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An interactive approach to creep behavior modeling

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ABSTRACT

Design and inspection of components used in high-temperature facilities, as well as evaluation of their lifespan requires detailed knowledge of creep behavior of the employed materials. Over the past decades, numerous phenomenological creep equations, describing creep strain dependency of physical quantities like time, stress or temperature via a set of parameters, have been developed. This paper deals with a novel approach of creep model parameter identification by an interactive graphical computer-based application aimed to significantly reduce evaluation time by automating necessary calculations as far as possible while, at the same time, providing a maximum of adjusting possibilities to program users—typically, materials experts. During evaluation, intermediate results are instantly displayed numerically and graphically. Verification purpose creep experiments on gradient specimens, as well as relaxation experiments, demonstrate the quality of this approach.

1. Introduction

In thermical machines and facilities, high-temperature components of heat resistant steels are being used. These must possess optimal strength and sufficient ductility especially in the long-term range. An important basis for design and maintenance of high-temperature components, as well as evaluation of their service lives, is information about their creep behavior [1].

Several "phenomenological" mathematical relations have been developed in the past decades in order to describe creep deformation analytically. These equations differ largely in their complexity, accuracy and range of input or result validity.

To describe creep behavior, both simple creep equations with few parameters and low performance, and powerful equations requiring intensive efforts of parameter identification, can be employed.

The purpose of the present work is to develop a conceptually innovative, graphical-interactive software (INCA—Interactive Creep Assessment) for creep behavior modeling. The application is aimed to significantly reduce necessary time efforts to identify creep equation parameters, as well as to enhance reproducibility and reliability of results. A window-based graphical program design shall assist users (material specialists) in visually interpreting result creep models, as well as enable them to fine-tune intermediate solutions in an intuitive manner.

INCA, despite being a ready-to-use stand-alone tool, shall not become an isolated application, but be designed to offer the necessary input and output interfaces (data formats) for interacting with other software (e.g. finite-element programs) in order to enable direct further processing of assessed creep models.

Verification experiments are being conducted along with program development in order to demonstrate the quality of parameter identification by INCA.

2. Overview of creep models

Creep strain, i.e. time-dependent deformation occurring under static load and elevated temperatures, is a function of time t, applied stress σ and temperature T. A typical creep curve, Fig. 1, displays creep strain ε_f in function of time at constant, uni-axial load and constant temperature, showing three characteristical creep stages: in the first part, strain rate decreases until transition time t_{12}, where approx. constant-rate second stage begins. Minimal creep rate is observed in this part.

Transition time t_{23} marks the beginning of the last stage, showing increasing creep rate and ultimately the rupture (at rupture strain A_u and time t_u) of the considered specimen or component.

To describe strain dependency of time, load and temperature mathematically, creep model equations have been established, this project dealing with phenomenological ones [2]. (Comparison of different types of creep models is available from other authors [3,4].) A relatively simple such equation with widespread industrial use for quick creep estimation is the Norton–Bailey law

$$\varepsilon_f = K\sigma^n t^m \quad (1)$$

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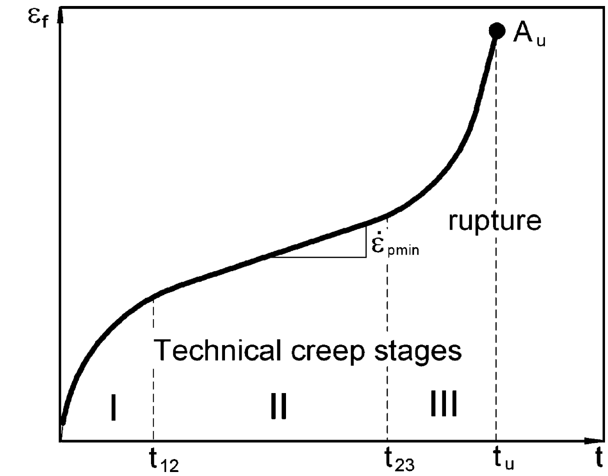

Fig. 1. Linear strain-time diagram with technical creep stages, schematically.

