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New flow rules in elasto-viscoplastic constitutive models for spheroidal graphite cast-iron

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ABSTRACT

A specific flow rules and the corresponding constitutive elasto-viscoplastic model combined with new experimental strategy are introduced in order to represent a spheroidal graphite cast-iron behaviour on a wide range of strain, strain rate and temperature. A "full model" is first proposed to correctly reproduce the alloy behaviour even for very small strain levels. A "light model" with a bit poorer experimental agreement but a simpler formulation is also proposed. These macroscopic models, whose equations are based on physical phenomena observed at the dislocation scale, are able to cope with the various load conditions tested – progressive straining and cyclic hardening tests – and to correctly describe anisothermal evolution. The accuracy of these two models and the experimental databases to which they are linked is estimated on different types of experimental tests and compared with the accuracy of more standard Chaboche-type constitutive models. Each test leads to the superiority of the "full model", particularly for slow strain rates regimes. After developing a material user subroutine, FEM simulations are performed on Abaqus for a car engine exhaust manifold and confirm the good results obtained from the experimental basis. We obtain more accurate results than those given by more traditional laws. A very good correlation is observed between the simulations and the engine bench tests.

1. Introduction

The design of high temperature components experiencing cyclic viscoplasticity is nowadays a major scientific issue in an industrial point of view. Reliability, which used to be and remains an important concern in the design of nuclear power station cores or in aeronautics and space, has become a crucial point in the automotive industry as it is now necessary to offer the most reliable components and machines to customers in a very competitive market. In the same time, car engines tend to be exposed to higher temperature and pressure during their nominal use, especially to improve the performance and to reduce the environmental impact. Taking into account of these evolutions, the understanding and the accurate description of the materials behaviour such as aluminium alloys or cast-iron alloys have become a major issue for the last thirty years.

Today, the design of components experiencing high temperature cyclic loading uses more frequently viscoplastic constitutive models due to the increase in computation capability (Krempl, 2000). Most of the principles of these macroscopic models were established, twenty years ago by various research groups and their complexity usually depends on the

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capabilities to describe the various phenomena resulting from the thermo-mechanical loads to which materials are subjected. Since the lifetime of a component is usually assessed using a post-processor of the stress analysis made from a finite elements model, the accuracy of constitutive models is a significant topic for researchers.

Many authors have proposed macroscopic constitutive models to describe the elasto-viscoplastic behaviour of metallic materials experiencing cyclic plasticity. Most of the time, their approaches are included in the framework of the thermodynamic of the irreversible processes (Germain et al, 1983; Halphen and Nguyen, 1974; Lemaître and Chaboche, 1994; Chaboche 2003; Voyiadjis and Al-Rub, 2003) and are divided into two kinds. On the one hand, one can find non-unified models (Cailletaud and Sai, 1995; Blaj and Cailletaud, 2000; Charkaluk et al, 2004; Velay et al 2006), which considers a partition between the viscous phenomena and the plastic ones. On the other hand, there are unified constitutive models which take account of a unique viscoplastic strain. Among them, the Chaboche model (Chaboche, 1986, 1989, 2008) is the core of lots of studies as it enables to correctly describe a wide range of inelastic material behaviours such as cyclic hardening/softening or stress relaxation for materials such as stainless steels and nickel-based superalloy.

To describe plasticity, isotropic and more usually kinematic hardening terms are used (Ohno, 1990). Lots of approaches can then be found in the literature (Prager, 1956; Mroz, 1969; Armstrong and Frederick, 1966; Chaboche, 1991; Corona et al, 1996; Ohno and Wang, 1994; Ohno et al, 1998; Abdel-Karim and Ohno, 2000; Guionnet, 1992) and most of time, they are quite performing to describe monotonic plasticity. Differences lie in their ability to reproduce shakedown and ratcheting effects (Bari and Hassan, 2000; Abdel-Karim, 2005; Hassan et al., 2008; Rahman et al., 2008).

