

Numerical and Experimental Validation of a New Damage Initiation Criterion

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Abstract. Most commercial finite element software packages, like Abaqus, have a built-in coupled damage model where a damage evolution needs to be defined in terms of a single fracture energy value for all stress states. The Johnson-Cook criterion has been modified to be Lode parameter dependent and this Modified Johnson-Cook (MJC) criterion is used as a Damage Initiation Surface (DIS) in combination with the built-in Abaqus ductile damage model. An exponential damage evolution law has been used with a single fracture energy value. Ultimately, the simulated force-displacement curves are compared with experiments to validate the MJC criterion. 7 out of 9 fracture experiments were predicted accurately. The limitations and accuracy of the failure predictions of the newly developed damage initiation criterion will be discussed shortly.

1. Introduction

Tata Steel aims to provide its customers not only with steel products but also with application knowledge. This research is aimed at the classes of application that require the creation of a weak spot during the forming process to enable controlled failure later in the use-phase. Sufficient strength must be left after forming, but at the same time the ultimate load must be limited. For this controlled failure to be in the specified tolerance range, without resorting to a lengthy and costly trial-and-error process it is essential that the softening can be modelled accurately. The intended weak spot will fail in different stress-states during the use phase. The forming operations and the use phase are modelled in Abaqus and therefore it make sense to use the built-in Abaqus Ductile Damage Model.

The current damage and fracture models are based either on physics [3, 12] or are phenomenologically determined [1, 2, 4]. Nowadays, it is widely accepted that failure is not only dependent on the triaxiality η , but also on the Lode parameter ξ . Combining the Lode parameter dependency with the triaxiality gives the opportunity to uniquely define the fracture strain for any given stress state. A lot of research is being conducted on the physics of failure, where the Lode angle dependency and triaxiality are related to void nucleation, growth and coalescence, see [9, 10, 11].

Normally, a coupled damage model needs to be fitted by means of reverse engineering. This iterative parameter fitting process by means of finite elements is very time consuming. Especially,



when a lot of different experiments are used for the calibration of the coupled damage model. Therefore, an improved damage initiation criterion has been developed to fit the initiation of damage and the moment of fracture for all performed fracture experiments accurately. By coincidence, the newly developed MJC DIS is build in such a way, that it can be fitted in one go without any reverse engineering using it in combination with the built-in Abaqus Ductile Damage Model with a single fracture energy value for the exponential damage evolution.

The newly developed MJC and the built-in Abaqus Ductile Damage model will be treated briefly in the next section. Then the parameter identification will be discussed and how the MJC DIS can be used in combination with the built-in Abaqus Ductile Damage Model. The simulated force-displacement curves are validated against the experiments during the reverse engineering process. Only the results of the final fit are shown. A short discussion will follow to explain the influences of some key factors on the failure predictions. Understanding these key factors will enable the use of the built-in Abaqus ductile Damage Model without any reverse engineering.

2. Modelling

The MJC criterion has been developed to make the original JC fracture criterion Lode parameter dependent. Here, the MJC represents the Damage Initiation Surface (DIS), while the JC is commonly used as a fracture criterion. The built-in Abaqus Ductile Damage Model will be discussed as well.

2.1. Modified Johnson-Cook (MJC)

The original Johnson-Cook (JC) fracture criterion [5] is only dependent on the triaxiality, strain rate and temperature. This model has five parameters D_1 to D_5 and is expressed as follows:

$$\bar{\epsilon}_f = [D_1 + D_2 \exp(D_3 \eta)] \left[1 + D_4 \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right] \left[1 + D_5 \frac{T - T_{room}}{T_m - T_{room}} \right] \quad (1)$$

