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Processing maps of Ti662 unreinforced and reinforced with TiC particles according to dynamic models

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Abstract

Ti–6Al–6V–2Sn produced by powder metallurgy by Dynamet unreinforced (CermeTi®-C-662) and reinforced with 12 vol.% of TiC particles (CermeTi®-C-12-662), and ingot Ti662 are deformed at high temperatures. The processing maps of these materials are derived using the dynamic material model (DMM) developed by Prasad et al., and the modified DMM developed by Murty and Rao. Although both models result in similar power dissipation values, the instability zones predicted by them are quite different. The processing maps predicted by the modified DMM can be correlated to the deformation behaviour of these materials, with respect to the shape of their flow curves and to their microstructure after deformation. The concentration of stresses produced during compression is released by cracking at the triple junction of grain boundaries in the CermeTi®-C-662, whereas in the CermeTi®-C-12-662 by fracture or debonding of the reinforcing particles.

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1. Introduction

Titanium alloys show high specific mechanical properties up to high temperatures, and corrosion resistance, that make them attractive not only for aerospace components, but also for automotive, industrial and medical applications [1,2]. Ceramic reinforcement can further improve some mechanical properties [3,4]. The particulate reinforced alloys are cheaper than the continuous fibre reinforced alloys, and can be forged, cut, formed, and their properties are more or less isotropic.

Although the mismatch in CTE between titanium matrix and TiC particles is not big enough to expect an important improvement in the strength by mismatch strains, the composite material has been widely studied [5–7]. The higher Young's modulus and hardness of TiC with respect to the matrix increases the specific stiffness and the wear resistance [8].

This work is dedicated to predict the forgeability of cogged Ti662 ingot with a globular microstructure and of Ti662 produced by powder metallurgy with 0 and 12 vol.% of TiC. Hot compression tests are performed in order to identify the best parameter window for forging, the mechanisms of deformation, and the internal damage of the materials. Experimental data of compressive flow stress (σ) as a function of the temperature (T), strain rate ($\dot{\varepsilon}$) and strain (ε) are produced. These hot deformation data were implemented into the dynamic material model (DMM) developed by Prasad et al. [9] and the modified DMM developed by Murty and Rao [10]. Montheillet et al. strongly criticised the model [11] as it is not based on material laws but is used as an heuristic approach. He proposed to apply the strain rate sensitivity of the stress exponent (m) to asses formability. The efficiency of the power dissipation is derived by Prasad [12] from the separation of the power into a component of heat dissipation and another of microstructural changes. Prasad [9] assumes a constant stress-exponent (m) for instantaneous values of power, whereas Murty and Rao [10] allow for strain rate dependent m-values. The following study compares the application of the dynamic material model and the modified one to titanium particle reinforced matrix (TiPRM) and provides some microstructural observations to be related to the predictions of the applied models.

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1.1. General assumption of the DMM

The material is considered to have the following characteristics for DMM [9]:

(1) *Dissipative*: The material essentially dissipates power during hot deformation and does not store energy significantly. This is true in our case of deformation at high temperatures, where only softening and steady state is possible.
(2) *Dynamic*: The constitutive response of the material at a given temperature during hot deformation depends essentially on the strain rate and to a smaller extent on strain. The strain component only defines the frame of the micro-system.
(3) *Non-linear*: The response of the material to the imposed variables like strain, strain rate and temperature is non-linear.
(4) *Far from equilibrium*: The material undergoing large plastic flow at high temperatures is far from equilibrium since the strain is not being applied in infinitesimally small increments.
(5) *Irreversible*: The extremum principles of irreversible thermodynamics from Ziegler as applied to large plastic flow [13] are applicable.

1.2. Dynamic material model (DMM)

The total power dissipated is related to the rate of entropy production inside the system $\dot{S}^{(i)}$ via:

$$P = T\frac{\mathrm{d}S^{(i)}}{\mathrm{d}t} \geq 0 \tag{1}$$

and it is always positive for irreversible processes (e.g. plastic deformation) and zero for reversible processes. Under isothermal conditions, the rate of entropy production is totally "internal" (P).

