

Modeling of Damage Evolution and Fracture in 5182 H111 Aluminum Alloy

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Abstract

This paper presents results of a numerical modeling of ductile fracture and failure of elements made of 5182H111 aluminum alloys subjected to dynamic traction. The analysis was performed using Johnson-Cook model based on ABAQUS software. The aim of the research was to specify and test the mechanical properties during numerical simulations. The experimental test results for the mechanical properties of the studies for steel were presented with a large description of the testing facilities. The test results were used to determine the temperature dependencies of the mechanical properties, yield strength, modulus of elasticity and thermal elongation.

Keywords: Mechanical properties, damage, structural steel, aluminum alloy

Introduction

The ductility of common aluminum alloys increases with temperature. The ideal framework for modeling ductile fracture is the one that has a good representation of polycrystalline plastic deformation combined with the ability to predict void nucleation, growth, and coalescence in various competing models. From the elementary micromechanisms of ductile damage, a key concept emerged for modeling ductile fracture: void growth and coalescence, on one hand, and matrix plasticity, on the other hand, are inherently coupled. There are two main challenges in simulating ductile fracture in 3D engineering plate/shell structures. First, the evolving crack surface leads to time-evolving traction-free boundary growth in computational domain, hence the finite element representation of evolving material geometry and topology to change accordingly. Second, the large scale ductile fracture often undergoes drastic plastic deformation, which makes ductile fracture a multi-scale problem [1]. In the recent decades, there have been many works reported in the literature studying how to predict ductile fracture, e.g. finite element approach (FEA) by [2] and [3], and meshfree approach by [4], [5, 6]. Ductile fracture is often accompanied with enormous high plastic deformation, and in turn the material plastic flow will generate a large amount of heat at the local area where material exhibits viscoplastic behavior. However, the various Gurson models mentioned above are still rate-independent plasticity model, and they do not consider thermo-mechanical coupling effects, [7, 8] proposed a rate-dependent plasticity constitutive model, which is referred to as the Johnson-Cook model. One of the most widely used models is Johnson-Cook model for ductile materials. This model describes fatigue behavior of 5182 H111 Aluminum alloy under cyclic loading and their applicability for modeling of low-cycle-fatigue are discussed in this report.

Numerical simulation has been used to study mechanical properties of materials such as the tensile strength, the yield strength and young's modulus which depends on the temperature because young's modulus of some tempered steels increases slightly at mid temperatures before decreasing at high temperature on mechanical properties is linked to transformations of the material structure due to various processes [9- 12]. Damage parameter is not incorporated into the constitutive equation

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and it is assumed that the presence of voids does not significantly alter the behavior of the material. The von Mises criterion is most frequently used as yield criterion in uncoupled models, Damage parameter is incorporated into constitutive equation and crack growth simulation is automatically performed using a complete deterioration of elements in front of the crack tip [13]. Ductile fracture is a geometry dependent event, whereas the fracture toughness or ductility of a material cannot be directly transferred from geometry to another. It depends on variation of geometry constraint level, thus conventional fracture mechanics parameters. Ductile fracture process is controlled by nucleation, growth and coalescence of micro voids, so it is natural to link material fracture behavior to the parameters that describe the evolution of micro voids rather than conventional global fracture parameters [15]. In order to describe the cyclic behavior of the material for analysis with finite element method (FEM) based analysis code ABAQUS, the test data, i.e. stress-strain curves, have to be processed.

Damage and fracture

There are two main challenges in simulating ductile fracture in 3D engineering plate/shell structures. First, the evolving crack surface leads to time – evolving traction-free boundary growth in computational domain, hence the finite element representation of evolving material geometry and topology have to change accordingly. Ductile fracture is often accompanied with enormous high plastic deformation, and in turn the material plastic flow will generate a large amount of heat at the local area where material exhibits viscoplastic behavior. To take into account the rate – dependent and thermomechanical coupling effects [7, 8], proposed a rate – dependent plasticity constitutive model, which is referred to as the Johnson-Cook model.

As for damage, the heterogeneity of such composite leads to diverse damage modes under thermomechanical loading. The continuum Damage Mechanics models are phenomenological models that relate nonlinear macroscopic material behavior to the Process of internal micro - cracking. The accomplishments and deficiencies of phenomenological models are discussed at length in Krajcinovic (2006)

Numerical method

To get a more complete understanding of the Mechanical properties of materials during testing, numerical simulations of the aluminum 5182 H111 alloy were performed. This is an approach, complementary to the experimental method described by [9], to evaluate thermal loads at different locations on the surface as well as within the specimen. The latter is quite difficult to achieve from an experimental point of view. The numerical analysis using the ABAQUS, explicit dynamic finite element software, was made in two steps, in order to develop and implement strain rate sensitive constitutive models. First, thermal analysis was performed to reproduce the surface thermal loads and to obtain the temperature evolution in the specimen. Second, a mechanical analysis was performed, using a Johnson-Cook model. Here, the numerical simulation methodology assumes a weak coupling between thermal and mechanical analyses. Due to the axisymmetrical geometry of the specimen, only a quarter of the specimen is meshed with four node rectangular axisymmetric elements and used in the calculations. The sample geometry and the axisymmetrical meshing is shown in Fig. 1. From the numerical simulations, temperature-strain loops at several locations in the specimen were obtained, and they were compared to those from the experimental tests.

