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CONSTITUTIVE EQUATIONS OF THE DEFORMATION OF P/M SUPER ALLOYS AT ELEVATED TEMPERATURES

M. Oktay Alniak
Bahçeşehir University, Institute of Science,
Vocational School, 343453 Şişli, İstanbul

Doğan Aydin
Bahçeşehir University, Şişli Vocational School

Atakan Kiraci
Bahçeşehir University, Engineering Faculty, 34353 Beşiktaş, İstanbul

ABSTRACT

Material parameters affecting the material structures can be used for modeling the deformation behaviour of super alloys. Thermo-mechanical processes are applied to P/M super alloys for consolidation. Stress-strain relationship can be established by the factors such as strain, strain rate, grain size, temperature and structural parameters. A new deformation model is suggested in this work by means of searching the compatibility of experimental results and analytical studies. In this study, P/M Rene´ 95 super- alloy was used as experimental material and micro-thermo-mechanical behaviors were investigated.

Keywords: P/M Rene´ 95, super alloy, modeling

SYMBOLS	
ε	true strain, $\ln(h/h_0)$ where h_0 is initial specimen height
$\dot{\varepsilon}$	true strain rate
$\dot{\varepsilon}_S$	strain rate in soft regions of model material
$\dot{\varepsilon}_R$	strain rate in hard regions of model material
F	volume fraction of soft recrystallized material
σ	flow stress
σ_P	peak flow strength
σ_{SS}	steady state flow strength
σ_0	back stress due to intragranular
σ_i	internal stress due to grain boundary ledges
m	strain rate sensivity of flow strength
P	grain size sensivity of flow strength
Q	activation energy
R	gas constant
T	absolute temperature in K
$C(S, \dot{\varepsilon})$	structure and strain rate dependent time constant
t	time
n	time exponent
A, A'	experimentally established material constants
$\dot{\varepsilon}_{gbs}$	rate equation for grain boundary sliding
$\dot{\varepsilon}_{gbs}/AV$	ibid (Ashby and Verall mechanism)
$\dot{\varepsilon}_{gbs}/G$	ibid (Gittus mechanism)

$\dot{\varepsilon}_{mdg}$	rate equation for intragranular flow by dislocation creep (motion of dislocation within grains)
D_V	volume diffusion coefficient
D_B	grain boundary on interphase boundary diffusion coefficient
Γ	grain boundary energy
b	Burgers' vector
μ	shear modulus
k	Boltzmann's Constant
λ	initial grain size
d	as-worked steady state grain size
N	number of steady state grain layers in partially recrystallized spherical grain model

1. INTRODUCTION

Modeling of deformation mechanisms of engineering materials can be expressed by constitutive equations. These are useful for calculation and estimation of strength of material subjected to hot or cold deformation or extrusion operations. Some factors affecting materials' yield stress could be grouped as direct or indirect. While direct factors are said to be as deformation, deformation rate, and temperature; indirect factors may be chemical and metallurgical composition of the material, grain size, and history of the material.

A theoretical formulation was investigated for super alloys, Rene´95 considering some parameters affecting stress and strain relations such as deformation rate, absolute temperature, activation energy and grain size. After consolidation of material at hot isostatic pressure, tests were carried out at elevated temperatures such as 1050 ^{0}C, 1100 ^{0}C. A new model constitutive equation for Rene´ 95 super alloy was investigated by taking into account the stress, deformation, deformation rate, material parameters and structural changes.

2. CONSTİTUTİVE EQUATIONS FOR DEFORMATION MECHANISMS OF POWDER METALLURGY

Material parameters can be used for description of deformation mechanisms. A function or function of functions "functional" can be composed of the parameters like structural parameters of materials; such as microstructure, transformations of grains, stress, strain deformation, temperature and deformations rate.

The idea of developing new models depending on these parameters had been used for this research for modeling of powder metallurgy super alloys.

In modeling of super alloys compression tests applied and data was obtained from tests under the conditions of constant pressure, temperatures and deformation. To obtain the constitutive equations, during test and calculations can be faced with complex situations because of fine grain size of these materials, microstructural changes during the deformation. High temperature deformation affects diffusionel flow which is occurs during tests, and high temperature also affects deformation mechanisms of grains [1].

One of the deformation mechanisms is motion of dislocation glide . The $\dot{\varepsilon}_{mdg}$ component in Eq.1 can be presented by a dislocation glide/climb controlled creep equation like the following form.

$$\dot{\varepsilon}_{mdg} = A' \frac{D_V \mu b}{kT} \left(\frac{\sigma - \sigma_0}{\mu}\right)^4 \qquad (1)$$

Another deformation mechanism may be originated from grain boundary slide. Grain boundaries' slides $\dot{\varepsilon}_{gbs}$ are important for the super alloys. Grain boundary sliding mechanism in a rather low deformation rate as a factor contribute to the deformation also GITTUS model is used to modeling of super alloys deformation [2].

$$\dot{\varepsilon}_{gbs/G} = 53.4 \frac{D_B \mu b}{kT} \left(\frac{b}{\lambda}\right)^2 \left(\frac{\sigma - \sigma_i}{\mu}\right)^2 \qquad (2)$$

