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Constitutive models for bcc engineering iron alloys exposed to thermal–mechanical fatigue

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ABSTRACT

The progress in designing high temperature components relies on more accurate viscoplastic constitutive models. The capability of various models under high temperature and variable temperature conditions is investigated for two body centred cubic alloys, cast iron and ferritic stainless steel. Improvements are shown to overcome problems encountered by standard viscoplastic models. Firstly a physically based modified flow equation predicts reliably the behaviour of cast iron under thermal–mechanical loading. Secondly further improvement is proposed drawing on dislocation models to describe static recovery effects in stainless steels. Good agreement is thus obtained between experiment and model prediction under various thermal mechanical loading path.

1. Introduction

The design of high temperature components uses more frequently visco-plastic constitutive models due to the increase in computation capability. Most macroscopic models were established, 20 years ago by various research groups [1,2]. Component design can have two different purposes. The first one is to ensure the lifetime of the components and to predict the initiation of cracks under thermal–mechanical fatigue loading [3–6]. The lifetime of a component is usually assessed using a post-processor of the stress analysis made from a finite element (FE) model, that requires a good description of the stabilised cycle at critical locations in the component. The second one is to assess changes in component dimensions to avoid the loss of component function due to the accumulation of inelastic strains, due to creep or ratchetting. This requires a good description of strain versus time or cycles at any location in the component. Hence the accuracy of constitutive models is a major issue.

Constitutive models are identified today from isothermal databases. Basic versions of these models are often unable to cope with the various complex conditions that occur in high temperature components involving small cyclic strains under service loading, high temperature excursion and multi-axial stress conditions. Thermal–mechanical fatigue (TMF) tests are especially appropriate to test the prediction capabilities of constitutive models: though there are only uni-axial tests, axial mechanical strain can be imposed to a specimen and the resulting stress is measured for different mechanical strain versus temperature path [7–12]. In particular Chaboche model has been shown to yield fairly good results for thermal–mechanical fatigue tests of cobalt and nickel base superalloys [8,3,13]; these equations form the basis of crystallographic models with multiple potentials used successfully for single crystals superalloys by Cailletaud and coworkers [13–15,3]. Thermal–mechanical fatigue is especially demanding for models due to its complexity as previously emphasized [3,8]. However under isothermal loading, softer materials like stainless steels require more complex modelling effort, and even more to account for ratchetting or multi-axial effects [13–20].

The technical context of this study come from automotive applications such as exhaust manifolds were severe thermal–mechanical loading occurs due to start-up and shut-down operation of the engine, involving high temperature excursion and multi-axial stresses. Large thermal gradients arise in highly constrained parts, which involves visco-plastic stress–strain behaviour of constitutive alloys. Basically these components are made in cast iron for diesel engines up to about 700 °C. Gasoline engines requires higher operating temperatures typically up to 850–950 °C where cast iron has to be replaced by stainless steels, either austenitic or ferritic alloys. As the ferritic structure has the advantage to offer a lower expansion coefficient than austenitic alloys, while having a lower cost due to the absence of nickel, it can be used at fairly large temperatures despite its lower yield strength as compared to austenitic refractory grades [21,22].

Despite their technical importance, the deformation mechanisms of alpha iron and ferritic iron alloys under cyclic loading

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are not very well documented. The increase in carbon content and increase of temperature has been reported to favour similar dislocation structures in alpha iron and fcc alloys [23]. In ductile Fe–Si cast iron with a ferritic microstructure with less than 5% pearlite, slight hardening with increased cumulative plastic strain was observed at room temperature with dislocation density gradient near graphite nodules [24]. Hardening until saturation was reported at room temperature in Fe–26 Cr alloy, and dislocations walls very similar to that of face-centred cubic alloys were observed [25]. Hardening and softening were reported in Fe–24Cr–Al with C at room temperature [26]. Recent work on 9–12% Cr alloys with ferritic–martensitic microstructure has emphasized the strong cyclic softening at room temperature which increases when temperature increases (from room temperature up to 550 °C) [27]. Constitutive models for these steels were recently proposed using Chaboche type equations [28] or dislocation-based equations [29]. A dislocation-based model was proposed for mild steel exhibiting yield plateau [30]. For cast iron with different forms of graphite, viscoplastic models were recently combined with Gurson model to account for damage-plasticity interactions [31].

The present paper reviews different attempts to improve macroscopic models and to circumvent these difficulties, in stainless steels and cast iron with a body-centred cubic (bcc) structure used for automotive components. The two materials studied are a ferritic SiMo rich cast iron with spheroidised graphite (SG) and a ferritic stainless steel corresponding to AISI 441 or EN 1.4509 grades.