Johnson Cook Material Failure

In addition to material damage model, material model is also an essential requirement in any simulation of deformation. The model of most of metals depends on deformation temperature and strain rate. In 1983 Johnson and Cook using Hancock and Mackenzie experiments on variety of metals developed an experimental relationship which states the influences of temperature, Strain and Strain rate on Von Mises Stress. Johnson-Cook model that its equations are given by [14]:

$$\sigma = [A + B\varepsilon_{pl}^n] \left[1 + C \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right]$$

Where \mathcal{E}_{pl} is the effective plastic strain, $\mathcal{E}^* = \frac{\dot{\epsilon}}{\epsilon_0}$ is the dimensionless plastic strain rate for a reference strain rate, and T^* is a form of homologous temperature given as $T^* = \frac{(T - T_{room})}{(T_{melt} - T_{room})}$.

The five material constants

A, B, C, m, n are fit to data collected for a particular material.

For thermo-mechanical coupled problem, the total deformation can be decomposed to elastic, plastic, and thermal parts as show in the following Equation:

$$d = d^e + d^p + d^t$$

in case of isotropic hardening, the plastic strain rate is, $d^p = \dot{\epsilon} \hat{n}$.

$$d^t = \frac{\gamma\lambda}{\rho C_p} \sigma_\epsilon \dot{\epsilon}$$

In adiabatic heating, the rate of deformation induced by thermal effect is,

Where γ is the coefficient of thermal expansion, λ denotes the fraction of plastic work converting to heat, ρ is specific heat, and σ_ϵ denotes the second order unit tensor.

The rate form of constitutive equation with thermal effect can be expressed as:

$$\overset{\nabla}{\sigma} = C : d^e = C : (d - d^p - d^t)$$

For explicit time integration, the stress and strain fields at time t_{n+1} are updated from the state at time t_n . Choosing the Jaumann rate as the objective rate in Eq. (59), the time stress derivative of the Cauchy stress can be found as:

$$\overset{\nabla}{\sigma}_{n+1} = \sigma_n + w_n \cdot \sigma_n - \sigma_n \cdot w_n^T$$

Then the stress state can be updated by:

$$\sigma_{n+1} = \sigma_n + \overset{\nabla}{\sigma}_{n+1} \Delta t$$

The crack propagation algorithm in section 3 needs a damage indicator in order o determine crack growth process. The Gurson model has the damage parameters f that can be used in the crack growth algorithm. For the Johnson-Cook model, an accumulative damage model [16] is adopted to estimate damage status of a material point, and hence a mesh free particle,

$$D = \sum \frac{\Delta \epsilon}{\Delta f}$$

$$\epsilon_f = \left[D_1 + D_2 \exp\left(D_3 \frac{\sigma_m}{\sigma_M}\right) \right] \left[1 + D_4 \ln \dot{\epsilon} \right] \left[1 + D_5 \Gamma \right]$$

Where $\Delta \epsilon$ is the plastic strain increment in one time step, and D_1, D_2, D_3, D_4, D_5 are material constants.

Mechanical properties and Materials Geometry

The substrate materials selected in this study is the 5182 H111 Aluminum alloy, with Young’s modulus $E_S = 70$ GPa, and identical Possion’s ratio $\nu_S = 0.3$. with length $L = 210$ mm and the depth $D = 5$ mm and the width 56 mm. Finite element modeling is performed by assuming 3D deformation. The mechanical loading

results from applying displacement traction at the outside extremity of the 5182 H111 Aluminum alloy. The main mechanical and thermal Properties of tested specimens are summarized in Table1. The specimens' geometries are shown in Fig1. Specimens are especially prepared for thermographic measurements. They are polished and cleaned to remove any oxide and grease.

To obtain a thermal stress loading under homogeneous uniform temperature distribution, the 5182 H111 alloy was restrained against axial expansion by creating an interaction boundary condition at its outside edge (Figs. 3).

In order to determine thermal strain in the analysis we have need to the thermal expansion coefficient α

[10].Poisson's coefficient does not depend on temperature and takes the constant value $\nu=0.3$..

