Aalto University
School of Engineering

COE-C2004 - Materials Science and Engineering

2021-2022 Autumn II

Assignment 3, 15.11.2021

Task 1. Fracture mechanics (10 points, Lecture5)

1.1 The fracture strength of glass may be increased by etching away a thin surface layer. It is believed that the etching may alter the surface crack geometry (i.e. reduce the crack length and increase tip radius). Calculate the ratio of the etched and original crack tip radii if the fracture strength is increased by a factor of 7.6 when 37% of the crack length is removed. (Please give the detailed calculation process.)

1.2 A structural component in the shape of a flat plate 17 mm thick is to be fabricated from a metal alloy for which the yield strength and plane strain fracture toughness values are 536 MPa and 25.0 MPa$\sqrt{\text{m}}$, respectively. For this particular geometry, the value of Y is 1.3. Assuming a design stress of 0.4 times the yield strength, calculate the critical length of a surface flaw. (Please give the detailed calculation process.)

Solution:

1.1

We assume that ρ_t = unetched crack tip radius, and ρ_t'= etched crack tip radius,

The maximum stress σ_{max} will be the same for both unetched and etched specimens, that is

$$\sigma_{max} = \sigma_{max}'$$

The etched crack length (a′) and unetched crack length (a) are related as:

$$a' = (1 - 37\%)a = 0.63a$$

And the relationship between the etched and unetched fractured strengths (denoted σ_0' and σ_0 respectively) is:

$\sigma_0' = 7.6\sigma_0$ (1 point)

Using the above notations, we write the following relationship between maximum stress and crack tip geometry as:

$$\sigma_{max} = 2\sigma_0(\frac{a}{\rho_t})^{1/2} = \sigma_{max}' = 2\sigma_0'(\frac{a'}{\rho_t'})^{1/2} \qquad \text{Eq. 1 (2 points)}$$

therefore,

$\frac{\rho_t'}{\rho_t} = (\frac{\sigma_0'}{\sigma_0})^2 \cdot \left(\frac{a'}{a}\right) = 7.6^2 \times 0.63 = 36.39$ (2 points)

1.2

According to the problem statement, the design stress is 0.4 times of the yield strength,

$$\sigma = 0.4 \cdot \sigma_y = 0.4 \times 536 \text{ MPa} = 214.4 \text{ MPa}. \text{ (1 point)}$$

According to the definition of stress intensity factor K_{Ic}:

$$K_{Ic} = \sigma \cdot Y\sqrt{\pi \cdot a_c} \qquad \text{Eq. 2 (2 points)}$$

where σ is the critical stress for crack propagation, Y is the dimensionless parameter, a_c is the crack length.

Therefore, the value of a_c is computed as follows:

$a_c = \frac{1}{\pi}(\frac{K_{Ic}}{\sigma \cdot Y})^2 = \frac{1}{\pi}[\frac{25.0 \text{ MPa}\sqrt{\text{m}}}{(214.4 \text{ MPa}) \times 1.3}]^2 = 2.6 \times 10^{-3} \text{ m} = 2.6 \text{ mm}$ (2 points)

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Task 2. Charpy test (20 points, Lecture5&6)

2.1 Please use the test results given in Table 1 to fit the transition curves for steel A. Give your fitting function and fitted parameters, show the fitting figure. (Hint: Use a proper equation e.g. the Boltzmann function to fit the data.)

Table 1 Charpy test results of steel A.

T, °C	-196	-140	-120	-120	-120	-100	-100	-100	-78	-78	-78	-40	-40	-40	25	100
A_V, J	10	12	33	19	18	26	41	30	86	105	129	210	243	220	245	246

2.2 Based on your curve fitting in Task 2.1, give the following characteristic values of a Charpy test:

(a) What is the temperature (in °C) with an impact energy of 27 J?

(b) What is the upper shelf toughness A_{Vmax} (in J)?

(c) What is the transition temperature $T_{AVmax/2}$ (in °C)?

2.3 Please add the schematic transition curve of an FCC material on the fitted curve in Task 2.1, and explain the failure mechanisms of BCC and FCC materials in Charpy tests at different temperatures.

2.4 The force-deflection curves of two Charpy impact tests are shown in Figure 1. Both of the tests were performed at 30°C. The areas under these two curves are the same, i.e. I=II. Which steel shall have a lower transition temperature? Please explain the reason.

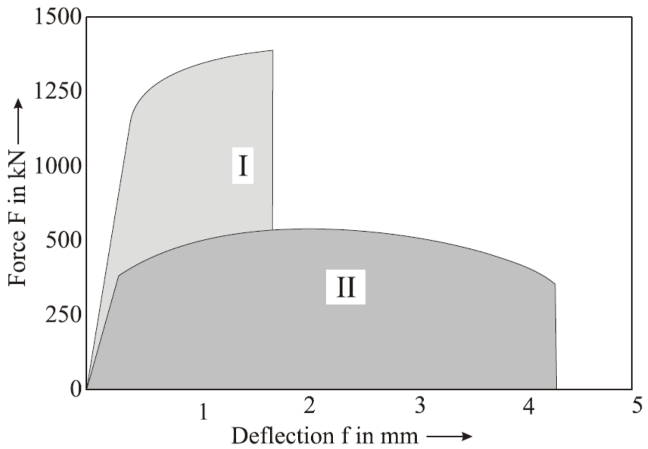


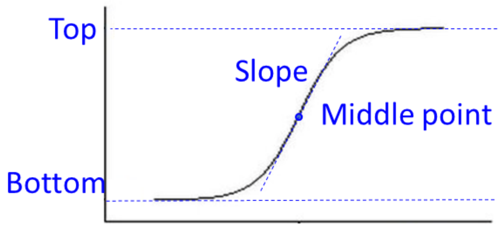
Figure 1 Force-deflection curves for the Charpy test. [1]