According to Basaran and Nie [14], "the entropy balance equation and laws of conservation cannot alone be used to solve the initial and boundary value problem, since this set of equations contain the irreversible flux as unknown parameter". And they demonstrate that the entropy production caused by the dissipations can be divided into four terms: two terms called the intrinsic dissipation or mechanical dissipation, which consists of plastic dissipation plus the dissipation associated with the evolution of other internal variables; and the two further terms are the thermal dissipation due to the conduction of heat and an internal heat source.

In the case that the microstructural changes and the heat dissipation can be separated, as Malvern also demonstrate [15], then it is possible to use the following statement:

$$P = G + J = \int_0^{\dot{\varepsilon}} \sigma \mathrm{d}\dot{\varepsilon} + \int_0^{\sigma} \dot{\varepsilon}\mathrm{d}\sigma = \sigma\dot{\varepsilon}. \tag{2}$$

This separation into content G and the co-content J is related to a partitioning parameter, in this case the strain rate sensitivity m. The content G can be represented by the area under the dynamic constitutive equation (σ as a function of strain rate) and co-content J represents the area above that curve. Relation 2 has not been verified by deformation mechanisms [11], although it provides useful prediction of material workability. Therefore experimental observations are required to try if a correlation to microstructural features can be found.

At a constant T and ε, the dynamic response of the (work-piece) material to hot deformation is represented by the power law $\sigma = K\dot{\varepsilon}^m$ where K is a constant and m is the strain rate sensitivity of the flow stress. The total derivative of Eq. (2) is:

$$\mathrm{d}P = \frac{\partial P}{\partial G}\mathrm{d}P + \frac{\partial P}{\partial J}\mathrm{d}P = \sigma \mathrm{d}\dot{\varepsilon}\,\mathrm{d}P + \dot{\varepsilon}\mathrm{d}\sigma\,\mathrm{d}P. \tag{3}$$

In this phenomenologic model, the factor that relates power between these two complementary terms is m, the strain rate sensitivity for an instantaneous value of P:

$$\left(\frac{\partial J}{\partial G}\right)_{\varepsilon,T} = \frac{\partial P}{\partial G}\frac{\partial J}{\partial P} = \frac{\sigma \mathrm{d}\dot{\varepsilon}}{\dot{\varepsilon}\mathrm{d}\sigma} = \left[\frac{\partial(\ln\sigma)}{\partial(\ln\dot{\varepsilon})}\right]_{\varepsilon,T} \equiv m. \tag{4}$$

For stable flow $0 < m < 1$. In the case of hot deformation, where no strain hardening occurs, the lower limit $m = 0$ represents strain rate independent deformation for which no power is dissipated within the deformed material. The upper limit $m = 1$ means plastic deformation like a viscous fluid (e.g.: superplastic material). In the deformation regime, where the power law is valid,

$$G = \frac{P}{1+m} \qquad J = \frac{mP}{1+m}. \tag{5}$$

However, the strain rate sensitivity m, is normally varying with the temperature and the strain rate. The variation can be normalized with respect to a linear dissipator ($m = 1$) where $J = J_{\max}$. The efficiency of power dissipation is defined as $\eta = J/J_{\max}$ and can be calculated as:

$$\eta = \frac{J}{P/2} = \frac{2m}{m+1}. \tag{6}$$

Since J is related to microstructural changes, $J_{\max}$ is the maximum value of all possible microstructural changes. η is correlated to the relative rate of entropy production due to microstructural dissipation [12], interpreted as the degree of microstructural transformations within the material. As we consider hot deformation, these microstructural features are recovery, recrystallisation, phase transformations and material damage [16].

The flow instability relies on the condition $\xi < 0$ [9]. It has been related to the flow parameters by:

$$\xi(\dot{\varepsilon}) = \frac{\partial \ln[m/m+1]}{\partial \ln\dot{\varepsilon}} + m < 0. \tag{7}$$

1.3. Modified DMM

The DMM was re-analysed by Murty and Rao [17], who demonstrated that if m varies with $\dot{\varepsilon}$ and T as in many engineering alloys, the flow stress does not obey one power law, and

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