Table 1. Mechanical and thermal properties of the tested specimens

Aluminum 5182 H111	
Tensile modulus MPa	2700
Tensile strength (Nmm ⁻²)	284
Yield stress (MPa)	154
Mass thermal capacity (Jkg ⁻¹ K ⁻¹)	909
Thermal conductivity (Wm ⁻¹ K ⁻¹)	209-232

Loads

A displacement boundary condition was applied to the grip end of the tensile specimen. The displacement was smoothly ramped up in the first portion of the test and then held constant as shown in Figure 3.



Figure 3. Load and boundary condition

1. Results and discussion:

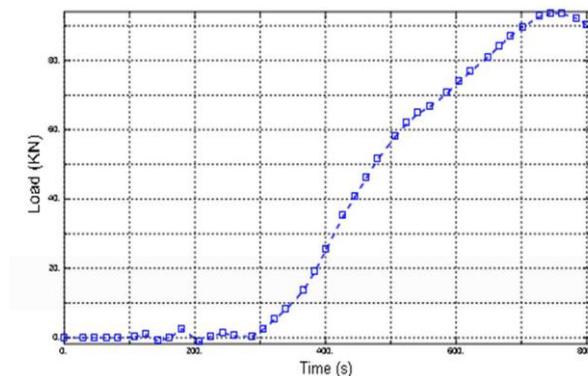


Figure 1. Variation of load vs time

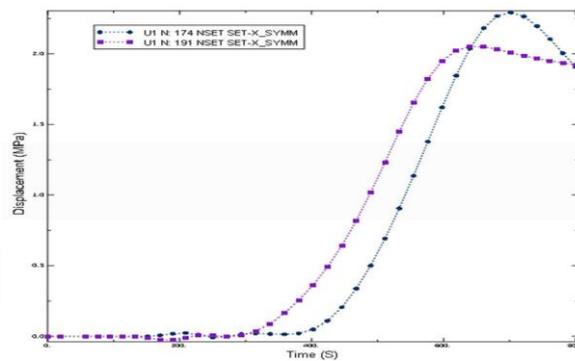


Figure 2. Variation displacement vs time

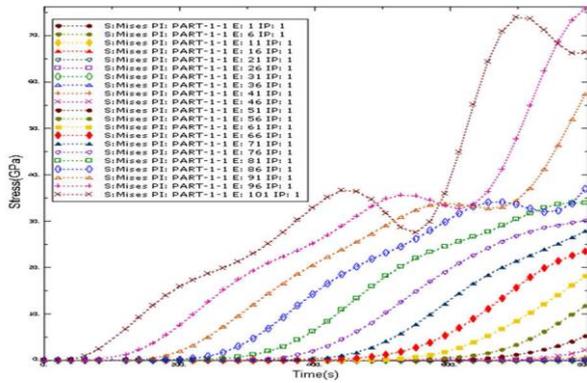


Figure 3. Variation of stress vs time

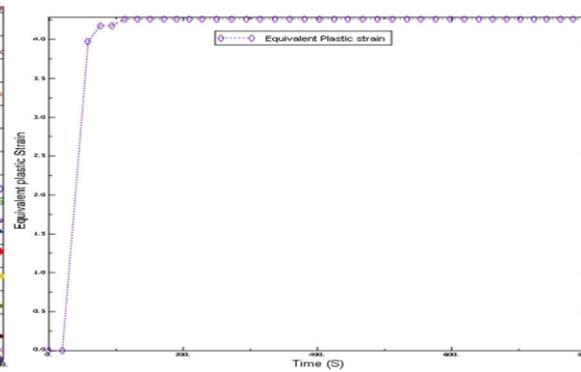


Figure 4. Variation equivalent plastic strain vs time

Figure 2.3 shows the development of the stress and the variation of displacement along the bar. For relatively small deformations, the stress distribution of the nonlocal and the gradient-dependent model match almost perfectly. At a certain stage the deformation and damage growth start to localize in an ever smaller region.

The stress and the displacement in the bar has been plotted of its right, U , in **figure 2.3**. the strongly localized deformations at the end of the process result in snap-back behavior. The responses of the model agree quite well in a qualitative sense. A crack has been thus initiated; a strain singularity may be unavoidable at the crack tip. It is important that the damage growth rate still remains finite, because the crack growth would otherwise be instantaneous.

Figure 2 shows that the maximum elongation before final failure line started. Thus, the failure doesn't start in this case because the plate has not yet reached the state of rupture. **Figure 1** shows the load vs. time the beginning of elastic deformation, the beginning of plastic deformation, reaching maximum force, the homogeneous plastic deformation to the final fracture of the specimen.

The results obtained give reason to doubt the applicability of the Johnson-Cook model to fracture problems.

