Simulating the mechanical behavior of AA2024-T3 with different strain rate and temperature.

1 Introduction

Aluminum alloy is widely used for their light weight and easy formability. Therefore, it is exposed with variable temperature. For example, aluminum can be used in the area of engine, then the boundary temperature is up to 120℃. Also, when the automobile is crashed, it has very high strain rate and high temperature, too. The objective of this project is to investigate the temperature and strain rate effect in mechanical behavior of Aluminum alloys with Johnson-Cook failure criterion.

In this work, ABAQUS VUMAT subroutine will be used to simulate. Based on HW9, ABAQUS VUMAT subroutine will be re-written by using constitutive equations in chapter 2.

2 Material Models

2.1 Elastic-viscoplastic material

In this project, aluminum alloys will be assumed to be an elastic-viscoplastic material. Therefore, a conventional constitutive model for viscoplasticity is applied to describe the constitutive relation of aluminum alloys.

The strain rate $\dot{\boldsymbol{\varepsilon}}$ can be decomposed into elastic and plastic part,

$$\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}^{e}} + \dot{\boldsymbol{\varepsilon}^{p}}$$

The elastic and plastic strain rates are expressed as follow:

$$\dot{\varepsilon}_{ij}^{e} = \frac{1+\nu}{E}\dot{S}_{ij} + \frac{1-2\nu}{E}\dot{\sigma}_{kk}\frac{\delta_{ij}}{3}$$

$$\dot{\varepsilon}_{ij}^{p} = \dot{\varepsilon}_e \frac{3}{2} \frac{S_{ij}}{\sigma_e}$$

where $S_{ij} = \sigma_{ij} - \sigma_{kk}\delta_{ij}/3$, $\sigma_e = \sqrt{\frac{3}{2} S_{ij} S_{ij}}$ and $\dot{\varepsilon}_e = \sqrt{\frac{3}{2} \varepsilon_{ij}^{p} \varepsilon_{ij}^{p}}$

2.2 Constitutive analysis using Johnson-Cook Model

The von Mises flow stress can be expressed in terms of the strain, strain rate and temperature as follow:

$$\boldsymbol{\sigma_e} = (\mathrm{A} + \mathrm{B}\, \boldsymbol{\varepsilon_e}^{n}) \left(1 + \mathrm{C} \ln \frac{\dot{\boldsymbol{\varepsilon}}_{\boldsymbol{e}}}{\dot{\varepsilon}_0}\right) (1 - T^{*m})$$

where $\boldsymbol{\varepsilon_e}$ is the effective plastic strain, $\dot{\boldsymbol{\varepsilon}}_{\boldsymbol{e}}$ is the effective plastic strain rate, ε_0 is a reference plastic strain rate and T^* is a homologous temperature, defined as:

$$T^* = \begin{cases} 0 & (T \leq T_0) \\ \dfrac{T - T_0}{T_m - T_0} & (T_0 < T < T_m) \\ 1 & (T_m \leq T) \end{cases}$$

T is current temperature of the material, T_0 is room temperature and T_m is the melting temperature. A, B, C, n and m are Johnson Cook coefficient which are in table 1. A is the yield stress at the reference temperature, B is strain hardening modulus, C is the strain rate effect, n represents the strain hardening effects and m is the coefficient of temperature softening of the material.

For the initial strain rate and temperature, strain rate = 0.02, 2 and 20 s^{-1}, T = 50, 250, 450℃ will be used.

From Johnson-cook equation, the effective plastic strain rate can be expressed as follows:

$$\dot{\varepsilon}_e = \dot{\varepsilon}_0 \exp\left\{\left(\frac{\sigma_e}{(A + B\varepsilon_e^{n})(1 - T^{*m})} - 1\right) \cdot \frac{1}{C}\right\}$$

2.3 Johnson-Cook failure criterion

Johnson-Cook failure model for plastic deformation depends on the plastic rate and the temperature. Failure criterion is based on the effect of stress triaxiality, strain rate and temperature. This failure criterion is expressed as

$$\mathrm{D} = \sum \frac{d\dot{\varepsilon}_e}{\varepsilon_f}$$

Where $\varepsilon_f = \left[d_1 + d_2 \exp\left(d_3 \frac{\sigma_m}{\sigma_e}\right)\right]\left[1 + d_4 \ln\left(\frac{\dot{\varepsilon}_e}{\dot{\varepsilon}_0}\right)\right][1 + d_5 T^*]$, which is the equivalent plastic strain at the onset of damage.

