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RHEOLOGICAL MODEL OF ALUMINIUM ALLOYS AT HIGH TEMPERATURES

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Abstract

The paper presents an overview of research on aluminium alloys and their applications as load-bearing structural components. It highlights the advantages and potential deficiencies of using elements made of aluminium alloys compared to steel, which remains the primary metal material in the construction industry, with the aim of encouraging more widespread use of aluminium. Particular attention is given to studies involving experimental testing of the mechanical properties of aluminium alloys at elevated temperatures, with a focus on the assessment of their reduced properties, especially time-dependent deformations - creep. Available rheological models are reviewed, including possibilities for their adequate adaptation and application to aluminium alloys. The intention is to develop a generalised creep model applicable to all aluminium alloys for structural purposes, also rheological model aimed at predicting mechanical properties following fire exposure.

Keywords: aluminium alloys; fire; constitutive behaviour; creep; rheological model.

1. Introduction

Although aluminium is the third most abundant element in the Earth's crust, it is a relatively modern material whose use in load-bearing structures was enabled by the development of suitable alloys. Today, beside steel, it is one of the most important metals in the construction industry. Its advantages include low density (about one-third that of steel), corrosion resistance without additional protective coatings, non-magnetic behaviour, and the retention of good ductility at low temperatures - unlike steel, which is prone to brittle fracture. It is highly recyclable, making it a sustainable material; estimates indicate that 70–98% of today's aluminium structures will be recycled [1]. Alloys from the 6xxx series suitable for structural applications include EN AW-6082, 6061, 6005A, 6106, 6063 and 6060 [2].

However, aluminium also has notable disadvantages. Its lower melting point and the more rapid degradation of mechanical properties at elevated temperatures make it less fire-resistant than steel. Degradation becomes noticeable above 100 °C and can become significant above 200 °C. Owing to its high thermal conductivity, heat spreads more rapidly through aluminium elements, which is a drawback for structural fire resistance. Furthermore, because of its crystalline lattice microstructure, whose vacancies enable atomic diffusion, the behaviour of aluminium alloys under sustained loading is characterised by time-dependent deformation (creep), particularly when exposed to elevated temperatures.

Creep has been shown to significantly influence the reduction in collapse time of structural elements made out of aluminium. Traditional rheological models (e.g., Burgers, standard solid models) represent only the primary and secondary creep stages. In addition to classical fire safety measures [3], and passive protections, mechanical properties and load-bearing capacity should be sufficient to allow all users to evacuate. Since the ability to predict the performance of aluminium structures exposed to fire is essential for ensuring sufficient load-bearing capacity, to address existing limitations, recent research aims to develop a model capable of incorporating all three creep phases and high-temperature behaviour of aluminium. If proven effective, it could be integrated into finite element-based codes.

2. Research Overview

2.1. Experimental Determination of Aluminium Alloy Properties

Numerous studies have focused on analysing the material characteristics and behaviour of aluminium alloys at ambient temperatures. However, their properties and reduced load-bearing capacity after exposure to elevated temperatures remain insufficiently investigated.

Experimental investigations to determine the stress-strain relationships of aluminium alloys at elevated temperatures were conducted by Maljaars et al. [4], paying particular attention to the influence of creep. The shape of the stress–strain curve depends on the type of alloy; moreover, even for the same alloy, the curve at ambient temperature differs from that at elevated temperatures [5], [6].

Torić et al. [7] performed two distinct types of tests to quantify deformation caused by mechanical loading and that associated with creep - steady-state creep tests. They proposed an analytical model suitable for interpreting deformation test results, incorporating all three stages of creep. For alloys 6063-T5 and 6061-T6, Su et al. [8] carried out steady-state and transient tests at temperatures up to 600 °C. Liu et al. [9] conducted a detailed analysis using steady-state tensile tests on 6082-T6 specimens heated from 100 °C to 550 °C and subsequently either air-cooled or water prior to testing. Working on alloy 6063-T5 up to 550 °C, Sun et al. [10] confirmed the pronounced effect of elevated temperatures on mechanical properties, particularly above 200 °C, and proposed a series of models for estimating the post-fire properties of this alloy. Megalingam et al. [11] tested aluminium alloy 7075 at a constant temperature of 250 °C under high, sustained stress levels to analyse its creep behaviour under long-duration thermal loading.