<u>Solution:</u>

<u>2.1</u>

Boltzmann function:

$$y = p1 + \frac{(p2 - p1)}{1 + \exp\left(\frac{p3 - x}{p4}\right)} \qquad \text{Eq. 3 (2 points)}$$



$$y = Bottom + \frac{Top - Bottom}{1 + \exp\left(\frac{Middle\ point - x}{Slope}\right)}$$

Figure 2 Schematic drawing of Boltzmann function.

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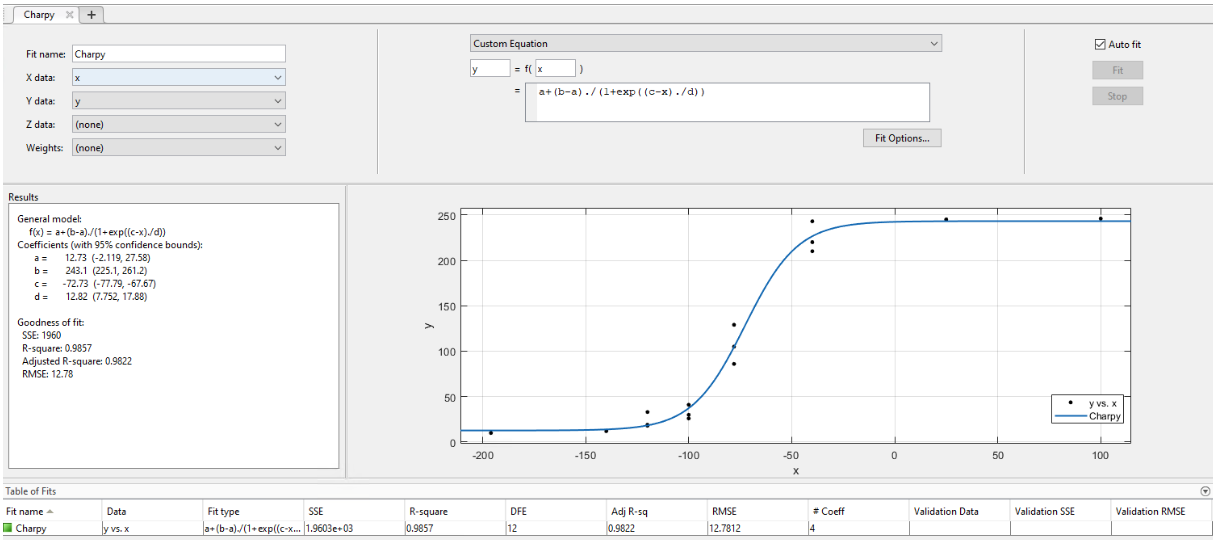
e.g.: fitting by Matlab:



The fitted function with parameters:

$$A_v = 12.73 + \frac{(243.1 - 12.73)}{1 + \exp\left(\frac{-72.73 - T}{12.82}\right)}$$

where T is the temperature and Av is the impact energy.

The experimental data and fitting curve are shown in Figure 3.

(2 points for fitting process, 2 points for fitting parameters.

+5 points if you have a better fitting quality than the solution given above.)

2.2

(a) When Av=27 J, according to the fitted function, $27 = 12.73 + \frac{(243.1-12.73)}{1+\exp\left(\frac{-72.73-T}{12.82}\right)}$, $T_{27\,J}$=-107.57 °C

(2 points)

Matlab commands for solving function:

```
%% Solve function
a = 12.73;
b = 243.1;
c = -72.73;
d = 12.82;
syms x
eqn = a+(b-a)/(1+exp((c-x)/d))==27;
S=solve(eqn,x,'Real',true);
double(S)
```

(b) According to the fitted function, A_{Vmax} = 244.6 J. However, in the experimental data, the upper shelf toughness A_{Vmax} shall be 246 J. (2 points)

(c) According to the fitted function, the transition temperature $T_{AVmax/2}$ = -73.82 °C. (2 points)

(Acceptable range of results: ±10% on $T_{27\,J}$ and $T_{AVmax/2}$; A_{Vmax}=240-250 J)

2.3

The schematic drawing FCC impact energy-temperature curve from the Charpy test is shown in Figure 3 with a solid blue line. The overall impact energy could be relatively higher or lower dependents on the strength/toughness of the FCC materials, but generally, for FCC, there is no transition zone in the Charpy test. At a large temperature range, the FCC metals show a consistent ductile fracture behavior, which is

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different from the BCC metals. In FCC metals, there is the most closely packed structure, while in BCC, the atoms on the slip plane are not in the most closely packed mode. Therefore, the thermal activation energy for dislocation slip in BCC is strongly temperature-dependent. At low temperatures, the dislocation slip in BCC might be frozen, and the overall plastic deformation is limited, which results in macroscopic brittle behavior. For FCC, the dislocation movement is not temperature sensitive, the impact energy is also relatively insensitive to temperature.

