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Hot workability in process modeling of a bearing steel by using combined constitutive equations and dynamic material model

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ABSTRACT

The high temperature workability of a 1%C–1.5%Cr steel was investigated by means of torsion experiments carried out between 1125 and 1000 °C. The main task of the study was the quantification of the effect of processing conditions (temperature and strain rate) on the flow stress, by means of constitutive models capable of providing the entire shape of the stress *vs* strain curves. An excellent description was indeed obtained by the Hensel and Spittel relationship, provided that the portions of each curve before and after the peak stress were described separately. The same model curves were then used to estimate the peak and steady state stress for each of the investigated conditions, again obtaining an excellent correlation with the experimental data. To further facilitate the identification of the optimum processing window for this material, dissipation efficiency maps were obtained using as input the stress *vs* strain rate values computed by a constitutive model, in this case based on the Garofalo *sinh* equation.

1. Introduction

The successful simulation by Finite Element Modeling (FEM) codes of a hot working process, such as forging or extrusion, requires a detailed knowledge of the material deformation path. In most cases, the material response under hot working conditions is provided in the form of constitutive equations relating flow stress to temperature (T) and strain rate ($\dot{\varepsilon}$), which are usually valid for a given strain ε or, if applicable, at steady state. The selection of a reliable constitutive model capable of correctly estimating the variation in the flow stress with temperature, strain rate and strain, as already stated by Duan and Sheppard [1], is thus the key factor for the accuracy of FEM modeling. In fact, both the strain path and the flow stress have major effects on simulation output, since the former has a decisive influence on the microstructural evolution, and the latter determines the working loads. An example of the procedure used to obtain the constitutive equations was illustrated by Yin et al. [2] in their modeling of the flow behavior of GC15 steel. The constitutive equation used by these authors had the form of the well known Garofalo *sinh* relationship, i.e.

$$\dot{\varepsilon} = A_\varepsilon \sinh(\alpha_\varepsilon \sigma)^{n_\varepsilon} \exp(-Q_\varepsilon/RT) \qquad (1)$$

where A_ε, α_ε, n_ε and Q_ε were strain-dependent parameters. A 6th order polynomial equation was used to quantify the dependence of these parameters on strain, leading to a set of 4 equations with 28 constants to be determined. The Garofalo equation has also been used, for example, to describe the hot workability of P91 [3] and 28CrMnMoV [4] steels.

An alternative approach is based on the use of a unique constitutive relationship capable of modeling the flow curve under a given combination of $\dot{\varepsilon}$ and T. An example is the simplified Hensel and Spittel [5] formulation used by Duan and Sheppard [1]

$$\sigma = A\exp(m_1 T)\varepsilon^{m_2}\dot{\varepsilon}^{m_3}\exp(m_4/\varepsilon) \qquad (2)$$

where A, m_1, m_2, m_3 and m_4 are material parameters. An obvious observation is that Eq. (2) requires a limited number of constants to be determined in comparison with the approach based on Eq. (1).

GC15 (1%C–1.5%Cr) is one of the most widely used high-C bearing steels; as observed by Yin et al. [2], a set of constitutive equations for this material was still missing until the publication of their work, which thus covered a gap that severely hindered the possibility to obtain reliable FEM modeling. However, these authors used compression testing as a source of experimental data, and the intrinsic limitations of this technique resulted in a maximum attainable strain of $\varepsilon = 0.65$–0.7, which is lower than the maximum deformation obtained in a workpiece during the forging of complex shapes [6]. A strain as high as 2.0–2.8 can in fact be reached in the bore rim transition region of a component produced by closed-die isothermal forging [7]. Thus, in compression tests, the major problem is that little information can be collected on the work-softening stage and on the steady state, which, in steels deformed in the austenitic range (see, for example, the case of the tool steel investigated by Imbert and McQueen [8]), should follow the peak in the flow curve as a result of dynamic recrystallization (DRX). The situation is even worse in the case of tensile

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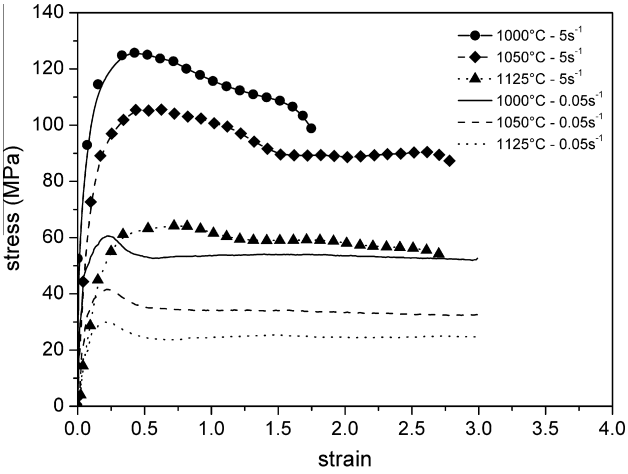

Fig. 1. Representative equivalent stress *vs* equivalent strain curves obtained by torsion testing.

testing, where necking occurs at strains lower than 0.1 [9]. Torsion testing, which has no instability constraints, could be used to overcome this problem, although the radial strain and strain rate gradients require the calculation of the equivalent stress and strain on the surface.