where $\bar{\epsilon}_f$ is the equivalent fracture strain, η is the triaxiality, $\dot{\epsilon}$ is the equivalent strain rate [s^{-1}], T_m is the melting temperature of the material [$^{\circ}C$], T_{room} is the room temperature [$^{\circ}C$] and T is the temperature [$^{\circ}C$]. For simplicity reasons parameter D_1 is equal to zero. No strain rate and temperature effects are considered here and therefore parameters D_4 and D_5 are equal to zero in this paper as well. The JC fracture criterion is now reduced to

$$\bar{\epsilon}_f = D_2 \exp(D_3 \eta) \quad (2)$$

The above simplified equation can be made Lode parameter dependent by assuming parameter D_2 and D_3 to be functions of ξ . This modified JC model is used as a DIS instead of a fracture curve. The MJC DIS can therefore be defined as follows:

$$\bar{\epsilon}_{DIS} = f_2(\xi) \exp(f_3(\xi) \eta) \quad (3)$$

where $\bar{\epsilon}_{DIS}$ is the equivalent strain at which damage initiation occurs. The moment of damage initiation needs to be used as input for the built-in Abaqus Ductile Damage Model, which will be discussed in more detail in the next sub-section.

2.2. Built-in Abaqus Ductile Damage Model

Using the built-in Abaqus Ductile Damage Model combined with the Damage Evolution will result in changing the characteristics of the stress-strain behaviour in two ways: softening of the yield stress and degradations of the elasticity, see Figure 1a.

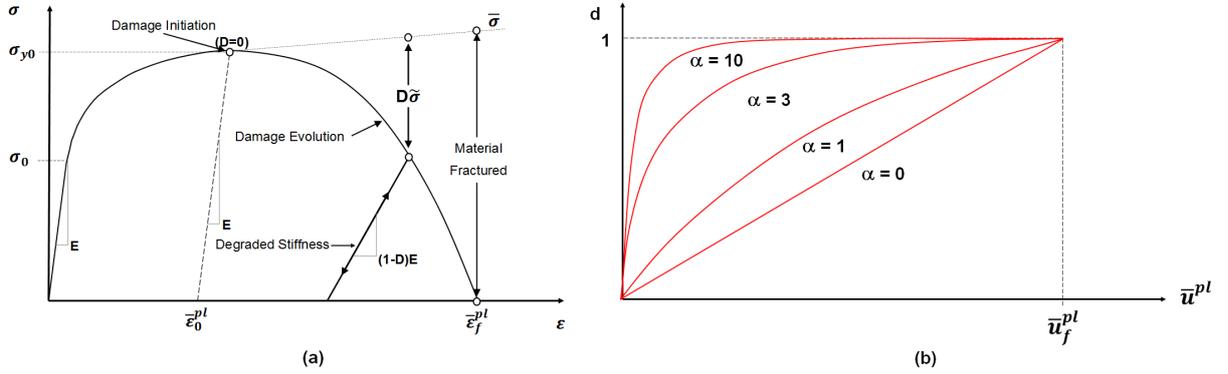


Figure 1. (a) Difference between a coupled- and uncoupled damage model, (b) Exponential Damage Evolution

When material damage occurs, the stress-strain relationship no longer represents the material behaviour accurately. Therefore, continuing to use the stress-strain relation introduces a strong mesh dependency based on strain localization, such that the energy dissipation decreases with a finer mesh.

The approach implemented in ABAQUS is proposed by Hillerborg in 1976, which follows the strain-softening branch of the stress-strain response curve. Hillerborg's Fracture Energy, G_f , is defined as the energy required to open a unit area of crack as a material parameter. The softening response after damage initiation is characterized by a stress-displacement response rather than a stress-strain response. The Fracture Energy is defined as

$$G_f = \int_{\bar{\epsilon}_0^{pl}}^{\bar{\epsilon}_f^{pl}} L \sigma_y d\bar{\epsilon}^{pl} = \int_0^{\bar{u}_f^{pl}} \sigma_y d\bar{u}^{pl} \quad (4)$$

