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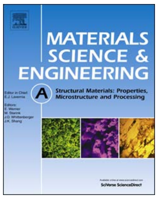

Method to decode stress-strain diagrams to identify the structure-strength relationships in aged aluminum alloys

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ABSTRACT

Leading-edge infrastructure renovation is driven by innovations in materials processing to optimize desired properties. The immediate challenge for the metal industry is the development of effective and efficient materials quality-control practices. At present, mechanical and sheet forming properties are assessed using standard tensile tests to measure yield and ultimate tensile strengths, as well as the total elongation to failure. The resulting stress-strain data is used as a "pass-fail" test to ensure that the product meets industry specifications. We report a new method of constitutive relation analyses (CRA) that can extract fundamental information regarding the underlying crystalline mechanisms of deformation and failure from standard stress-strain data. The CRA method is applied to industrial extrusion product made from AA6063 aluminum alloy to demonstrate how this type of forensic examination can be used to direct changes to thermo-mechanical processing to optimize desired material properties. The CRA prediction of point-defect generation and nano-void formation leading to ductile failure during plastic flow was validated by small angle X-ray scattering (SAXS) studies.

1. Introduction

Ductility of metals and alloys which enables the fabrication of any designed shape is due to the existence of crystalline line defects, termed dislocations, in the microstructure. Surface or traction forces applied to stock metals develop internal stresses which act as line-forces to move the dislocations causing slip, the basic atomic-layer shear process. This process is characterized by Burgers vector b and its intrinsic correlation with the imposed shape change results in the final form. The industrial product is produced by casting of ingots which are subsequently hot and cold rolled to form flat stock. Typically, heat-treatments upon cold rolling results in recrystallization whereby the large dislocation density created to comply with the imposed shape change is annihilated or annealed out. The resultant matrix is polycrystalline, consisting of an aggregate of crystallites characterized by an average grain size and low dislocation density. This structure is referred to as the soft condition. The structure-strength correlation arises from introducing obstacles in the matrix which resist dislocation passage and/or disrupt the atomic layers by introducing solute atoms which result in an intrinsic friction force. This process is known as solid-solution strengthening. The obstacles can be introduced by embedding foreign material, such as nano-oxide particles resulting in a matrix comprised of dispersed-particles, or by heating supersaturated alloys at selected temperatures to cause precipitation of inter-metallic particles, the process of artificial ageing. The craft of materials engineering is the know-how in the manipulation of the thermal-mechanical processing to produce the desired material performance. The means to characterize this evolution of structure from atom clusters to precipitates using advanced X-ray, electron and atomic force metallography has been described [1] but a direct correlation of this information to plasticity is still nebulous. Obtaining insight into this essential microstructure property correlation will significantly reduce the development time and the cost of engineered metal products.

The response of the microstructure to plastic flow is assessed by standard tensile testing in the form of true stress (σ) versus true strain (ε) diagrams. These diagrams are usually monotonic with strain and to the present time, only the approximate curve-fitting constitutive relations of Hollomon [2] and Voce [3] are used to interpret this information. From the measured data, the yield stress at 0.2% true or plastic strain ($\sigma_{0.2\%}$) and the ultimate tensile strength (UTS) are

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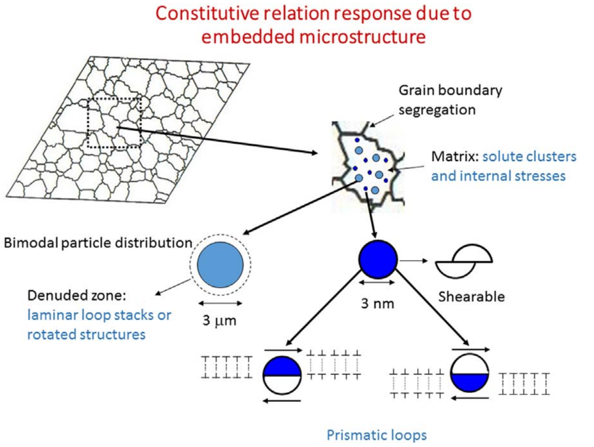

Fig. 1. Schematic illustration of the components of a typical microstructure in Al alloy. The materials engineering challenge is to determine how the effects of these constituents are manifested in the stress-strain diagram.

determined. The UTS occurs at the termination of uniform elongation (ε_U) when the magnitude of the work-hardening slope decreases to match the increasing true applied stress wherein geometrical instability results in diffuse necking. This is followed by localized necking due to micro-shear banding in many alloys. On the other hand, ductile failure is due to nano-void growth and coalescence at a critical void dimension and volume fraction resulting in double-cup fracture. The drawback to these earlier analyses is that it is not based on the slip mechanism which gives rise to plastic flow but purely arbitrary polynomial fits to the data. Hence any back- or forward-extrapolation is not slip model based.