The stress deformation responses of the symmetric problems are given in **figure 3**. The curve for the specimen with an imperfection clearly shows a bump. The damage growth corresponds to this stress – displacement. Initially, the growth of damage is essentially symmetric. The specimen has been modeled with 1724 elements with an eight-noded quadratic displacement field and a bilinear nonlocal equivalent strain.

Conclusion

The principal objective of the research reported in this paper was to simulate a ductile material's damage and describe that fracture processes in 3D engineering structures is still an ongoing researching subject. In this paper we have presented analytical Johnson-Cook model Formulas, constitutive modeling, The Numerical results for the tensile properties of 5182 H111 Aluminum alloy, considered in this paper, illustrate that the proposed method can successfully simulate crack growth in plate structures undergoing finite deformation and large plastic yielding and indicate the fact that the testing of metal structures requires new contactless methods. The ABAQUS simulation using the Johnson-Cook methods of fracture mechanics was applied due to the safety assessment of metal structures. The Numerical results proved that Johnson-Cook model offers the possibility of non-destructive and real time testing to observe the physical process of metal degradation and to detect the occurrence of energy dissipation. Numerical simulations of ductile fracture have benefited from various developments in computational mechanics. Conversely, the challenges posed by ductile fracture modeling have often motivated the development of new methods.

References

1. Antoun, T., Seaman, L., Curran, D.R., Kane, G.I., Razorenov, S.V., Utkin, A.V. "Spall Fracture." Springer, New York. 2003
2. Anderson, T.L. "Fracture Mechanics-Fundamentals and Applications," 2nd ed. CRC Press, Boca Raton,

- FL. 1995
3. Mikkelsen, L.P. “Post-necking behaviour modelled by a gradient dependent plasticity theory.” *International Journal of Solids and Structures* 34, 4532–4546. 1997
 4. Li, S., Simonsen, B.C. “Meshfree simulations of ductile crack propagation.” *International Journal of Computational Engineering Science* 6, 1–25. 2005
 5. Ren, B., Li, S., Qian, J., and Zeng, X. “Meshfree simulations of spall fracture.” *Computer Methods in Applied Mechanics and Engineering* 200, 797–811. 2011a
 6. Ren, B., Qian, J., Zeng, X., Jha, A.K., Xiao, S., and Li, S. “Recent developments on thermo-mechanical simulations of ductile failure by meshfree method.” *Computer Modeling in Engineering and Sciences* 71, 253–277. 2011b
 7. Johnson, G.R. and Cook, W.H. “A constitutive model and data for metals subjected to 1176 large strains, high strain rates and high temperature.” In: *Proceedings of the 1177 Seventh International Symposium on Ballistics*, pp. 1–7. 1983
 8. Johnson, G.R. and Cook, W.H. Fracture characteristics of three metals subjected to 1179 various strains, strain rates, temperatures and pressures. *Engineering Fracture* 21, 31–48. 1985
 9. F. Mata Cabrera, J. Tejero Manzanares, I. Hanafi, A. B. Arenas, I. Garrido, V. Toledano, and M.L. Rubio, “Investigation the deformation and damage scenario under tensile loading of ductile specimens using thermography,” *Int.Rev.Appl.Sci.Eng.*5(2014), 1, 1–8.
 10. Achraf Zineb and khamlichi Abdellatif, Francisco Mata Cabrera, “Effects of cycle duration and phasing on thermomechanical Fatigue of Dog-Bone specimens Made form steel.” *American J. of Engineering and applied Sciences* 3(4), 740-748 , 010.
 11. Bauvineau, L., Burlet, H., Eripret, C., and Pineau, A. “Modelling ductile stable crack growth in a CMn steel with local approaches,” in: *Proceedings of the first European Mechanics of Materials Conference on Local Approach to Fracture*, Fontainebleau, France, pp. 26-38. 09- 11.09.1996
 12. Bashir Younise, Marko Rakin, Bojan Medjo, and Aleksandar Sedmak “Numerical Simulation for Studying Constraint Effect on Ductile Fracture Initiation Using Complete Gurson Model” *FME Transactions*, 200, Vol. 38, No. 4, 2010.
 13. V. Vely, G. Bernhart, L. Penezzi, A. Persson and J. Bergström. “Thermal fatigue of a tool steel: Experiment And Numerical Simulation”, 6th International Tooling Conference. Karlstad University, Sweden. pp. 793-814. 2002.
 14. Rafal Olaf Smerd, “Constitutivie behavior of aluminum alloy sheet at high strain rates,” thesis presented to the university waterloo, Ontario, Canada. 2005 50th.
 15. M. Abendroth, and M. Kuna, “Determination of deformation and failure properties of ductile materials by means of the small punch test and neural networks”, *computational materials Science* 28 (2003) 633-644.
 16. Simkins, D.C. and Li, S. “Mesh free simulations of thermo-mechanical ductile fracture. *Computational Mechanics* 38, 235-249. 2006.