were L is the characteristic length of the element, $\bar{\epsilon}_f^{pl}$ is the equivalent plastic strain at the onset of damage, $\bar{\epsilon}_f^{pl}$ is the equivalent plastic strain at failure and \bar{u}_f^{pl} is the equivalent plastic displacement at failure. (4) introduces the definition of the equivalent plastic displacement \bar{u}^{pl} , as the fracture work conjugated of the yield stress after the onset of damage in terms of work per unit area of crack. Before damage initiation $\bar{u}^{pl} = 0$ and after damage initiation $\dot{\bar{u}}^{pl} = L \dot{\bar{\epsilon}}^{pl}$. The rate equation at integration point level can be rewritten into

$$d\bar{u}^{pl} = L d\bar{\epsilon}^{pl} \quad (5)$$

Using (5) to numerically integrate the stress and strain results in (4) to calculate the Fracture Energy G_f or total dissipated energy. The total dissipated energy is computed in the same way as (4), but than with different upper- and lower limits. The Damage Evolution in terms of G_f can be computed based on the nodal results. It is better to do this calculation directly from the integration point of the element of interest. Nevertheless, the nodal results are used later on to fit the DIS for the chosen Damage Evolution (DE). The damage value d can be calculated as follows using a exponential type of DE

$$d = \frac{1 - \exp\left(-\alpha \left(\frac{\bar{u}^{pl}}{\bar{u}_f^{pl}}\right)\right)}{1 - \exp(-\alpha)} \quad (6)$$

Figure 1b shows the exponential DE versus the effective plastic displacement, \bar{u}_f^{pl} and the exponent α . The assumption is that the dissipated energy is equal to the Fracture Energy after damage initiation, see [13]. After damage initiation fracture is then governed by the Fracture Energy G_f (4).

3. Experiment

When experimental data is available, the question remains how this data can be used to fit a damage or a fracture model. The parameter identification is done on a TH550N, a packaging grade, which has a yield strength of 550 MPa and a thickness of 0.21 mm. A von Mises yield locus and tabulated strain rate sensitivity according to Bergström-van Liempt refs.[7, 8] have been used for the reverse engineering FEA. An explicit solver is used for the reverse engineering FEA. Therefore, the punch velocity for the Nakajima simulations and the tensile velocity for the Notched Tensile simulations are increased to speed up the computation time. The strain rate sensitivity has been scaled properly for each simulation. The MJC DIS will be used in combination with the built-in Ductile Damage Model to validating the accuracy of the failure predictions. An exponential damage evolution is used with a single fracture energy value to describe the softening behaviour.

3.1. Parameter Identification

A schematic overview of the used fracture experiments is given in Figure 2a. The numbering sequence in Figure 2a corresponds to 1. the Slight Notched Tensile Test, 2. the Intermediate Notched Tensile Test, 3. the Plane Strain Notched Tensile Test and the Nakajima experiments with the following width of parallel sections: 4. 55 mm, 5. 80 mm, 6. 95 mm, 7. 105 mm, 8. 200 mm and 9. 200 mm fully clamped. The in-house fracture experiments are always performed in the transverse direction. The principal strains are measured with a GOM Aramis optical strain measurement system, where the force-displacement curve of the testing device has been logged by the GOM Aramis system as well. The Aramis stages have been used as a basis for the time points for the Abaqus simulations. The fracture experiments are first simulated without the built-in Abaqus Ductile Damage Model.

The fracture experiments are designed to fail from the middle of the sample to exclude preparation artefacts e.g. fracture from the machined edge. From the expected failure location, the triaxiality, Lode parameter, equivalent strain and dissipated plastic energy are all obtained, see Figure 2b for a single experiment. Figure 2b shows the corresponding values of the most critical nodal point.

