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Stress Analysis of a Rocket Engine Copper Alloy Using Gurson Micromechanical Model

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Abstract: ***Tensile failures in structures can be classified into two: brittle fracture and ductile fracture. Different constitutive models are available for capturing ductile failure, one of which is called conventional plasticity models like von Mises, Tresca etc. and the other is the damage mechanics based models. Von Mises theory is independent of hydrostatic stress in the material. So it is not able to capture ductile fracture process accurately. In recent years different damage mechanics models have been proposed to model ductile fracture. One of the best known damage models is the micromechanical model proposed by Gurson, which uses the void volume fraction as the main damage parameter. In this paper, the modified Gurson model known as the Gurson-Tvergaard-Needleman (GTN) model is employed for constitutive modeling of a high conductivity-high ductility copper alloy (Cu-Cr-Zr-Ti alloy) used in a rocket engine thrust chamber at four temperatures (300 K, 550 K, 77 K and 20 K). The model parameters are evaluated from tensile tests conducted on smooth round subscale sized specimens in a high temperature and cryogenic UTM. Stress analysis of the tensile specimens has been performed using solid of revolution elements, considering both material and geometric nonlinearities. The Multilinear Isotropic Hardening plasticity model in association with Gurson model is used for damage modeling of the material using the ANSYS (Version 15) FEA code [2]. Nine GTN model parameters of the alloy have been identified based on comparison of engineering stress strain graphs from tests and analysis. The parameters thus evaluated are subsequently used for ductile crack growth analysis of the copper specimenat room temperature.***

Keywords: Copper alloy, Ductile failure, elevated temperature, Gurson model, Micromechanical modeling, voids, etc.

1. Introduction

The ductile failure of metallic materials most often occurs by nucleation, growth and coalescence of micro voids. For most of the engineering alloys, voids can get nucleated from non metallic inclusions and second phase particles by particle fracture or interface de-cohesion [8, 10-12].

One of the best known micromechanical models is due to the one by Gurson [5], which uses the void volume fraction as the main damage parameter. In materials where there is a strong interaction between the particle and metallic matrix, the nucleation stage is the dominant one in the failure process. On the other hand, when there is weak particle–metallic interaction, the dominant stage is void coalescence. Different models for analysis of ductile failure are explained below:

A. Conventional Plasticity Models

One of the most popular yield criteria for metallic materials is the von Mises yield criterion which is dependent only on the deviatoric stress. Here, the material is assumed to be initially defect free. In this model, ductile failure is usually based on equivalent plastic strain reaching the fracture strain of the material (obtained from a tension test). Since, fracture strain of a material is dependent on hydrostatic stress in the material, this theory is not able to model ductile fracture accurately.

B. Micromechanical Models

Microscopic voids are present in any metallic material. Under plastic deformation, the material volume will not change. But voids will grow and material volume will increase during plastic straining under hydrostatic tensile stress. Instead of explicitly modeling the pores in the structure, homogenized modeling has been done. One of the best known micromechanical models is due to Gurson, which uses the void volume fraction as the main damage parameter. Gurson considered, through a yielding function the presence of voids of material, growth of voids under plastic straining and hydrostatic tensile stress and softening effect of the material due to voids. It is applicable for monotonic loading situations.

2. Gurson-Tvergaard-Needleman Model

The ductile failure of metallic materials most often occurs by nucleation, growth and coalescence of micro voids. The growth, nucleation and coalescence of voids in microscopic scale in a material are shown schematically in Fig.1.

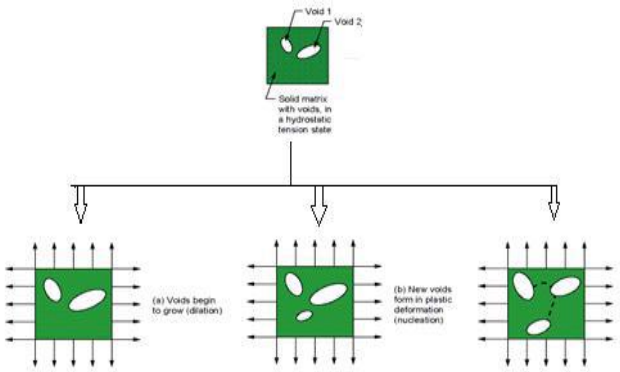

Figure 1: Growth, Nucleation and Coalescence of voids in microscopic scale

A. Void growth

The structural degradation of a ductile material will involve growth of the existing voids, which is strongly related to the presence of a hydrostatic stress. Rice & Tracey [4] found out that the void growth rate in a homogenous material is exponentially dependent on the remote hydrostatic stress.

B. Void nucleation phenomenon

During plastic straining, fresh voids get nucleated in alloys from second phase particles and large inclusions. The reasons for this are (i) decohesion of these particles or inclusions from the matrix or (ii) fracture of these particles or inclusions. Chu & Needleman [4] proposed a statistical approach for nucleation of fresh voids.