2.2. Assessment of Aluminium Alloy Properties

Suzuki et al. [12] carried out fire loading tests on aluminium-alloy columns and beams to establish the link between stress and critical temperature. From these results, they formulated numerical expressions to predict temperature rise and to estimate the critical temperature of heated members. Disregarding the effects of initial imperfections and creep, Fogle et al. [13] proposed a simple analytical model for predicting failure under fire conditions. Maljaars et al. [14] highlighted limitations of Harmathy's constitutive model [15], particularly for 6xxx-series alloys, which exhibit an early onset of the tertiary creep phase. To verify constitutive behaviour of aluminium alloys in fire, they developed a FE model, and proposed extending the Dorn-Harmathy stress-strain model to transient state conditions for fire-exposed aluminium alloys [16]. Maljaars's extended model, with parameters adjusted for specific alloys, was also used by Soyal [17], who confirmed it via transient tests with rising temperature under constant or variable loading. By further augmenting Maljaars's model with additional parameters, Kandare et al. [18] enabled the assessment of failure in compression-loaded aluminium members under fire.

Torić et al. [19] investigated creep deformation of aluminium at high temperatures. They identified dislocation climb to a neighbouring slip plane as the key high-temperature creep mechanism and developed a rheological model encompassing all three creep stages. Within the constraints set out in their study, the model is applied to metals susceptible to high-temperature creep, and was calibrated for S275 steel and for aluminium alloy 6082-T6. Zheng and Zhang [20] examined the behaviour of aluminium beams, specifically alloys 5083-H112 and 6060-T66, with and without protection, at ambient and elevated temperatures. From their results and developed models, they pointed to the conservatism of the Eurocode 9 approach to critical temperature and proposed alloy-dependent simplified equations for temperature rise and for determining critical temperature. Under diverse thermal and mechanical conditions, Li et al. [21] formulated a family of constitutive models for alloy 7050 by establishing the link between creep deformation and age hardening. These models enable reliable prediction of material properties regardless of initial states and loading history. Through tests on alloy 7075-T6, Sun et al. [22] determined reduction factors for material properties over 20–550 °C and proposed a set of models to estimate stiffness and strength of high-strength aluminium alloys during and after fire exposure. To capture the full range of elevated-temperature behaviour, the authors adapted the modified two-stage Ramberg–Osgood model previously proposed by Yun et al. [23], which is based on an extensive database of more than 700 ambient-temperature stress–strain curves.

Spigarelli and Sandström [24] developed a model for estimating creep in pure aluminium, for which the chemical composition, stress and temperature must be determined experimentally.

3. Rheological Model of Aluminium

To model the mechanical behaviour of a material with sufficient accuracy, it is necessary to provide an analytical description of the relationship between stress and strain. The overall deformation process of metallic materials at elevated temperatures, consisting of three components of which one specifically represents creep deformation, was introduced in the 1980s in work of Anderberg [25].

$$\varepsilon_{tot} = \varepsilon_{th}(T) + \varepsilon_{\sigma}(\sigma, T) + \varepsilon_{c,r}(\sigma, T, t) \tag{1}$$

Where proposed total strain ε_{tot} formulation is described with thermal component $\varepsilon_{th}(T)$ dependent on temperature, a stress-related $\varepsilon_{\sigma}(\sigma, T)$ component governed by both applied stress and temperature, and a creep strain component $\varepsilon_{c,r}(\sigma, T, t)$. The latter is most complex, as it depends on stress, temperature, and time.

The existing models like described ones in the previous section, models for predicting individual material characteristics, are necessary for defining a rheological model of aluminium. One of the first rheological model was developed in the 1970s: a Kelvin model composed of a spring and a dashpot with associated constants, devised to assess nonlinear deformations and load-bearing failure in concrete [26]. To represent viscoelastic responses in steel, Chindam et al. [27] used Kelvin-Voigt and Maxwell models - the parallel and the series connection of spring and dashpot (Figure 1). Analysing the influence of heat on the material during cyclic testing, they identified the Kelvin–Voigt model as the more suitable option for capturing the mechanical and thermo-mechanical behaviour of polycrystalline materials in the elastic regime, motivating its application to aluminium.