The aim of the present paper was to investigate the hot workability of GC15 (AISI 52100) steel by providing a set of reliable constitutive equations, suitable for use as input for the FEM simulation of a deformation process such as forging. A comparative analysis of the constitutive models was then performed in order to define an appropriate and reliable approach aimed at combining phenomenological equations and processing maps.

2. Experimental procedures

The investigated steel was the 1%C and 1.5%Cr (wt.) GC15 (AISI 52100). Specimens for torsion tests, 10 mm in diameter with a gauge length of 15 mm, were strained by a computer-controlled hot torsion machine at 1000, 1050 and 1125 °C. The samples were heated by a high frequency induction coil at 1 °C/s from room temperature to the testing temperature and maintained at this temperature for 300 s. Subsequently, the samples were strained up to rupture. Ruptured samples were quenched by a water-jet.

The torque M and the number of revolutions N were recorded and converted to von Mises equivalent stress σ and equivalent strain ε at the surface:

$$\sigma = \frac{\sqrt{3}M}{2\pi \cdot R^3}(3 + n' + m') \tag{3}$$

$$\varepsilon = \frac{2 \cdot \pi \cdot N \cdot R}{\sqrt{3}L} \tag{4}$$

where R and L are respectively the radius and the length of the gauge, $m' = (\partial \log M / \partial \log \dot{N})$ is determined at constant strain, and $n' = (\partial \log M / \partial \log N)$ at constant strain rate. For the peak-stress condition, clearly $n' = 0$ and, for the sake of simplicity, m was also taken equal to 0. The surface equivalent strain rates were 0.005, 0.05, 0.5 and 5 s^{-1}. To avoid the oxidation of the surface, the samples were protected by Argon gas in a quartz tube.

3. Results

Fig. 1 presents representative equivalent stress *vs* equivalent strain curves obtained by torsion testing. In all cases, the curves show a more or less pronounced peak, followed by flow softening down to a steady state, i.e. the expected behavior of materials which undergo dynamic recrystallization. Only in one case, i.e. the test carried out at 1000 °C–5 s^{-1}, did the sample rupture at strains lower than 2; in addition, this particular test exhibited continuous flow softening after the peak, an effect which is partly due to adiabatic heating.

Figs. 2 and 3 show representative flow curves obtained in compression on a similar material by Yin et al. [2]; Fig. 3, in particular, compares the torsion and compression curves. It can be easily observed that a general similarity exists between the shapes of early parts of the torsion flow curves and the compression ones, albeit the two datasets exhibit a different dependence of the flow stress on temperature. This behavior can be probably attributed to the different initial state and heating schedules. Compression curves, as above mentioned, do not extend above 0.65 and are thus of limited use for the description of the DRX-controlled stage of deformation. As already noted by McQueen and Ryan [10], DRX starts during high temperature deformation of austenite at $\varepsilon \cong 0.6\varepsilon_p$, with ε_p being the strain corresponding to the peak flow stress, and is approximately 30% completed at the peak. For this reason, one important aspect of both compression and torsion curves is the determination of the strain rate and temperature dependence of the peak strain, which can be described, for example, by an empirical equation in the form [11]

$$\varepsilon_p = A_{\varepsilon,p}[\dot{\varepsilon}\exp(Q_{\varepsilon,p}/RT)]^k \tag{5}$$

with $A_{\varepsilon,p}$ and k being material parameters, and $Q_{\varepsilon,p}$ an activation energy. Interpolation of the experimental data obtained in torsion in this study and in compression by Yin et al. [2] (Fig. 4), gave the values of the different parameters reported in Table 1.

4. Discussion

4.1. Constitutive analysis: flow curves

As mentioned in the opening section of this study, Yin et al. [2] (2013), in their comprehensive analysis of the high temperature compression of GC15 steel, proposed a model based on Eq. (1), properly modified and rewritten in the following form:

$$\sigma = (1/\alpha_\varepsilon)\left\{(Z'_\varepsilon/A_\varepsilon)^{1/n_\varepsilon} + \left[(Z'_\varepsilon/A_\varepsilon)^{2/n_\varepsilon} + 1\right]^{1/2}\right\} \tag{6}$$

where

$$Z'_\varepsilon = \dot{\varepsilon}^{4/3}\exp(Q_\varepsilon/RT) \tag{7}$$

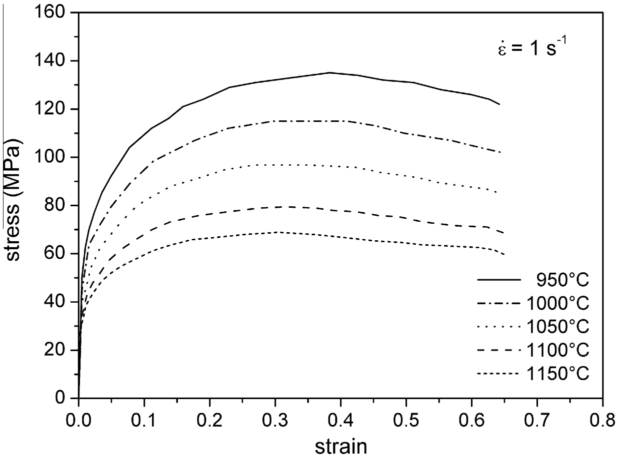

Fig. 2. Representative compression curves obtained in compression by Yin et al. [2].