C. Void coalescence

The final stage of the ductile material separation process is the coalescence of voids. The most widely used and implemented void coalescence criterion in conjunction with the GTN model, which is proposed by Tvergaard and Needleman [10], is that coalescence of voids occur at a critical value *fc* of the void volume fraction. When the total void volume fraction exceeds the critical porosity of the material, void growth gets accelerated. Another parameter called fracture porosity, *fF*is also introduced. When void volume fraction reaches fracture porosity, total separation of material takes place.

3. Tensile Testing Of Copper Alloy Specimens

For the evaluation of mechanical properties of the alloy at different temperatures, tensile specimens are tested in a high temperature and cryogenic Universal Testing Machine. An average of 3 specimens was tested at each temperature and the results corresponding to the lowest yield strength case used for analysis.

For the evaluation of mechanical properties of the alloy at different temperatures, tensile specimens are tested in a high temperature and cryogenic Universal Testing Machine (UTM) at a strain rate of 1×10^{-2} mm/mm/s. Symmetry boundary conditions were supplied at the bottom nodes of the model. To impose axisymmetric condition, nodes falling along the symmetric axis are constrained along the X direction. Nodes at the top end of the model are coupled in the axial direction to simulate uniform axial elongation. The master node of the coupled set is pulled by 8 mm in the axial direction to simulate loading in a UTM for 300 K and 550 K and pulled by 30 mm in the axial direction to simulate loading in a cryogenic UTM for 77 K and 20 K. FE model for the specimen is given in Fig.2

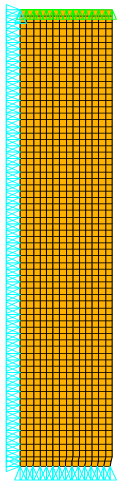

Figure 2: FE model with boundary conditions and loading

4. True Stress-Strain Modeling Beyond Necking at Elevated Temperatures

True stress and true (logarithmic) strain are evaluated till the onset of yielding by standard formulae as given below:

$$\text{True stress, } \sigma = s(1+e) \quad (1)$$

$$\text{True strain, } \varepsilon = ln(1+e) \quad (2)$$

Where,

s = engineering stress, e = engineering strain

Beyond necking, the above formulae are not applicable due to the localization of displacement in the neck region. It is difficult to directly evaluate true stress and strain from simple tensile tests and indirect methods have to be applied. The commonly adopted indirect methods are:

Method 1: By fitting a power law graph to the true stress-strain data till necking and then extrapolating it beyond necking till fracture [16].
Method 2: By drawing a tangent to the true stress-strain curve at the necking point (linear extrapolation) till fracture [14].
Method 3: By choosing a weighted average of the above two curves [14].

Figure 3 shows the engineering stress-strain graph and extrapolated true stress-strain graph at room temperature

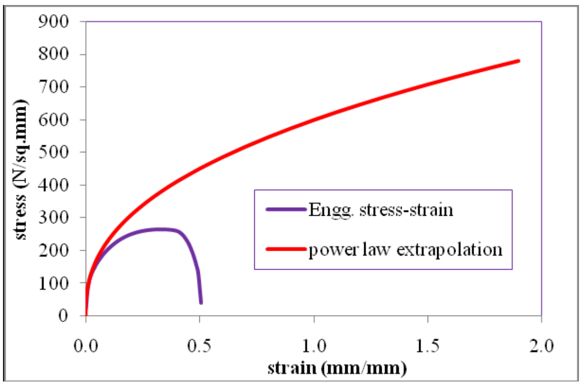

Figure 3: Extrapolated true stress- true strain graph up to fracture strain

5. Gurson Modeling at different Temperatures

The Gurson-Tvergaard-Needleman (GTN) model parameters are fundamental properties of a material. There are nine parameters which can be evaluated by fitting stress strain data from simple tensile tests to finite element analysis results. Using these parameters, micromechanical modeling and failure analysis of any structure of the same material can be done.In order to perform stress analysis of this alloy, it is required to input its true stress strain characteristics to the finite element analysis software employed. It is found that the best way to represent the material is to use either Multilinear Kinematic Hardening (MKIN or KINH) or Multilinear Isotropic Hardening (MISO) plasticity models. Young's modulus of the material as a function of temperature is taken from literature .

Stress analysis of tensile test specimen is done for two cases, ie, tensile specimen without GTN model and tensile specimen with GTN model.

A. Analysis of copper specimen at room temperature

Copper without GTN model is analysed first and then analysis trials are done changing Gurson parameters to get values matching with experimental results. That values which has the best match with experimental stress strain plot are taken as the true parameters of the copper alloy at that particular temperature and strain rate. The figure showing the graph with GTN model at room temperature is shown in fig 4.