The fracture energy is needed to describe the amount of damage evolution or dissipated energy due to softening. The assumption is that the Fracture Energy or Hillerborg parameter, is a constant and independent of the stress-state in terms of triaxiality and Lode parameter. Then, it is valid to subtract the Fracture Energy from the total dissipated plastic energy, see

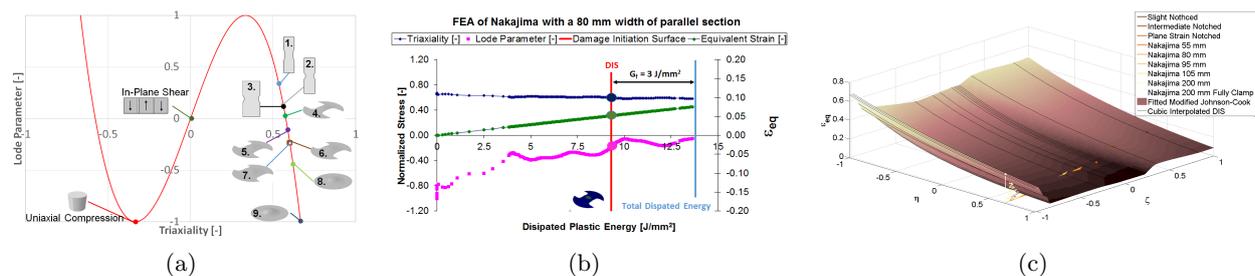


Figure 2. (a) Overview Fracture Experiments, (b) Fitting Methodology, (c) Fitted MJC DIS

figure 2b. A Fracture Energy of $3 J/mm^2$ is subtracted from the total dissipated energy, see the light blue line in Figure 2b.

This then represents the amount of dissipated plastic energy, when damage initiation is assumed to occur. Now, the triaxiality, Lode parameter and equivalent strain can be used to fit the MJC DIS eq.(3), see the red line with the enlarged round markers in Figure 2b. These values are used to fit the MJC DIS shown in Figure 2c.

3.2. MJC DIS used in combination with built-in Abaqus Damage Model

The fitted MJC DIS is used as tabulated input in the Abaqus built-in Ductile Damage Model. The tabulated MJC DIS is in triaxiality and Lode parameter space. The MJC DIS describes the moment of damage initiation, see Figure 2c. The trajectory after damage initiation will be described by a Damage Evolution law. For which an exponential damage evolution has been chosen. The exponential damage evolution only needs a single Fracture Energy value to describe the energy dissipation during softening.

4. Validation

The accuracy of the fitted MJC DIS will be validated with the experimentally determined force-displacement curves. The limitations and the accuracy of the failure predictions will be discussed after the comparison.

4.1. Results

The results for the arbitrarily chosen Fracture Energy of $3 J/mm^2$ are presented in Figure 3. The choice of the Fracture Energy value will be discussed in the next sub-section. 2 out of 9