The first attempt uses Chaboche unified viscoplastic model as shown for 441 stainless steel. Then changing the flow equation in the constitutive model is shown for cast iron and application in TMF is shown for both alloys. Finally changing the internal variable description is shown for 441 stainless steel and TMF.

Table 1
Chemical composition of F17TNb (weight%).

Cr	C	Si	Mn	Ti	Nb	N
17.8	<0.02	0.5	0.3	0.16	0.5	<0.02

Table 2
Chemical composition of SiMo cast-iron (weight%).

C	Si	Mo	Mn	S	P	Ni	Cr	Cu
3.2	3.92	0.58	0.13	0.01	0.01	0.062	0.03	0.016

2. Materials and mechanical tests database

The F17TNb® is a 17% Cr stabilized ferritic stainless steel corresponding to AISI 441 or EN 1.4509 provided by Aperam Research Centre (Isbergues, France). It has a full ferritic structure up to 1000 °C [21,22]. Chemical composition is given in Table 1.

Cylindrical solid low cycle fatigue (LCF) specimens and hollow thermal mechanical (TMF) specimens were machined from a hot rolled slab with a thickness about 30 mm. Specimen geometry can be found elsewhere [21,3,7,10].

SiMo spheroidal graphite cast-iron is widely used by the automotive industry. For our study, it was formed into solid round bars of 25 mm diameter and 200 mm longitudinal length by sand casting [32].

The bars were not subjected to any heat treatment and their microstructure is the same as one can observe on an exhaust manifold designed for a diesel engine. The chemical composition of the material is given in Table 2.

Test specimens were machined from the round bars in the longitudinal direction. The specimens used for monotonic tension tests and cyclic hardening tests have respectively a 2.5 and 8 mm in diameter circular cross section. They are designed in order to have a homogeneous inelastic tensile strain in the middle of the specimen.

The yield strength and ultimate tensile strength of the two alloys are shown in Fig. 1. Cast iron exhibits a high strength up to 400 °C and then its strength decreases rapidly up to 700 °C. Stainless steel shows a lower strength but its yield strength exceeds that of cast iron above 650 °C and this alloy has a low yield strength at 850 °C.

The database used involves isothermal cyclic tests under strain-controlled conditions with a strain hold time, under fully reversed strain conditions. Incremental cyclic stress–strain tests are made at increasing strain amplitudes. At a given strain, amplitude is kept constant until the hysteresis loop stabilizes approximately (usually 10 cycles). Then, the strain level is increased and the cycling

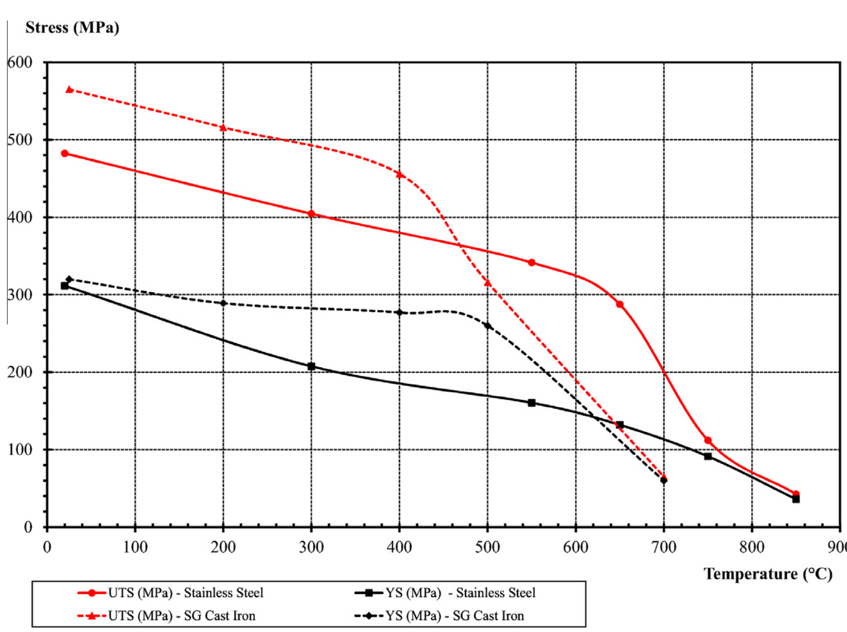

Fig. 1. Variation of yield strength and ultimate tensile strength of the two alloys studied as a function of temperature.