided structure with an overall reinforcement layer thickness comparable to the 0.4 mm wire wrap (Fig. 1a). By comparison to C-65°, F-42° (Fig. 1d) is comprised of many finer wires arranged in a tighter weave to give increased surface coverage.