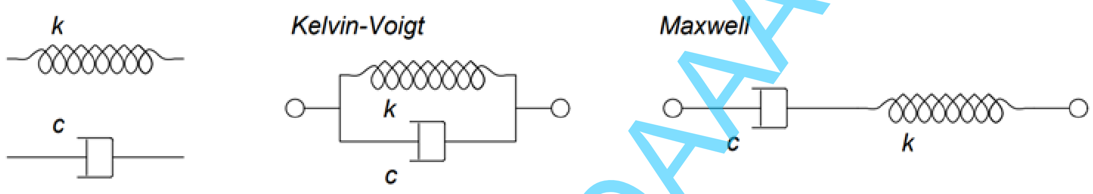

Fig. 1. Spring, dashpot, the Kelvin-Voigt and the Maxwell model

Models comprising multiple series-connected Kelvin–Voigt elements have been proposed, each describing a particular type of deformation response. Torić and Burgess developed a rheological model of two series-connected elements (Figure 2), in which the first represents the mechanical component of deformation and the second the viscous (creep) component, while the thermal deformation component, dependent solely on temperature, is omitted. By employing a serial connection of two Kelvin–Voigt elements, the development of creep deformation can be monitored under both stationary and transient heating conditions [28].

Torić and Burgess initiated their investigation of creep in S275 grade steel, providing a detailed description of the experimental procedures required to validate the analytical creep model in their study [29]. To develop an explicit creep model for S275 steel and an aluminium alloy 6082-T6, stationary-creep tests were conducted on cylindrical coupons and columns of the same materials. These tests highlighted the necessity of also accounting for the duration of exposure to elevated temperature.

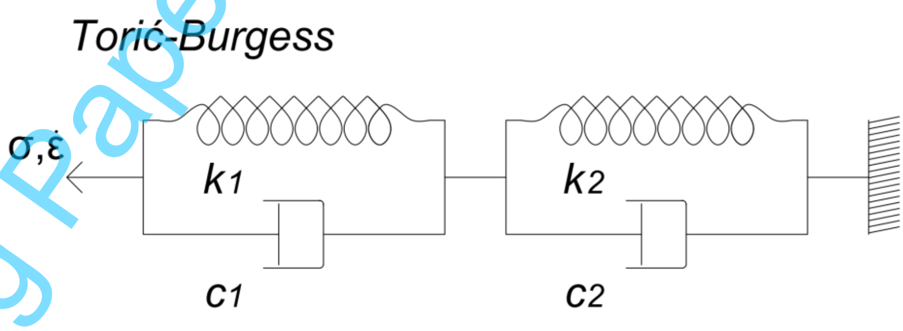

Fig. 2. Torić-Burgess model

The differential equation for each of the Kelvin-Voigt element can be defined as:

$$\frac{\sigma}{c_i} = \frac{k_i}{c_i}\varepsilon_i + \dot{\varepsilon}_i \quad (i = 1,2) \tag{2}$$

where total strain rate is constant and it can be defined:

$$\dot{\varepsilon} = \dot{\varepsilon_1} + \dot{\varepsilon_2} \quad (3)$$

Equation can be solved using Euler integration, where differential equations have to be integrated with respect to time by using small time increments. Type of solution (stress or strain-rate controlled) depends on type of loading. Verification of each constitutive component, as well as of the overall rheological model, was carried out against experimental datasets from various studies [30] and against the authors' own tests on S275 steel over 400–600 °C and on aluminium alloy 6082-T6 over 200–300 °C [19], [30]. With appropriate calibration, the model is considered applicable to any grade of carbon steel (S235–S355) and may be regarded as a foundation for a universal rheological model for metals characterised by high-temperature creep.
In order to explore the potential for application, it is necessary to address several new challenges that would provide a clearer understanding of the behaviour of individual alloys, thereby establishing a database of constitutive components that would reduce the number of experimental investigations required in the future.
For example of adaptation to different steel type is the process of determining the exponents in the Ramberg–Osgood model [31], which represents the strain value as a function of stress, the modulus of elasticity, and the corresponding exponents that must be identified and calibrated for each alloy [23], [32], and it is essential for accurately assessing the material behaviour.
The difficulty in predicting the modulus of elasticity lies in the remaining shortcomings concerning the required number of tests that would consistently capture the reductions associated with a given alloy and temperature. Eurocode [33] considers reduction coefficients for a single, unified material, whereas Figure 3 demonstrates that, even across a few examples of different alloys, varying ratios between reduced and initial values are obtained.

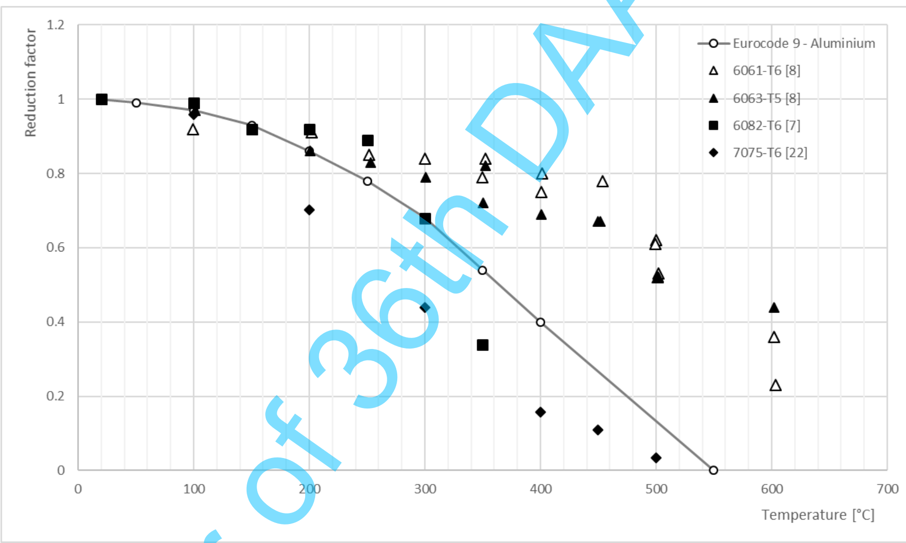

Fig. 3. Reduction factors of the in-fire elastic modulus test results and Eurocode 9 values

Various constitutive material models are already developed. Given the frequent use of the 7075 alloy in high-temperature applications, the behaviour of the stress exponent in relation to temperature and stress, as well as the creep deformation mechanisms expected to dominate under such conditions, have been examined [34], [35], [36]. Constitutive models at elevated temperatures have been developed [37], [38], along with a creep model for these high-performance aluminium alloys [39].

4. Conclusion

In recent decades, aluminium has been employed across engineering domains, primarily owing to its strength-to-weight ratio and excellent corrosion resistance. Given these benefits, the aim of this paper is to encourage its wider use in civil engineering. Aluminium comprises families of alloys with differing properties, with further distinctions between alloys within the same family. Owing to these numerous differences, in addition to studies on individual alloys, comparative analyses are required. To address the lack of critical information for load-bearing members, the creep behaviour of aluminium elements will be considered. In view of the identified challenges of fire resistance, particular attention will be devoted to these analyses. To reduce the need for costly and complex experimental programmes, parameters should be investigated through numerical analyses. The present review motivates the development of a rheological model for aluminium structures subjected to extreme conditions, encompassing all time-dependent deformation components. All critical thermomechanical variables (temperature and its rate of increase, stress, and strain rate) must be identified and accounted for. Following experimental characterisation of alloy behaviour at high temperatures, creep models tailored to those alloys will be developed, alongside a generalised model applicable to structural aluminium alloys used in civil engineering. Eventually, a rheological model will be defined to assess the extent of damage and the residual mechanical properties of aluminium elements after fire exposure.

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