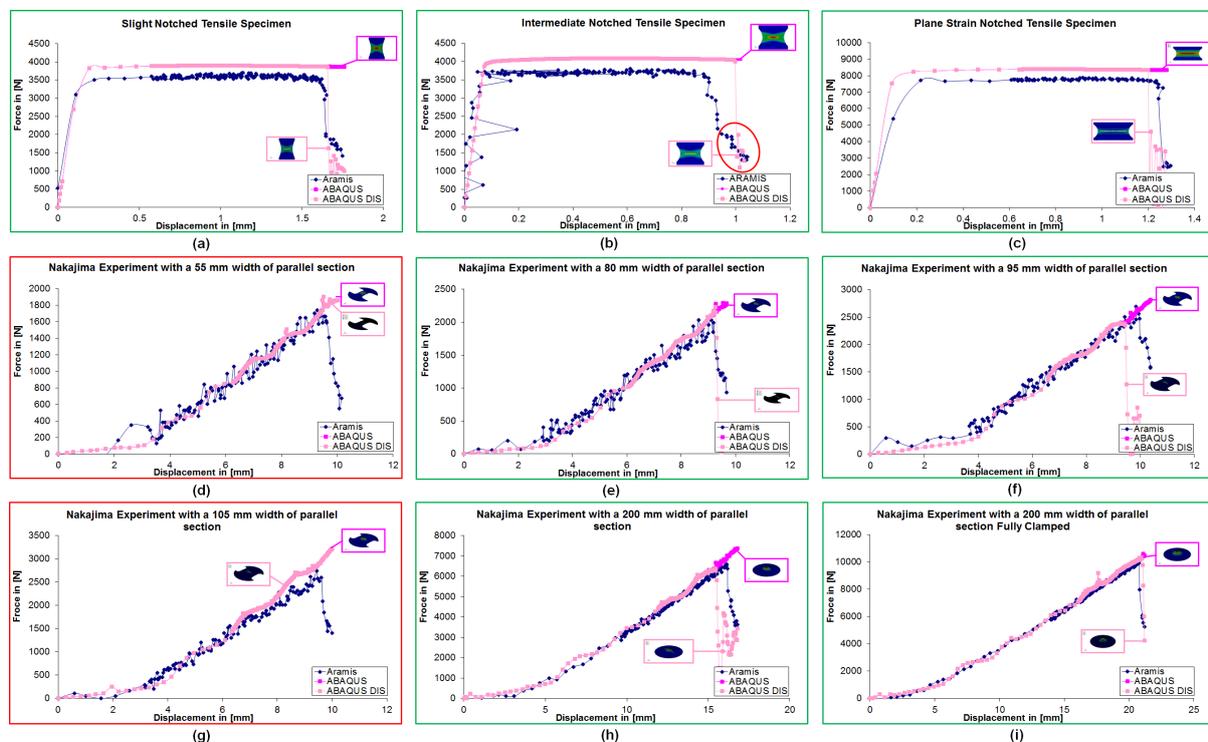


Figure 3. Results of using the fitted MJC DIS based on a fracture energy of $3 J/mm^2$ and fitted without the Nakajima with a 55 mm width of parallel section

force-displacement curves can not be predicted accurately with the MJC DIS fit shown in Figure 2c. As mentioned earlier, the parameter identification is done by means of reverse engineering. During this iteration process it became clear that a few key factors will influence the accuracy of the failure predictions. These key factors will be treated in the discussions.

4.2. Discussions

During the development of the MJC, it became clear that the DIS could have been fitted directly from the experiments, because the same data, i.e. the triaxiality, Lode Parameter, equivalent stress and strains can be directly computed from the measured surface strain history captured by the GOM Aramis system. For this the strain history need to be captured and an accurate plasticity model is required. The influence of failure predictions using different plasticity models are discussed in [12]. In this paper the coupled MJC damage initiation criterion is build in such a way, that it can be fitted in one go without any reverse engineering using a single fracture energy value for the exponential damage evolution.

The key factors that found to be influencing the accuracy of the failure predictions are the choice of the fracture energy, the smoothness of the DIS and the loading path. Understanding these key factors will enable the use of the built-in Abaqus ductile Damage Model without any reverse engineering. The conclusions will be treated in the next section.

Influence of Fracture Energy

As these same experiments were used to calibrate the DIS, it was expected that all predictions would be more accurate. However, analysis revealed that the premature failure is due to the waviness of the loading path which crosses the DIS not at the intended location. The waviness in the force-displacement curve or loading path is due to the explicit solver.

Initially, the reverse engineering process started with arbitrarily chosen Fracture Energy of 5 J/mm^2 . Reducing the Fracture Energy from 5 J/mm^2 to 3 J/mm^2 will increase the equivalent damage initiation strain. This will reduce the risk to premature failure by shifting the DIS upwards. This is the reason why only 3 out of 9 fracture experiments were predicted accurately for a fitted DIS based on a Fracture Energy of 5 J/mm^2 , see Figure 4. Therefore, the fitted DIS needs to be checked against the loading paths to prevent premature failure predictions afterwards by reducing the Fracture Energy.