When D = 1, the failure occurs. The material stiffness is reduced based on the following equation.

$$E^* = (1 - D)E$$

Therefore, D was set under 1 in the simulation because a residual stiffness needs to be positive value.

Table 1. Mechanical properties and Johnson-Cook Coefficient of AA2024-T3

	E (GPa)	ν	Tm (℃)	T_0 (℃)	A (MPa)	B (MPa)	C
AA2024-T3[5]	73.1	0.33	502	20	265	426	0.018

	n	m	d_1	d_2	d_3	d_4	d_5
AA2024-T3[5]	0.34	1	0.13	0.13	-1.5	0.011	0

3 ABAQUS VUMAT Subroutine

The main purpose of this project is to simulate this material model as an ABAQUS VUMAT subroutine. Therefore, Johnson-Cook code has been implemented as ABAQUS VUMAT subroutine. The codes are in the Github. The steps in the calculation is as follows:

At first, as we did in homework 9, calculate the deviatoric strain increment and stress

$$\Delta e_{ij} = \Delta\varepsilon_{ij} - \Delta\varepsilon_{kk}\delta_{ij}/3$$

$$S_{ij}^{n} = \sigma_{ij}^{n} - \sigma_{kk}^{n}\delta_{ij}/3$$

Then, calculate the elastic predictor for the deviatoric and the effective stress

$$S_{ij}^{*} = S_{ij}^{n} + \frac{E}{1+\nu}\Delta e_{ij}$$

$$\sigma_e^{*} = \sqrt{\frac{3}{2}S_{ij}^{*}S_{ij}^{*}}$$

Using Newton-Raphson iteration, solve the following equations for the plastic strain increment.

$$\sigma_e^{*} - \frac{3E\Delta\varepsilon_e}{2(1+\nu)\sigma_e^{*}} - \left\{1 + \mathrm{C}\ln\left(\frac{\Delta\varepsilon_e}{\Delta t\dot{\varepsilon_0}}\right)\right\}(A + B\ {\varepsilon_e}^{n})(1 - T^{*m}) = 0$$

Finally, it is possible to update new stress as below.

$$E^{*} = (1-D)E$$

$$\sigma_{ij}^{n+1} = \left(1 - \frac{3E^{*}\Delta\varepsilon_e}{2(1+\nu)\sigma_e^{*}}\right)S_{ij}^{*} + (\sigma_{kk}^{n} + \frac{E^{*}\Delta\varepsilon_{kk}}{(1-2\nu)})\frac{\delta_{ij}}{3}$$

The J-C model constants and material properties for this simulation were used in table 1. The input file what I was using is in the Github.

4 Results

4.1 The effect of temperature

To compare with my results, I put the experimental results which are shown in Figure 1(d). Figure 1(a)-(c) are the simulated data with my VUMAT subroutine. To test my code, I used three different temperature, 50℃, 250℃ and 450℃, respectively. From the simulation results, it turns out that the stress was getting lower when the temperature is getting higher. It is consistent with the experimental results. It is also found that the tendency of the simulated stress-strain curve is similar with that of the experimental data. It is not exactly same because they have different coefficient, but it is possible to use for checking briefly.