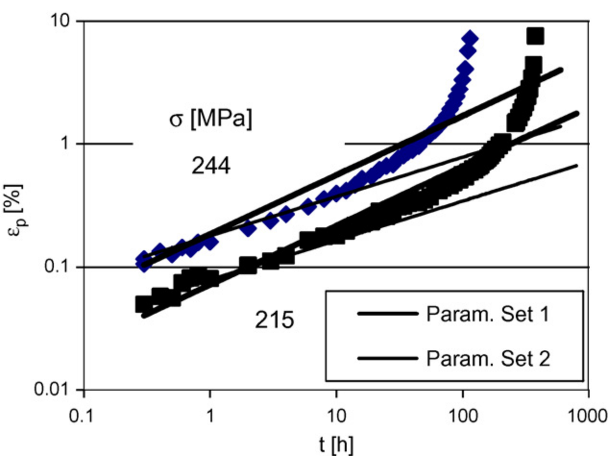

Fig. 2. Norton–Bailey approach: comparison of model function curves for two different parameter sets, plastic strain ε_p.

where parameters K, n and m can be assessed using linear regression after taking the logarithm of both sides of the equation. Major advantage of the Norton–Bailey approach is rapid estimation of its parameters. However, its applicability is limited to creep stages I and II, its accuracy is modest and, since it does not contain temperature dependency, an assessed parameter set is valid for a single temperature only.

A comparison between experimental creep data curves (at two different loads and same temperature) and model curves (plastic strain ε_p whereby initial strain ε_i and recovery strain ε_k are neglected) established using Norton–Bailey law can be observed in Fig. 2 for a widely used 10% CrMoV steel [5].

Creep data represented by plotted points is approximated by model curves (lean and bold straight lines) that have been obtained using the two assessed parameter sets of Table 1. A set of parameters is always computed using all available creep data curves of a temperature, thus in result, we obtain a set of model curves for all data curves.

Table 1
Norton–Bailey parameter values for two sets of parameters displayed in Fig. 2.

	K (%)	m	n
Parameter set 1	2.30×10^{-19}	0.48	7.5
Parameter set 2	5.42×10^{-17}	0.32	6.5

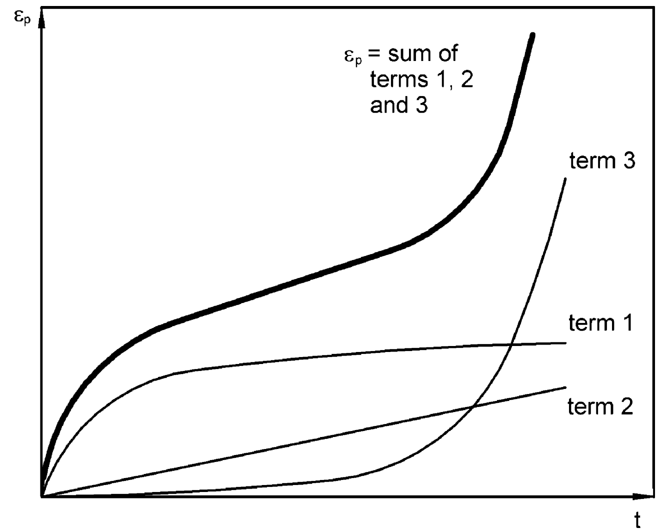

Fig. 3. Graham–Walles approach: superposition of three individual terms, schematically.

The degree of sensitivity of model curves to changes in parameters is well observable. The best mathematical fit need not be the optimum solution, since the material scientist only knows which parts of the underlying data are most important to approximate by the model.

If more accuracy and applicability over all three creep ranges is required, the Graham–Walles creep equation

$$\varepsilon_p = K_1\sigma^{n1}t^{m1} + K_2\sigma^{n2}t + K_3\sigma^{n3}t^{m3} \quad (2)$$

composed of three (Norton–Bailey-style) strain terms for each creep stage that are added up to obtain overall plastic strain ε_p can be used (Fig. 3):

Note that the second term is linear to time, thus time exponent m_2 equals 1. The sum of terms approximates well the typical creep curve shape along all three stages. However, this equation still does not have temperature dependency, and assessment of now eight parameters requires more effort and creep data from all creep stages.

A powerful creep equation developed at the Institut für Werkstoffkunde Darmstadt (IfW) that has been proving successful in industrial applications is the modified Garofalo equation as discussed in detail, e.g. in [6]. This approach also includes temperature dependency and produces very accurate models. However, its number of parameters being about 20, assessment requires large efforts and iterative optimization steps of intermediate solutions. Since implementation of this equation in INCA is planned, but not yet realized, it shall not be dealt with closer here.

Beyond these phenomenological equations, other engineering approaches of creep modeling and assessment exist as well. The most important other group is that of constitutive equations that directly exploit physical properties of considered materials. Also, phenomenological equations bearing a damage parameter are actively being researched elsewhere.

3. Program development

3.1. General concept

The purpose of the considered creep modeling application is to enable material specialists to assess creep models in an intuitive, graphical-interactive manner. The workflow, as presented in Fig. 4, includes reading in and displaying creep data, offering the necessary tools for assessment of data with a chosen creep equation,