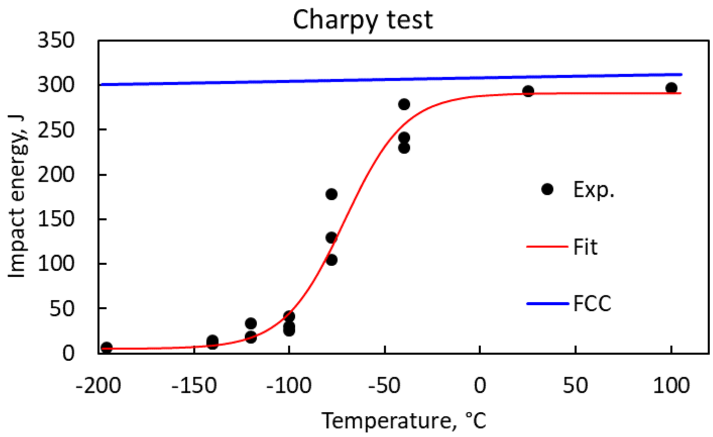

Figure 3 Charpy test transition curve.

(FCC curve plotting: 2 points with explanation: 2 points)

2.4

At 30 °C, these two steels have the same impact energy. However, steel I has been broken with a limited plastic deformation while steel II has been deformed with a larger plastic strain. That means, the steel I broke at the lower or transition zone while steel II broke at its upper toughness zone, as shown in Figure 4. It can be driven that steel II has a lower transition temperature, $T_{II}<T_{I}$.

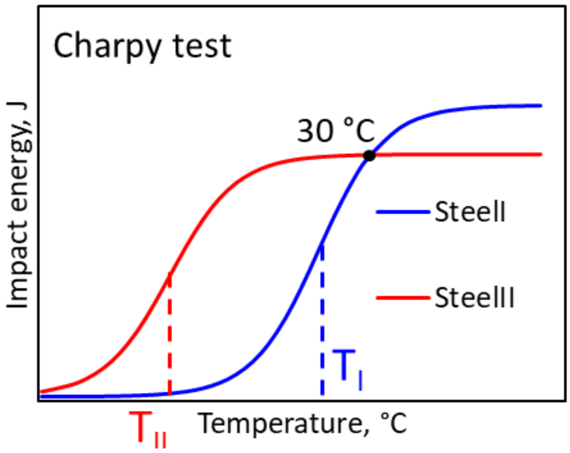

Figure 4 Schematic drawing of the Charpy test transition curve of steel I and II.

($T_{II}<T_{I}$: 2 points with explanation: 2 points)

Task 3. Failure behavior (30 points, Lecture5&6)

Choose three of the failure types of metals from the list, and give a description of each:

- Creep,
- Fatigue,
- Corrosion,
- Cleavage fracture,
- Ductile fracture,
- Abrasion.

The description shall include the following aspects:

(1) a brief definition of this term,
(2) an example,
(3) the conditions/situation this failure might happen,
(4) affecting factors,
(5) how to improve the resistance to this kind of failure.

Solution:

- **Creep:**

(1) Definition

Materials are often placed in service at elevated temperatures and exposed to static mechanical stresses (e.g., turbine rotors in jet engines and steam generators that experience centrifugal stresses, and high-pressure steam lines). Deformation under such circumstances is termed creep. Defined as the time-dependent and permanent deformation of materials when subjected to a constant load or stress, creep is normally an undesirable phenomenon and is often the limiting factor in the lifetime of a part. It is observed in all materials types; for metals, it becomes important only for temperatures greater than about $0.4T_m$ (T_m: absolute melting temperature). Amorphous polymers, which include plastics and rubbers, are especially sensitive to creep deformation.

(2) Example

The creep of a turbine blade could cause the blade to contact the casing, resulting in the failure of the blade.

Moderate creep in concrete is sometimes welcomed because it relieves tensile stresses that might otherwise lead to cracking.

(3) The conditions/situation this failure might happen

It is usually of concern to engineers and metallurgists when evaluating components that operate under high stresses or high temperatures. Depending on the magnitude of the applied stress and its duration under elevated temperatures, the deformation may become so large that a component can no longer perform its function.

(4) Affecting factors

The rate of deformation is a function of the material's properties, exposure time, exposure temperature, and the applied structural load. The influence of stress and temperature on creep behavior is shown in Figure 5. At a temperature substantially below $0.4T_m$, and after the initial deformation, the strain is virtually independent of time. With either increasing stress or temperature, the following will be noted: the instantaneous strain at the time of stress application increases; the steady-state creep rate is increased; and the rupture lifetime is diminished.