The red encircled part of the predicted force-displacement curves in Figure 4a matches very well with the experimental determined force-displacement curves. However, the red encircled part of the predicted force-displacement curves in Figure 3b does not match very well, when a lower Fracture Energy of 3 J/mm^2 is chosen. A lower Fracture Energy value results in a smaller amount of softening. Therefore a stress-state dependent Fracture Energy will result in a better softening prediction for different experiments. This is currently the limitation of using a single fracture energy value for the exponential damage evolution.

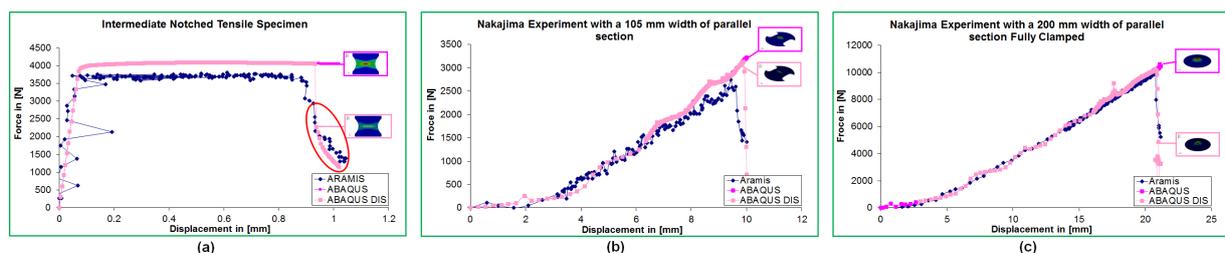


Figure 4. Results of using the fitted MJC DIS based on a fracture energy of 5 J/mm^2

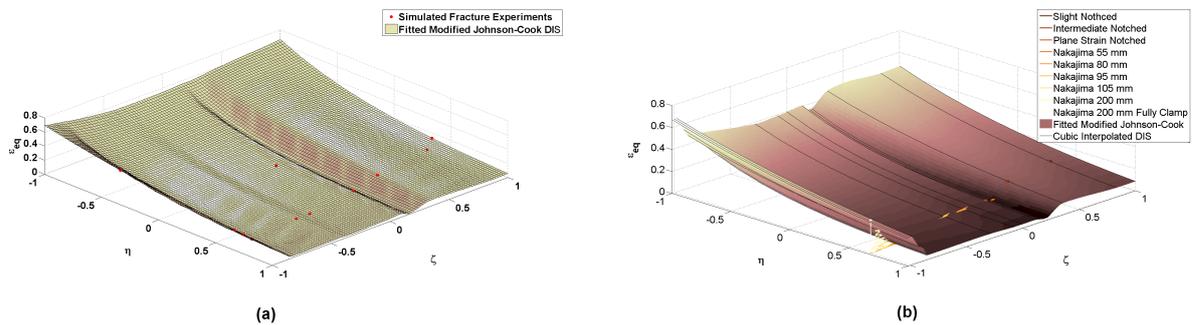


Figure 5. (a) Fitted MJC DIS based on a $G_f = 5 \text{ J/mm}^2$ with a biharmonic spline interpolation scheme, (b) Fitted MJC DIS based $G_f = 3 \text{ J/mm}^2$ with a cubic interpolation scheme

Influence of the smoothness DIS

Different fracture energies have been tried to accommodate accurate failure predictions. However, there is an additional difference in the used interpolation scheme between the fitted MJC DIS based on a fracture energy of 5 J/mm^2 and 3 J/mm^2 . In the first case the Matlab 4 griddata method (biharmonic spline interpolation) is used and in the second case a cubic interpolation scheme is used to build the MJC DIS, see Figure 5. The failure prediction changed to no failure occurrence at all for the Nakajima simulation with the 105 mm width of parallel section when using the fitted MJC DIS based on a G_f of 3 J/mm^2 , compare Figure 4b with Figure 3g. The interpolation scheme chosen for the second case is less smooth. Therefore, it is thought, that this problem can be resolved by using a different interpolation scheme. When a smoother interpolation scheme is used to fit the MJC DIS based on a fracture energy of 3 J/mm^2 , it is expected that 8 out of 9 fracture experiments are predicted accurately. Another solution to resolve the non-smooth surface or sharp edge is to use a return mapping algorithm for non-smooth surfaces in a VUMAT/UMAT, see [6].