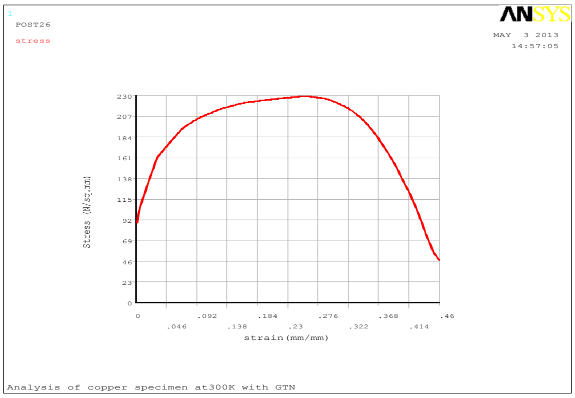

Figure 4: Engg.stress strain plot of copper specimen withGTN model at 300 K

B.Analysis of copper specimen at 550 K

Trials are done varying Gurson parameters to get matching values with experimental results.That values which has the best match with experimental stress strain plot are taken as the true parameters of the copper alloy at that particular temperature and strain rate. The figure showing the graph with GTN model at 550 K is shown in fig 5

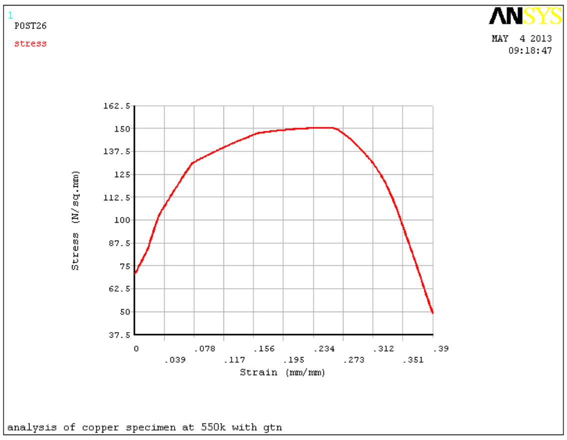

Figure 5: Engg.stress strain plot of copper specimen with GTN model at 550 K

C. Analysis of copper specimen at 20 K

Various trials are done varying Gurson parameters to get matching values with experimental results.That values which has the best match with experimental stress strain plot are taken as the true parameters of the copper alloy at that particular temperature and strain rate. The figure showing the graph with GTN model at 20 K is shown in fig 6.

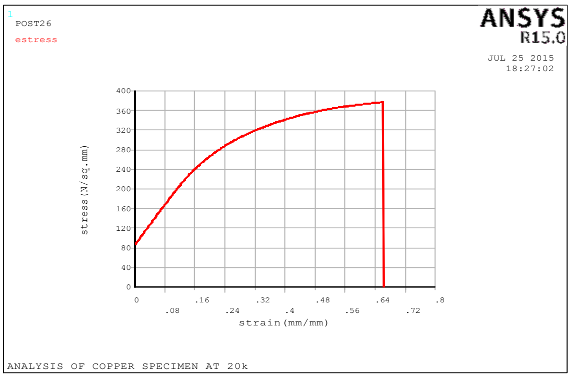

Figure 6: Engg.stress strain plot of copper specimen with GTN model at 20 K

D. Analysis of copper specimen at 77 K

Various trials are done varying Gurson parameters to get matching values with experimental results. That values which has the best match with experimental stress strain plot are taken as the true parameters of the copper alloy at that particular temperature and strain rate. The figure showing the graph with GTN model at 77 K is shown in fig 7.

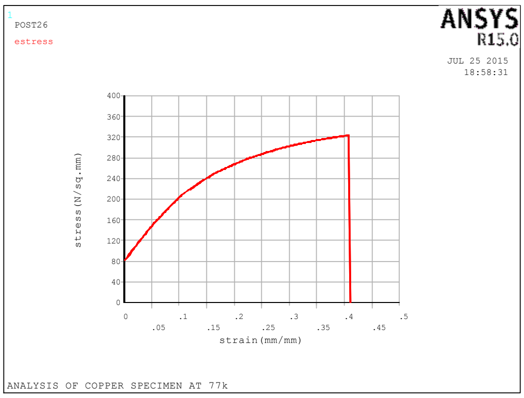

Figure 7: Engg.stress strain plot of copper specimen with GTN model at 77 K

6. Conclusion

In this paper, detailed study of micromechanical modeling process using the well known GTN model has been performed. GTN modeling of a high conductivity-high ductility copper alloy used in a rocket engine thrust chamber has been attempted at room temperature and one elevated temperature(500 K) and two cryogenic temperatures (20 K and 77 K) based on tensile tests conducted on smooth round threaded subscale sized specimens in a high temperature and cryogenic UTM. Nine GTN parameters of the alloy are identified based on comparison of engineering stress strain graphs from tests and analysis through a large number of trials. In the light of the above study and observations, it is recommended to use the GTN model for ductile failure prediction of engineering structures since this model can account for the presence of voids and hydrostatic stresses in the structure.

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