In addition, the internal material factors include melting temperature, elastic modulus, and grain size. In general, the higher the melting temperature, the greater the elastic modulus, and the larger the grain

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size, the better a material's resistance to creep. Relative to grain size, smaller grains permit more grain boundary sliding, which results in higher creep rates. This effect may be contrasted to the influence of grain size on the mechanical behavior at low temperatures.

(5) Common methods to reduce creep

Solid solution strengthening, particle dispersion strengthening, precipitation hardening, grain refinement (blocking dislocation motion). For example, stainless steels and superalloys are especially resilient to creep and are commonly employed in high-temperature service applications. The creep resistance of the superalloys is enhanced by solid-solution alloying and also by the formation of precipitate phases. In addition, advanced processing techniques have been utilized; one such technique is directional solidification, which produces either highly elongated grains or single-crystal components.

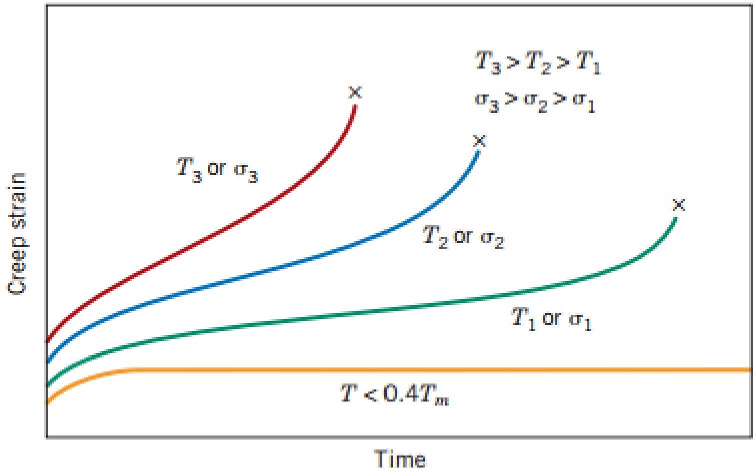

Figure 5 Influence of stress and temperature on creep behavior. [2]

- **Fatigue**

(1) Definition

Fatigue is a form of failure that occurs in structures subjected to dynamic and fluctuating stresses. Under these circumstances, it is possible for failure to occur at a stress level considerably lower than the tensile or yield strength for a static load. The term fatigue is used because this type of failure normally occurs after a lengthy period of repeated stress or strain cycling and results in progressive and localized structural damage and the growth of cracks. Fatigue failure is brittle like in nature even in normally ductile metals, in that there is very little, if any, gross plastic deformation associated with failure. The process occurs by the initiation and propagation of cracks, and ordinarily, the fracture surface is perpendicular to the direction of applied tensile stress. Furthermore, fatigue is catastrophic and insidious, occurring very suddenly and without warning.

(2) Example

Fatigue is important inasmuch as it is the single largest cause of failure in metals, estimated to comprise approximately 90% of all metallic failures (e.g., bridges, aircraft, and machine components). Polymers and ceramics (except for glasses) are also susceptible to this type of failure.

(3) The conditions/situation this failure might happen

Once a fatigue crack has initiated, it will grow a small amount with each loading cycle. The crack will continue to grow until it reaches a critical size, which occurs when the stress intensity factor of the crack exceeds the fracture toughness of the material, producing rapid propagation and typically complete fracture of the component.

(4) Affecting factors

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the fatigue behavior of engineering materials is highly sensitive to a number of variables. Some of these factors include loading stress level (maximum stress, mean stress, the ratio of maximum stress and minimum stress), geometrical design, surface effects, and metallurgical variables, as well as the environment. For example, increasing the mean stress level leads to a decrease in fatigue life. Besides, thermal fatigue is normally induced at elevated temperatures by fluctuating thermal stresses. Corrosive environments have a deleterious influence and produce shorter fatigue lives, which is regarded as corrosion fatigue.

(5) Common methods for improving fatigue life:

Reducing mean stress, introducing compressive surface stresses (reducing stress amplitude) by shot peening or carburizing, component design (avoiding sharp corner).

- **Corrosion**

(1) Definition

Corrosion is a natural process that converts a refined metal into a more chemically stable form such as oxide, hydroxide, or sulfide. It is the gradual destruction of materials (usually a metal) by chemical and/or electrochemical reactions with their environment. It is electrochemical and ordinarily begins at the surface.

(2) Example

Familiar examples include the rusting of automotive body panels and radiator and exhaust components.

(3) The conditions/situation this failure might happen

Many structural alloys corrode merely from exposure to moisture in the air, but the process can be strongly affected by exposure to certain substances. It may be considered essentially as an electrochemical phenomenon.

(4) Affecting factors

The electrochemical activity of material, ordinary environment (humidity and temperature), extraordinary environment (acidity). External loading conditions, e.g. stress corrosion results from the combined action of applied tensile stress and a corrosive environment.

(5) Common methods to improving corrosion resistance

Deposition of coating layer is used to reduce the activity of the exposed surface, such as passivation and chromate conversion, can increase a material's corrosion resistance. Decreasing the application temperature. Physical barriers prevention. Alloy design by introducing corrosion-resistant elements, e.g. add Cr in the stainless steels.

