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Irrecoverable deformation of tin in terms of the synthetic theory

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ABSTRACT

The paper addresses the issue of the plastic and creep deformation of tin, a material with low melting point; main attention is focused on its plastic deformation and steady-state creep. The modelling of these deformations has been accomplished in terms of the synthetic theory of permanent deformation whose main peculiarity is only one constitutive equation governs both plastic and creep deformation. The stress–strain as well as strain-rate vs. stress diagrams constructed on the base of this theory show good agreement with experimental data.

1. Introduction

Tin's main uses are in tin plating, solder, coating, and in the manufacturing of chemical compounds which are used in a variety of ways. Tin and its alloys, due to their low melting temperatures and wide availability, are the most commonly used solder materials.

In electronic assemblies, solder joints serve as both electronic connection and mechanical support for components and substrates. They play crucial roles in the reliability of joint assemblies in electronic packaging because they provide electrical, thermal and mechanical continuity in electronic assemblies. During service, they are subjected to many thermo-mechanical stresses and hence stand as one of the weakest point in assembly and usually determine the lifetime of the whole component.

The melting point of tin (Sn) is very low (505 K), and thus, deformation at the ambient temperature corresponds to the hot working temperature region in this metal. Since room temperature gives the high value of homology temperature for tin, its plastic flow is accompanied by active softening processes that manifest themselves in the following thermal activated processes (i) dynamic recrystallization, (ii) diffusion of atoms unlocking dislocations from obstructions in their path (solute atmospheres, precipitate particles, dislocation jugs, and dislocation tangles), i.e. dislocations become mobile and are able to cross-slip and climb, break away from their obstacles and cut through the forest dislocations, and (iii) dislocation annihilation, etc. As a result, tensile experiments on pure tin specimens exhibit a typical σ–ε curve, which yields work hardening in the early stage of straining, followed by steady state flow stress (see Fig. 1). Fig. 1 represents the true stress–strain relation calculated on the basis of nominal stresses and strains obtained by tensile testing. Since the synthetic theory models only small strains, the problem of necking is not considered here.

Much research has been done to address the mechanical properties of Sn and Sn-based alloys. Basic studies of irrecoverable deformation in metals with the low melting point such as lead or tin were mostly conducted before 1980, Mohamed et al. [8], Bolling [3]. Among the later researches Adeva et al. [1], Hamada et al. [5], Miltin et al. [7], Nagasaka [9] and Suh et al. [14] can be proposed. All the authors point to the multifactor nature of the phenomenon discussed, it depends on the temperature of experiments, the loading rate, as well as the stress range, determining which mechanism, hardening or softening, dominates.

The purpose of this paper is to present a model aimed at analytical description of the irrecoverable (both plastic and steady-state creep) deformation of tin. This model is the synthetic theory of irrecoverable deformation [12]. The main feature of this theory is a uniform approach to calculate any form of deformation, i.e. formulae for both plastic and (un)steady-state creep strains are derived from a single constitutive equation.

2. Synthetic theory

2.1. Synthetic theory as two-level model

The synthetic theory is based on the Batdorf–Budiansky slip concept [2] and the Sanders flow theory [13] and deals with small irrecoverable (plastic/creep) deformations of hardening materials

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(the case of finite deformation is considered in [15]). This theory incorporates (synthesizes) a physical interpretation of the development of irrecoverable strain (slip concept) and its mathematical representation via a flow theory (the Sanders theory).

Similarly to the Batdorf–Budiansky concept, the deformation of material is calculated on its two structural levels: macro- and micro-level. A point of a body is considered as an elementary volume of the body, $\mathbb{V}$. The volume $\mathbb{V}$ consists of a large quantity of microvolumes (grains), $\mathbb{V}_0$, each being an element of the continuous, capable of deforming under the applied forces (Fig. 2). The mechanism of irrecoverable deformation within the microvolume $\mathbb{V}_0$ is slip of one part of $\mathbb{V}_0$ in relation to another. It is assumed that the number of $\mathbb{V}_0$ is so great (theoretically it tends to infinity) that every possible orientation of slip systems exists within volume $\mathbb{V}$. Accordingly to Budiansky, the stress state in every volume $\mathbb{V}_0$ (slip system) is the same as that in the volume $\mathbb{V}$. The stress acting in $\mathbb{V}$ is obtained in a conventional way by solving the equilibrium equation of the body together with consistency and boundary conditions (the problem is the simplest for the case of e.g. tension, or torsion when a homogenous stress distribution is observed). It must be noted that, in contrast to a uniform distribution of the stress among microvolumes $\mathbb{V}_0$, the magnitude of slip strongly depends on the orientation of the slip system relative to the direction of the acting stresses. The total deformation in $\mathbb{V}$ is determined as the sum of micro-deformations developed in volumes $\mathbb{V}_0$.