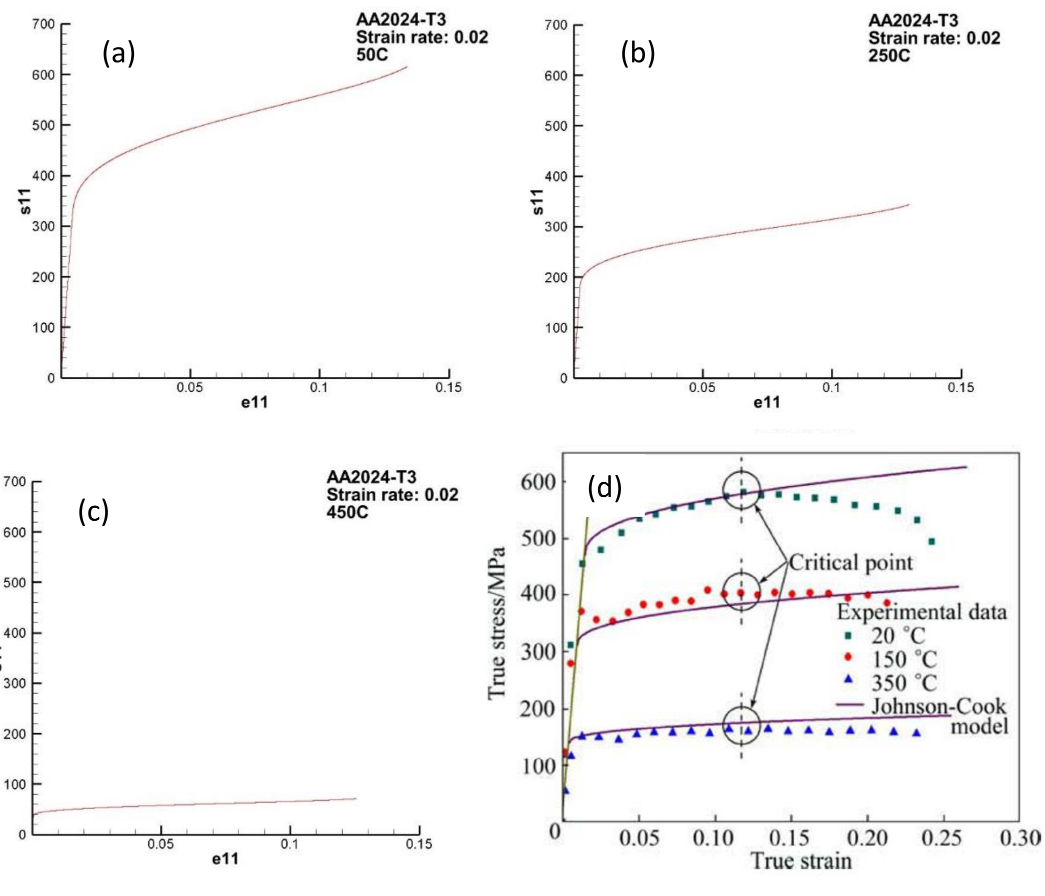

Figure 1. Comparison of simulated stress-strain curves with strain rate=0.02 and different temperature: (a) 50℃ (b) 250 ℃ (c) 450 ℃. (d) Experimental data of 2xxx series aluminum alloy. [1]

4.2 The effect of strain rate

The mechanical data is usually strain rate dependent as shown in figure 2(d). Thus, I simulated my code with different strain rate, 0.02, 2 and 10, respectively. Figure 2(a)-(c) are the simulated data. I was able to prove that the stress-strain curve is strain rate dependent, but not as much as the temperature.