The materials engineering challenge is to discover a constitutive method of interpreting stress-strain data to reveal the effects of the microstructure components schematically represented in Fig. 1. The cartoon shows the polycrystalline form with a given grain size, the matrix of which can comprise solid solution and effects such as segregation of solutes to both grain and particle interfaces. If the dispersed particles are of nanometer (nm) size, they can be sheared and if not, they produce geometric necessary prismatic dislocation loops [4] (GNPL) as illustrated. Inevitably micrometer (μm) sized dispersoids are also embedded and in cases of surface-reactive elements such as aluminum (Al), such particles are necessary to prevent galling or sticking during rolling; that is, it assists in the lubrication process. However, these larger non-shearable particles cause localized deformation near their interfaces. This gives rise to either graded densities of stacked dislocation loops or, if the flow stress in the matrix reaches a critical stress due to ageing, a new process of lattice rotation whereby regions in compression rotate towards those in tension [5]. These rotated structures are short segments of aligned dislocations to account for the lattice rotation. This formation of rotated structures adjacent to large particles would be facilitated by the occurrence of solute-denuded zones which reduce the formation of nano-precipitates in the affected regions.

The role of grain size is most important in materials engineering of metal stock since reduction of grain size is the only known strengthening method which simultaneously improves ductility. All other means of strengthening will reduce ductility. The dislocation-based kinematic mechanisms for strengthening by structures depicted in Fig. 1 have been modelled and are the bases of a large body of literature [6]. Nevertheless, a methodology to decode the stress-strain diagram to show the role of the various components during work hardening is not generally known. In the new constitutive analyses [7], at least two functional constitutive relations based on Taylor slip model [8] are digitally superposed on the measured data to achieve an optimum fit. A novel attribute of the present modelling is that back- or forward-extrapolation is model-based rather than the result of arbitrary polynomial fit. Within the present context, this means that any shape change is presumed to take place by crystalline slip mechanism.

2. Motivation

Work-hardening theories and experiments have primarily evolved from the study of pure metals especially for face-centred cubic metals (fcc). Adaptation of these dislocation-based mechanistic theories to engineering age-hardenable alloys are most difficult wherein the co-ordination of plastic flow with strengthening mechanisms are difficult to elucidate. The new Saimoto-Van Houtte [7] derivation of a functional constitutive relations shows that the intrinsic assumption that plastic flow under any microstructure conditions is based on Taylor type of slip analyses [8] results in at least two fitted loci to the measured stress-strain curve. Not surprisingly, these curves which can replicate the measured data takes the power-law form of the Hollomon relation. The intersection of these loci using shear stress (τ) -shear strain (γ) analysis results in parameters τ_3 and γ_3 which when used as normalizing parameters results in a master curve independent of temperature and strain rate [9,10]. The inferences from this observation which has been examined are the prediction of point defect generation with strain [10], initiation of Stage IV deformation region [11] and prediction of yield locus under plane stress conditions [12]. The success of these interpretations has motivated the current study whereby work-hardening in age-hardened aluminum (Al) alloys may be similarly assessed. The current focus on decoding σ - ε data is derived from prior work wherein correlation between the yield stress and fracture strain was found to exist [13] and has been modelled to be due to nano-void formation and growth at coherent nano-precipitate [14]. These findings suggest that the plastic flow as represented by σ - ε curve directs the evolution of microstructure eventually leading to ductile failure. The embedded structures if not shearable will result in generation of defects to maintain strain compatibility and thus the mean slip distance evolution results not only from generation and annihilation of dislocations but also other strain-produced products. The present work briefly summarizes constitutive relation analyses (CRA) [7] and investigates whether it can decode the underlying structure-strength relationships.

3. New constitutive relation analyses (CRA): decoding of the stress-strain diagram

The new Saimoto-Van Houtte (S-VH) relation [7,9] that replicates the σ-ε curve using two-fitting loci is based on balancing the energy required to account for the increase in total dislocation length during the slip process with that of the retained or stored dislocation density. The dislocation length increase during the slip process is required to comply with the imposed strain. Heat generation during plastic deformation indicates that the creation energy due to the shear flow stress is much larger than that stored. This decrease in energy during plastic flow is attributed to dynamic dislocation annihilation. Energy balance is achieved by introducing an annihilation factor, A, into the S-VH relation.

The key to data replication is enabled by precisely deriving the mean slip distance λ from the data set, as follows:

$$\lambda = \phi b \mu^2 / \left(2\tau \partial\tau / \partial\gamma_{|T,\dot{\gamma}}\right) \qquad (1)$$

whereby the flow shear stress τ is determined from $(\sigma - \sigma_0^{\mathrm{final}})/M$; the shear strain, $\gamma = M\varepsilon$ in which M is the Taylor factor which converts tensile parameters to shear ones; μ, the shear modulus; b, the Burgers vector. The calibration factor ϕ is derived from $\theta_{cal} = \partial\tau/\partial\gamma$ at 0.2% ε whereby $1/\phi = (\mu/\theta_{cal})/2\alpha$. The average linear spacing between obstacles retarding dislocation passage (ℓ) is related to the flow stress as $\tau = \alpha\mu b/\ell$ wherein α is the measure of line-force necessary to overcome the obstacle at a given internal angle ψ defined by the dislocation line-tension. Hence the activation work is given by $\tau\ \nu$ wherein the