The modeling of irrecoverable deformation takes place in the three-dimensional subspace ($\mathscr{R}^3$) of the Ilyushin five-dimensional space of stress deviators, $\mathscr{R}^5$ [6]. The loading process is expressed by a stress vector, $\vec{\mathbf{S}}$, whose components are converted from the stress deviator tensor components – S_{ij} $(i,j=x,y,z)$ – as follows [11] (Rusinko and Rusinko, 2011):

$$\vec{\mathbf{S}}\left[\sqrt{3/2}S_{xx}, S_{xx}/\sqrt{2}+\sqrt{2}S_{yy}, \sqrt{2}S_{xz}\right] \in \mathscr{R}^3, \tag{1}$$

where $S_{ij}=\sigma_{ij}-\sigma\delta_{ij}$, and δ_{ij} is Kronecker's delta, $\sigma=(1/3)\sum_{i=1}^{3}\sigma_{ii}$. The length of vector $\vec{\mathbf{S}}$ (S) equals to the von-Mises (effective) stress, i.e. is related to the second invariant of stress deviator tensor, J_2, as $S=\sqrt{2J_2}=\sigma_{eff}$.

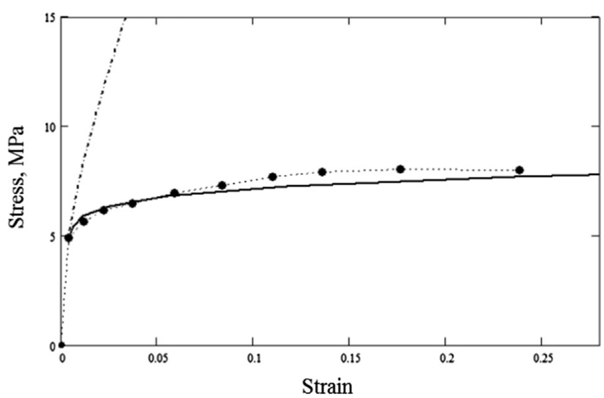

Fig. 1. Stress vs. strain diagram of tin at home temperature; • – experiment [5], line – analytical result, and dot-dash line – analytical result without accounting for dynamic softening.

3. Microlevel

3.1. Yield criterion

The locus of the onset of residual deformation in $\mathscr{R}^3$ is a sphere of radius $\sqrt{2/3}\sigma_P$, which corresponds to the von-Mises yield criterion,

$$S_1^2+S_2^2+S_3^2=2/3\sigma_P^2, \tag{2}$$

where σ_P is a creep limit of material in uniaxial tension. The criterion (2) contemplates that the creep limit of material is taken as its constant at a given temperature, while its yield strength (σ_S) is a function of loading rate, $\sigma_S=f\left(\dot{\vec{\mathbf{S}}},\sigma_P\right)$, where the formula for f will be shown later.

According to Sanders [13], through each point on the sphere we draw a tangent plane. So, the yield surface can be thought of the inner envelope of the equidistant planes.

The position of plane in $\mathscr{R}^5$ is defined by the following two quantities: (i) the unit vector $\vec{\mathbf{N}}$ normal to the plane, and (ii) the distance from the origin of coordinates to the plane, H_N. Since we assume that $\vec{\mathbf{S}} \in \mathscr{R}^3$ it is quite sufficient to consider the projections of $\mathscr{R}^5$-planes on $\mathscr{R}^3$ whose orientations are given by unit vector $\vec{\mathbf{m}}$ normal to the plane tangential to sphere (2). The orientation of $\vec{\mathbf{m}}$ is established by spherical angles α and β as shown in Fig. 3, and a relationship between the $\vec{\mathbf{N}}$ and $\vec{\mathbf{m}}$ components is $N_k=m_k \cos\lambda$ $(k=1,2,3)$, where λ is an angle between $\vec{\mathbf{N}}$ and $\vec{\mathbf{m}}$ [11] (Rusinko and Rusinko, 2011). Despite the fact that $\vec{\mathbf{S}} \in \mathscr{R}^3$, all the planes, both tangent to sphere (2) and the traces of planes tangential to the five-dimensional yield surface (which fill the space beyond the sphere (2)), must be taken into account. It is the angle λ that makes it possible to distinguish between these planes.

3.2. Hardening rule

To establish a ***hardening rule***, we extend the provision that a surface can be constructed as an inner envelope of planes to the

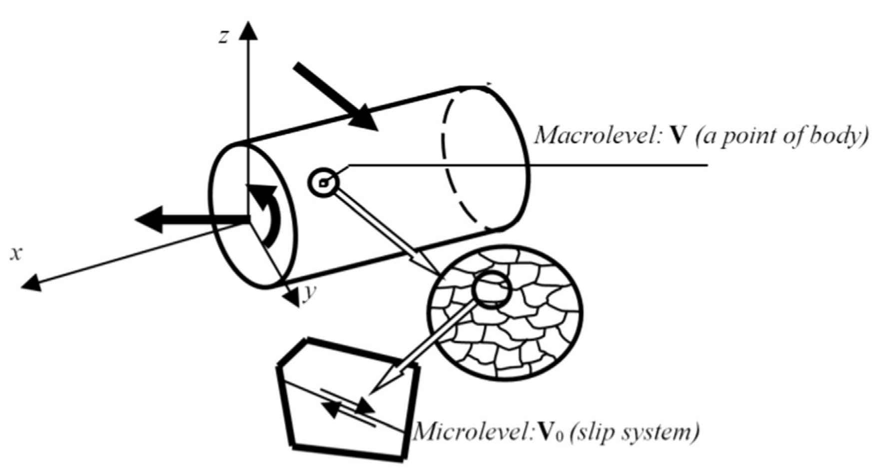

Fig. 2. Two levels of material structure: an elementary volume of loaded body ($\mathbb{V}$) consists of grains (slip systems) $\mathbb{V}_0$ producing deformation on microlevel.