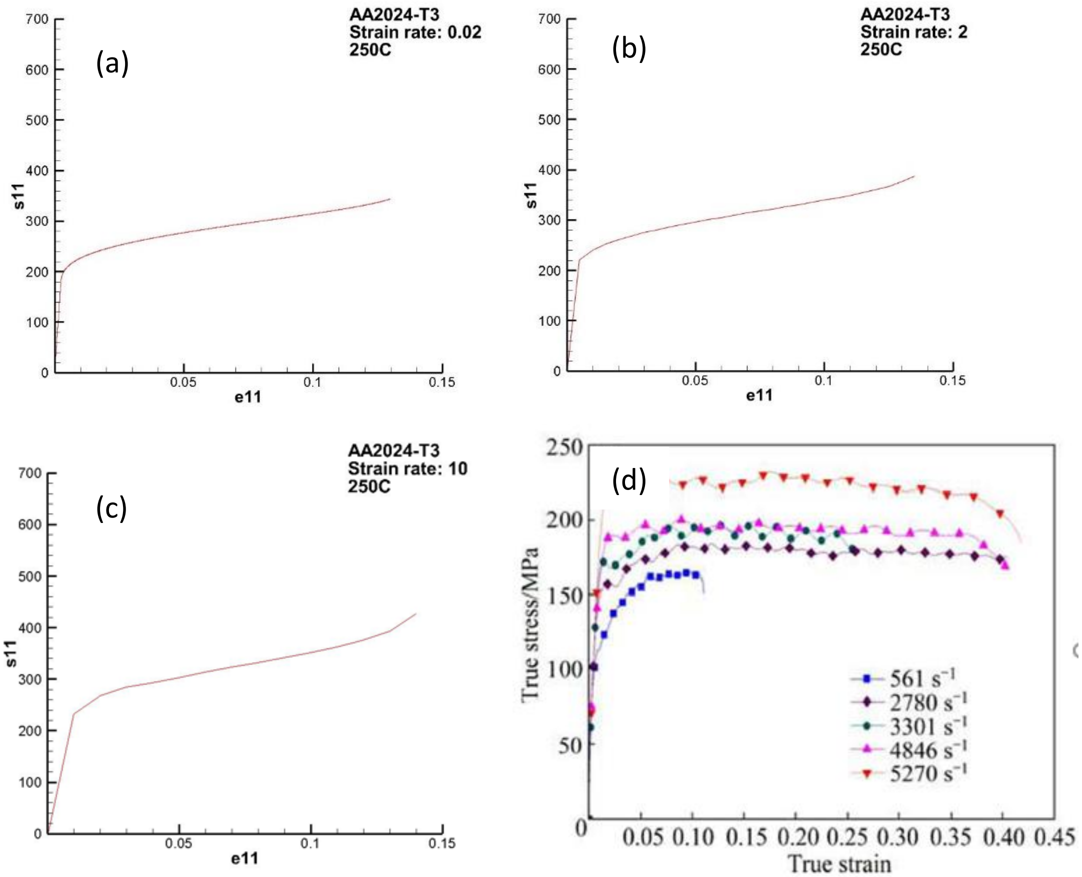

Figure 2. Comparison of simulated stress-strain curves with T=250 ℃ and different strain rate: (a) 0.02 (b) 2 (c) 10. (d) Experimental data of 2xxx series aluminum alloy. [1]

5 Future work

I have only tested Johnson-Cook failure model with a single element, so it may be needed to test with more complicated input file. It works well for small strain rate, but would likely be insufficient for large strain rate. Also, the simulation was done at constant temperature, so it helps to understand the temperature effect to implement some code for the more complicated temperature analysis.

6 Reference

[1] W. H. Liu, Z. T. He, Y. Q. Chen, S. W. Tang, "Dynamic mechanical properties and constitutive equations of 2519A aluminum alloy", Trans. Nonferrous Met. Soc. China 24(2014) 2179−2186

[2] N. S. Brar, V. S. Joshi, B. W. Harris, "Constitutive Model Constants for Al7075-T651 and Al7075-T6", AIP Conference Proceedings;12/28/2009, Vol. 1195 Issue 1, 945-948

[3] I. M. Moravec, "Effect of temperature in ductile damage models"

[4] E. Corona, G. E. Orient, "An Evaluation of the Johnson-Cook Model to Simulate Puncture of 7075 Aluminum Plates"

[5] K. Giasin, S. A. Soberanis, T. French, V. Phadnis, "3D Finite Element Modelling of Cutting Forces in Drilling Fibre Metal Laminates and Experimental Hole Quality Analysis", Appl. Compos. Mater.

Github: https://github.com/yoojinkim15/EN234_FEA.git