Influence of the loading path

When the MJC DIS is fitted without the Nakajima simulation with a 55 mm width of parallel section, then failure can be correctly predicted for the Plane Strain Notched Tensile simulation, see Figure 3c. The valley around a ξ of 0.2 is now less deep compared to Figure 6a, therefore the absolute distance is bigger between the DIS and the loading path of the Plane Strain Notched

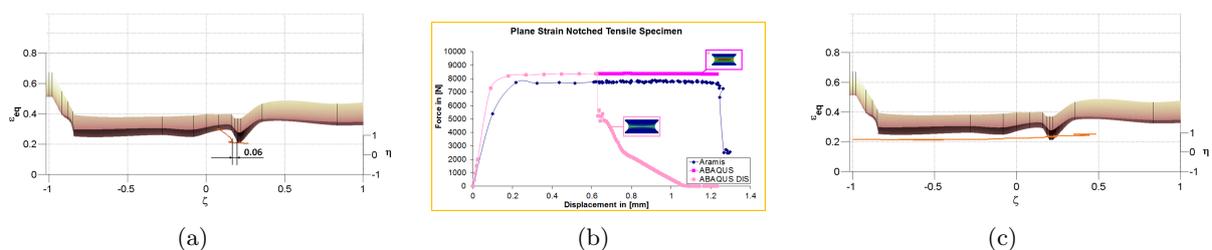


Figure 6. (a) Absolute distance between the Plane Strain Notched Tensile loading path and the fitted MJC DIS, (b) Premature failure prediction for the Plane Strain Notched Tensile simulation, (c) Low gradient of loading path for the Nakajima with a 55 mm width of parallel section

Tensile simulation. The distance between the loading path and the DIS should not be equal or smaller than 0.06 in Lode Parameter, see Figure 6a. Otherwise, Abaqus will start damage initiation even without the loading path touching or crossing the MJC DIS. This will result in premature failure of the Plane Strain Notched Tensile simulation, see Figure 6b. A different solving scheme should be used in the return mapping algorithm to resolve this issue.

Predicting failure for the Nakajima simulation with the 55 mm width of parallel section is practically impossible due to the very small gradient in the loading path, which will create a valley in the fitted MJC DIS, see Figure 6c. This valley is artificial, because the simulated loading path lacked a gradient due to localized instability. In this case, the localized instability could not be predicted by the von Mises plasticity model. Whereas, for the other fracture experiment simulations a certain amount of localized instability was predicted even without using the built-in Abaqus Ductile Damage Model.

5. Conclusions

The following conclusions can be made:

- It is possible to predict failure with the built-in Abaqus ductile damage model for multiple applications using this in combination with the newly developed MJC DIS with an exponential damage evolution.
- Omitting the Nakajima with a 55 mm width of parallel section in the MJC DIS fit results into 7 out of 9 accurate failure predictions for the different fracture experiments.
- The failure prediction success rate is higher for lower Fracture Energy values, due to the assumption that the softening behaviour is independent of the stress-state.
- 2 out of 9 FEA did not predict fracture due to:
 - the non-smooth damage initiation surface or sharp edge resulted into premature failure for the Nakajima simulation with a 105 mm width of parallel section.
 - the lack of localized instability, which causes for the low gradient in the Nakajima loading path with a 55 mm width of parallel section.

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