- **Cleavage fracture**

(1) Definition

In cleavage (brittle in macroscopy) fracture, little or no apparent plastic deformation with low energy absorption takes place before fracture. Brittle fracture typically involves little energy absorption, spontaneous and rapid crack propagation, and occurs suddenly and catastrophically without any warning.

(2) Example

The sinking of the Titanic.

(3) The conditions/situation this failure might happen

In brittle crystalline materials, fracture can occur by cleavage as the result of tensile stress acting normal to crystallographic planes with low bonding (cleavage planes). It occurs due to dislocation accumulation at grain boundaries or local area with high stress concentration (precipitates or inclusions).

(4) Affecting factors

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Material microstructure and alloy composition, Material fracture toughness (Kc), applied stress level (σ), introduced flaw geometry (a), service conditions including temperature, strain rate, stress state, etc.
(5) Common methods to avoid brittle fracture
Low loading stress, smooth crack tip and small defects, as well as avoiding low-temperature environment will enhance the fracture strength to resist brittle fracture.

- **Ductile fracture**

(1) Definition
In ductile fracture, substantial plastic deformation with high energy takes place before fracture. The terms rupture or ductile rupture describe the ultimate failure of ductile materials loaded in tension. The extensive plasticity causes the crack to propagate slowly due to the absorption of a large amount of energy before fracture.
(2) Example
Tension on an aluminum rod at room temperature until breaking into two pieces.
(3) The conditions/situation this failure might happen
Voids typically coalesce around precipitates, secondary phases, inclusions, and at grain boundaries in the material. Ductile fracture is typically transgranular and deformation due to dislocation slip can cause the shear lip characteristic of the cup and cone fracture.
(4) Affecting factors
Material microstructure and alloy composition, Material fracture toughness, applied stress level (σ), and introduced flaw geometry (a), service conditions including temperature, strain rate, stress state, etc.
(5) Common methods to improve ductility
Heat-treatment (microstructure modification like transformation from martensite to ferrite, small particle size, grain refinement, moderate dispersity of secondary phase, spheroidization of precipitates, etc.), avoiding sharp crack tip, avoiding low-temperature application below ductile-brittle transition temperature (DBTT).

- **Abrasion**

(1) Definition
It is defined as the loss of material due to hard particles or hard protuberances that are forced against and move along a solid surface.
(2) Example
Machine parts lose their original design functions due to excessive abrasion and large dimension deviations.
(3) The conditions/situation this failure might happen
Abrasive wear occurs when a hard and rough surface slides across a softer surface.
(4) Affecting factors
Hardness, applied stress level, the shape of asperity, the degree of wear by an asperity, wear coefficient, sliding distance.
(5) Common methods to improve abrasion
Enhancing hardness, decreasing the surface roughness, decreasing sliding distance, hard coatings.

3 failure behavior * 5 terms * 2 points

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Task 4. Simulation (25 points, Exercise3)

Build up the 2D CAE model according to the specimen geometry drawing in Figure 6. Run a plastic deformation simulation until 10% global engineering strain using the flow curve given in A3T4data.txt. Define the boundary conditions. Give the resulting von Mises stress and strain distribution patterns for the whole sample, including the legends. Extract and plot the reflection force–displacement curve. (Hints: Use the ¼ symmetry model. Use a mesh size as finer as possible with total nodes less than 1000. Show your definition of loading condition for the requested global engineering strain. Except for the final result patterns, you are welcome to give any necessary figures to show your simulation process.)

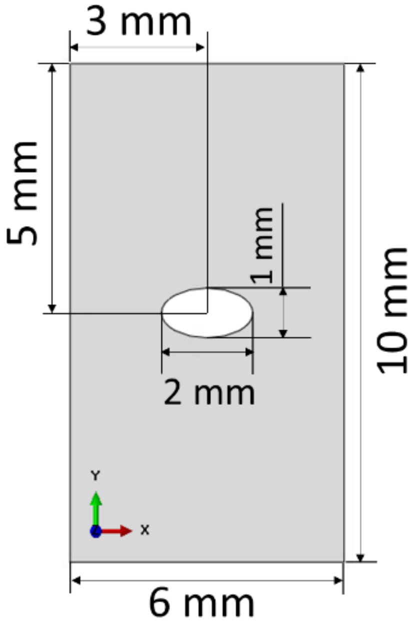

Figure 6 Specimen geometry drawing for Task 4.

Solution:

The displacement-controlled loading is used for this job. With the initial specimen length 10 mm, 10% pre-defined global engineering strain related to an elongation of 1 mm. Considering the ¼ symmetry model, ½ displacement (i.e. 0.5 mm) shall be applied at the top edge to achieve the tension along y direction in the model, as shown in Figure 7. The von Mises stress and strain pattern are shown in Figure 8. The shear band can be clearly seen in the von Mises strain pattern. The predicted force–displacement curve is shown in Figure 9 with the solid red line. The comparison to the flow curve used in Exercise 03 (solid blue line) is also attached. It can be seen that for a material with a higher strength but lower ductility, i.e. data from A3T4data.txt, the reaction force is increased, and uniform elongation is reduced.