As Chaboche showed (Chaboche, 2008), many models give an answer to the problem of cyclic plasticity and particularly ratcheting. Evolutions of the hardening representation also enable to take account of many complex phenomena that could occur in some materials such as plastic strain memory effect (Chaboche et al, 1979), dynamic recovery (Ohno and Wang, 1993; Yaguchi et al, 2002a, 2002b; Kang et al., 2003), non-proportional loadings (Benallal and Marquis, 1987: Hassan et al, 2008) or even pre-stresses effects (Nouailhas, 1989). Studies also proposed specific yield limit representations (Yoshida, 2000; Yoshida et al., 2008; Voyiadjis et al., 2008) or included damage evolution (Cicekli et al., 2007).

The description of the material viscosity is generally realized through a flow rule, which takes very usually a power-function form (Norton, 1929) and episodically a hyperbolic sine-function form (Sellars and Teggart, 1966) or a exponential form (Kocks et al., 1975) to mostly describe the relaxation behaviour of the material (Krempl, 2001). Kang and Kan (2007)) choose to compare three kinds of models including a unified visco-plastic one and a creep-plasticity superposition model. They show that the creep creep-plasticity superposition model, using a hyperbolic sine function is reasonable when the creep is a dominant factor of the deformation, underlining the importance of the way such effect as viscosity is taken into account for a material experiencing high temperature conditions.

As noticed by Chaboche (2008), we found only eight noticeable attempts to find a new form for the flow rule with main differences monitored for slowest strain rate regime ($<10^{-8}\ \mathrm{s}^{-1}$) and for higher ones ($>10^{-2}\ \mathrm{s}^{-1}$). Mayama et al (2007) manage to correctly describe the behaviour of a 316L stainless steel thanks to a modified Ramberg–Osgood law using a classical power law for the flow rule. Unfortunately, the constitutive model is only tested at room temperature where viscosity is less important than, for example, for a cast-iron at 600 °C. In the same way, Ho (2008) obtain good results in describing relaxation behaviour of a stainless steel using a Norton law but once again for temperature (400 °C) where viscosity is not yet preponderant over plasticity.

However, basic versions of all these constitutive models and of viscosity flow rules 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. Indeed, a proper understanding of these phenomena often requires a multi-scale approach from a materials science standpoint (Estrin, 1998), using crystal plasticity and dislocation theory (Berveiller and Zaoui (1979); Essmann and Mughrabi, 1979; Estrin and Kubin, 1986; Estrin et al, 1996; Capolungo et al., 2006; Shenoy et al, 2008; Capolungo et al, 200). These microscopic or even crystallographic models (Flouriot et al, 2003) very often require very specific experimental data and microscopic observations (Mughrabi et al, 1981; Sommer et al, 1998). As we can see, this is a major area for researchers but the complexity of such an approach prevents to using it in engineering design today or in the near future, as length of such FE model computation is nowadays too expensive in an industrial context.

Designers, in the automotive industry, always prefer using quite phenomenological but still accurate constitutive models. Thus, macroscopic models are widely represented for the description of the behaviour of aluminium alloys (Smith et al., 1999; Lederer et al., 2000; Nicouleau et al., 2002; Guillot et al. 2002), cast-iron alloys (Thomas et al., 2004; Bastid, 1995) and even stainless steels (Bucher et al., 2006). Most of the time, it is a classical Norton law which is used to describe viscosity.

In this context, we made the choice to focus our work on new methods to describe the viscoplastic flow, drawn from deformation mechanisms at microscopic levels. Indeed, if hardening seems to be well represented by standard models, fewer attempts have been made to improve the flow rule while cast-irons could present specific viscoplastic behaviour. Our goal is to improve macroscopic models and to circumvent the classic difficulties in the case of a particular cast iron (Silica Molybdenum or SiMo alloy) used for automotive exhaust manifold. Based on a unified viscoplastic framework, macroscopic model parameters were identified using an enriched database. An adapted experimental strategy enables us to develop a new constitutive law and to propose two versions, the first one containing all the equations, the other one a bit simplified. The capability of these new models are tested against experiments on specimens under complex loading conditions such as 1D ratcheting, tests with strain rate variations, thermal–mechanical loading. Finally, thermal–mechanical FEM simulations on complex structures are performed and the accuracy of different models is discussed.