The deformation models that defines fine grained super alloys' (between 2 and 9 micron) deformation mechanism at related deformation rates were offered in this study. There may be three different deformation mechanisms at these deformation rates:

$$\dot{\varepsilon}_{(10^{-4}S^{-1}\sim 10^{-2}S^{-1})} = \dot{\varepsilon}_{gbs}$$
$$\dot{\varepsilon}_{(10^{-2}S^{-1}\sim 10^{-0}S^{-1})} = \dot{\varepsilon}_{mdg} \qquad (3)$$
$$\dot{\varepsilon}_{(10^{-4}S^{-1}\sim 10^{0}S^{-1})} = \dot{\varepsilon}_{gbs} + \dot{\varepsilon}_{mdg}$$

At 1050°C, at a wide deformation strain rates between 10^{-4} $S^{-1}$and 10^{0} S^{-1} the constitution equation of Rene´ 95 could be written as below:

$$\dot{\varepsilon} = 53{,}4\frac{D_B}{kT}\left(\frac{b}{\lambda}\right)^2\left(\frac{\sigma-\sigma_i}{\mu}\right)^2 + A'\frac{D_B}{kT}\left(\frac{\sigma-\sigma_0}{\mu}\right)^4 \qquad (4)$$

This constitutive equation proves experimental results for P/M 713 LC and RENE´ 95 super alloys. Also in this work, material parameters had been used by modified and results of test have ensured accuracy of theoretic formulation.

In a research carried out at constant deformation rate at 1100 ^{0}C high temperature; diffusion mechanism might be considered as a factor of deformation such as dislocation movements and mechanism of grain boundary slides. Namely, diffusionel flow contributes deformation mechanisms.

The constitutive equation of Rene´ 95 is then written as follows between 10^{-4} S^{-1} and 10^{0} S^{-1} at 1100^{0}C.

$$\dot{\varepsilon} = \dot{\varepsilon}_{mdg} + \dot{\varepsilon}_{gbs/G} + \dot{\varepsilon}_{gbs/AV} \qquad (5)$$

Regarding Ashby's and Veral's work, general constitutive equation is expressed as in the following manner [3].

$$\dot{\varepsilon} = 53{,}4\frac{D_B}{kT}\left(\frac{b}{\lambda}\right)^2\left(\frac{\sigma-\sigma_i}{\mu}\right)^2 + A'\frac{D_B}{kT}\left(\frac{\sigma-\sigma_0}{\mu}\right)^4 + \frac{100\,\Omega}{kT\lambda^2}\left(\frac{0.72\Gamma}{\lambda}\right)D_V\left(1+\frac{3.3\delta}{\lambda}\frac{D_B}{D_V}\right) \qquad (6)$$

This proposal made as the first time for Rene´ 95 at 1100 ^{0}C, can be accepted as constitute equations. This equation is based on material parameters and used atomistic model. This equation has been obtained from three different deformation mechanism's super position. The theoretical results obtained from the constitute equation has confirmed by the experimental data.

3. CONCLUSIONS

RENE´ 95 alloys were tested at high temperature experiments like 1050 ^{0}C and 1100 ^{0}C after they were consolidated in constant pressure. New two models for these temperatures were offered using the stress, deformation, deformation rate relationships. Modified material parameters according to test temperatures are the following [3].

Symbol	Parameter	Value
A'	Power law creep constant	[a]
A' (1323K)	Power law creep constant at 1323 K	4.7×10^3
A' (1373K)	Power law creep constant at 1373 K	9.3×10^3
B (m)	Burgers vector	1.7×10^{-10}
K (MN m/K)	Boltzmann's constant	1.38×10^{-29}
μ (MN/m^2)	Shear modulus	[b]
μ (1323 K)(MN/m^2)	Shear modulus at 1323 K	5.0×10^4
μ (1373 K)(MN/m^2)	Shear modulus at 1373 K	3.5×10^4
D_v (m^2/s)	Volume diffusion coefficient	[c]
D_v (1323 K)(m^2/s)	Volume diffusion coefficient at 1323 K	1.1×10^{-17}

D_v (1373 K)(m^2/s)	Volume diffusion coefficient at 1373 K	3.2×10^{-17}
σ_i (MN/m^2)	Back stress due to grain boundary ledges	<1 [19]
D_B (m^2/s)	Boundary diffusion coeff	[d]
D_B (1323) (m^2/s)	Boundary diffusion coefficient at 1323 K	2.1×10^{-11}
D_B (1373) (m^2/s)	Boundary diffusion coefficient at 1373 K	3.6×10^{-11}
Ω (m^3)	Atomic volume	1.1×10^{-29}
δ (M)	Boundary thickness ~ 2*b*	3.0×10^{-10}
Γ (J/m^2)	Boundary energy	0.1
R (J/mol/K)	Gas constant	8.3143
Q_V (kJ/mol/K)	Activation energy for volume diffusion	318
Q_B (kJ/mol/K)	Activation energy for boundary diffusion	159

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