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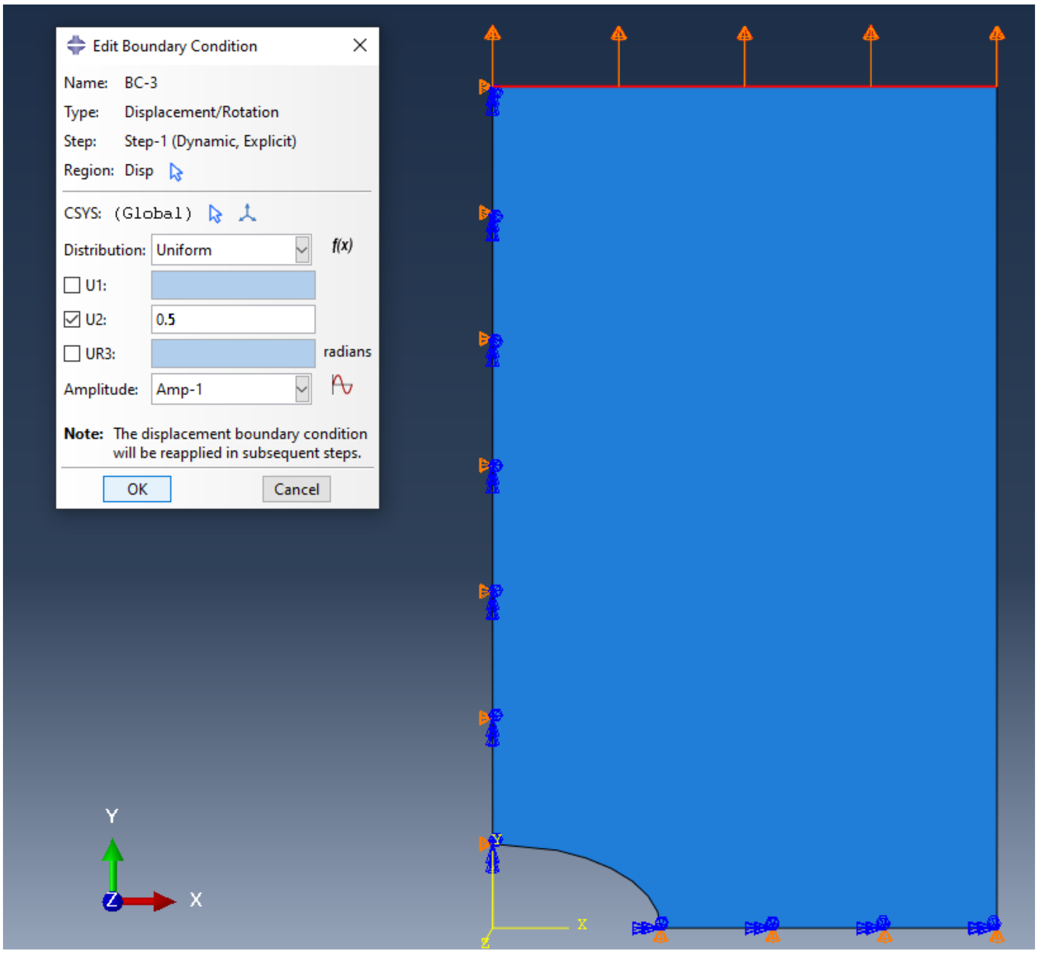

Figure 7 Boundary condition setting.

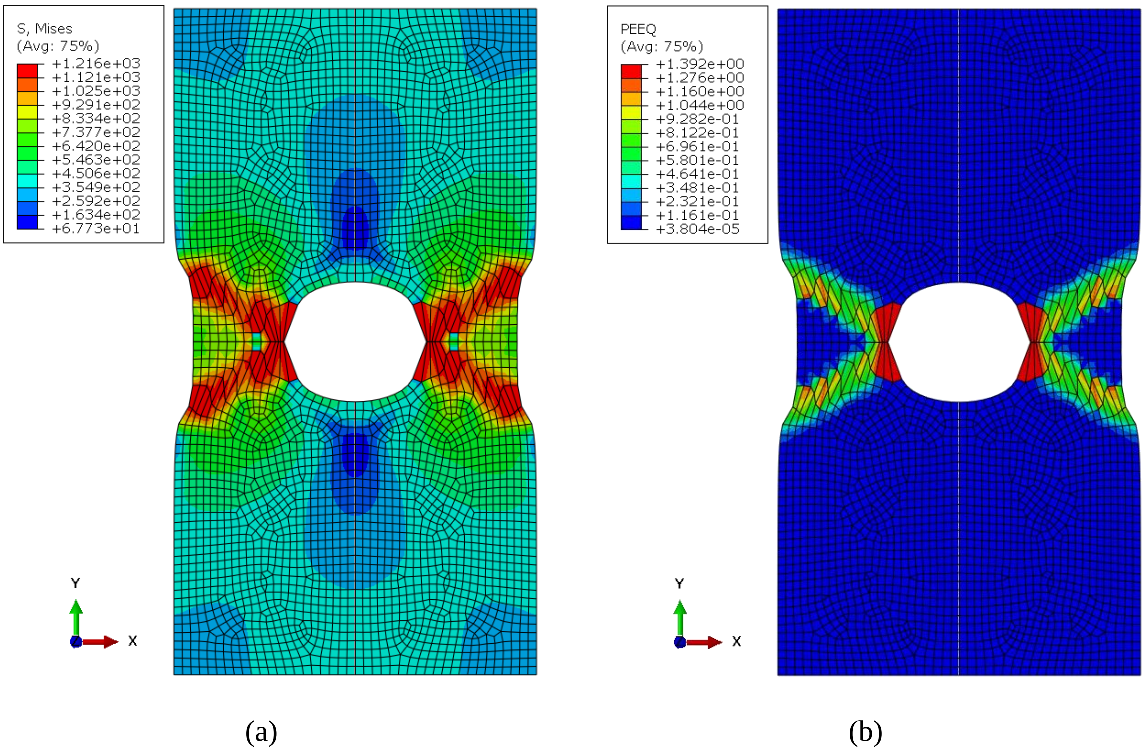

Figure 8 Predicted von Mises stress (a) and strain (b) pattern.

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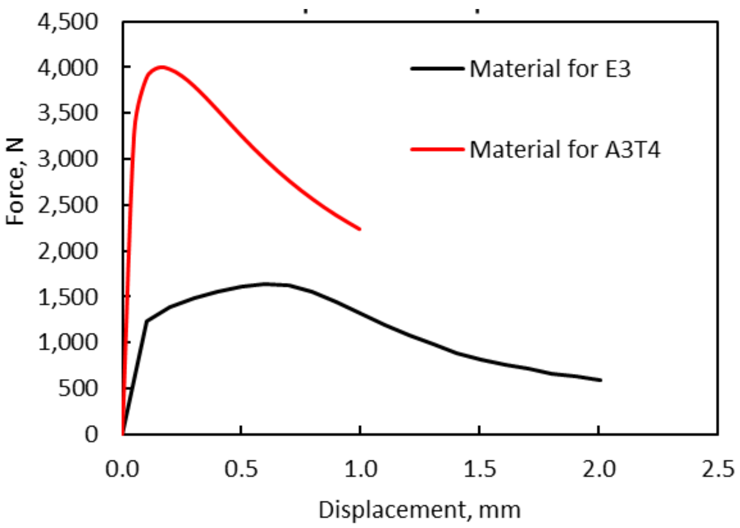
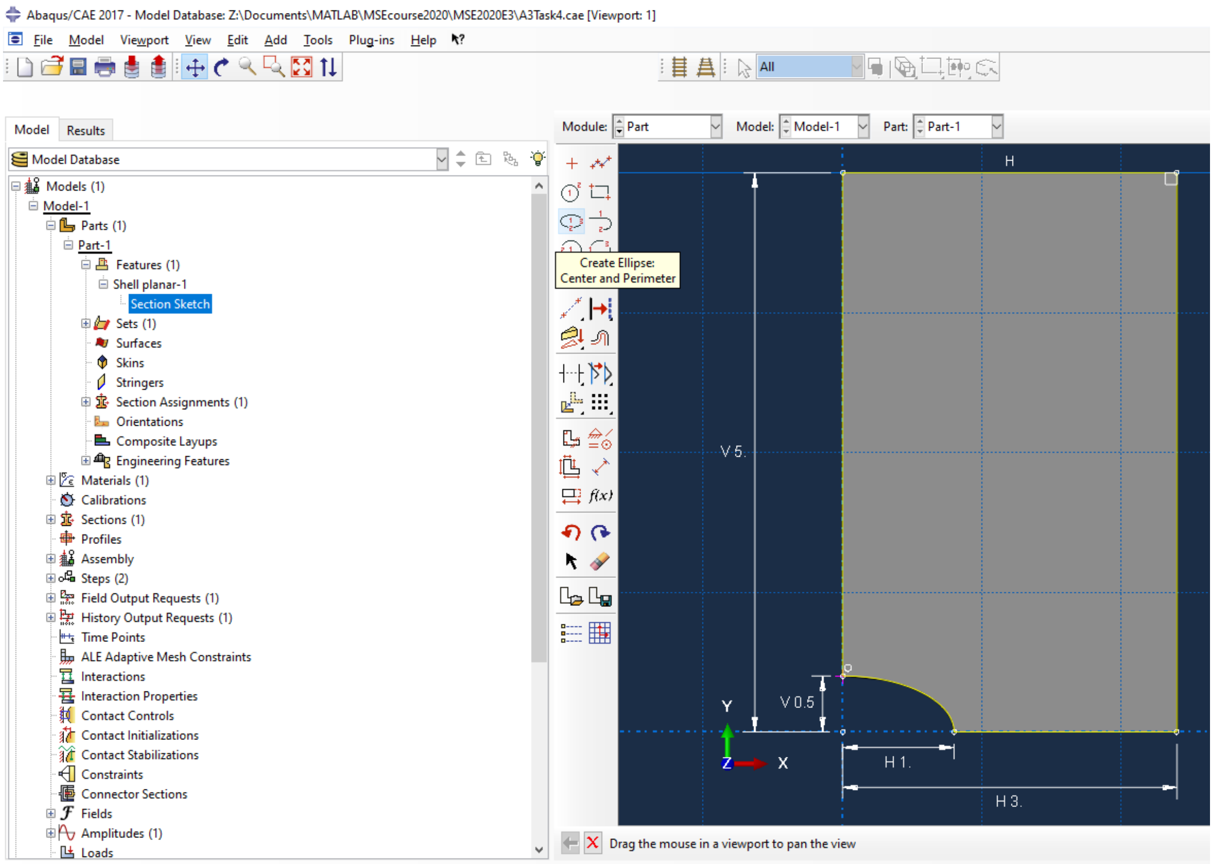


Figure 9 Predicted force–displacement curve.

Key steps in Abaqus:

Generally same to the Exercise 03 slides - "Abaqus - Elastoplastic analysis" part, here are three different settings:

1. Generate a 2D ¼ model according to dimensions in Figure 6.



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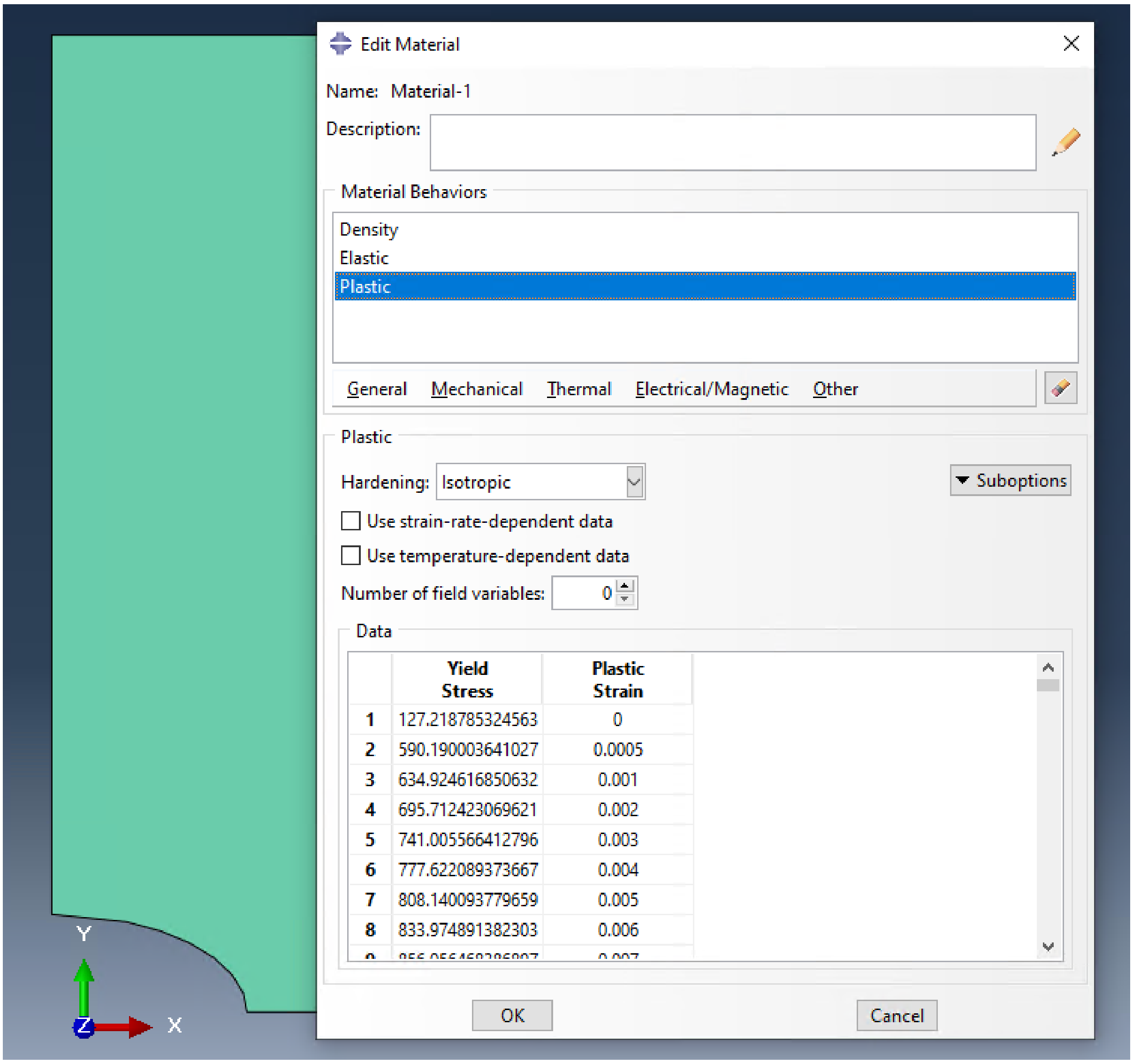
2. Assign the material hardening law according to the given flow curve (A3T4data.txt).



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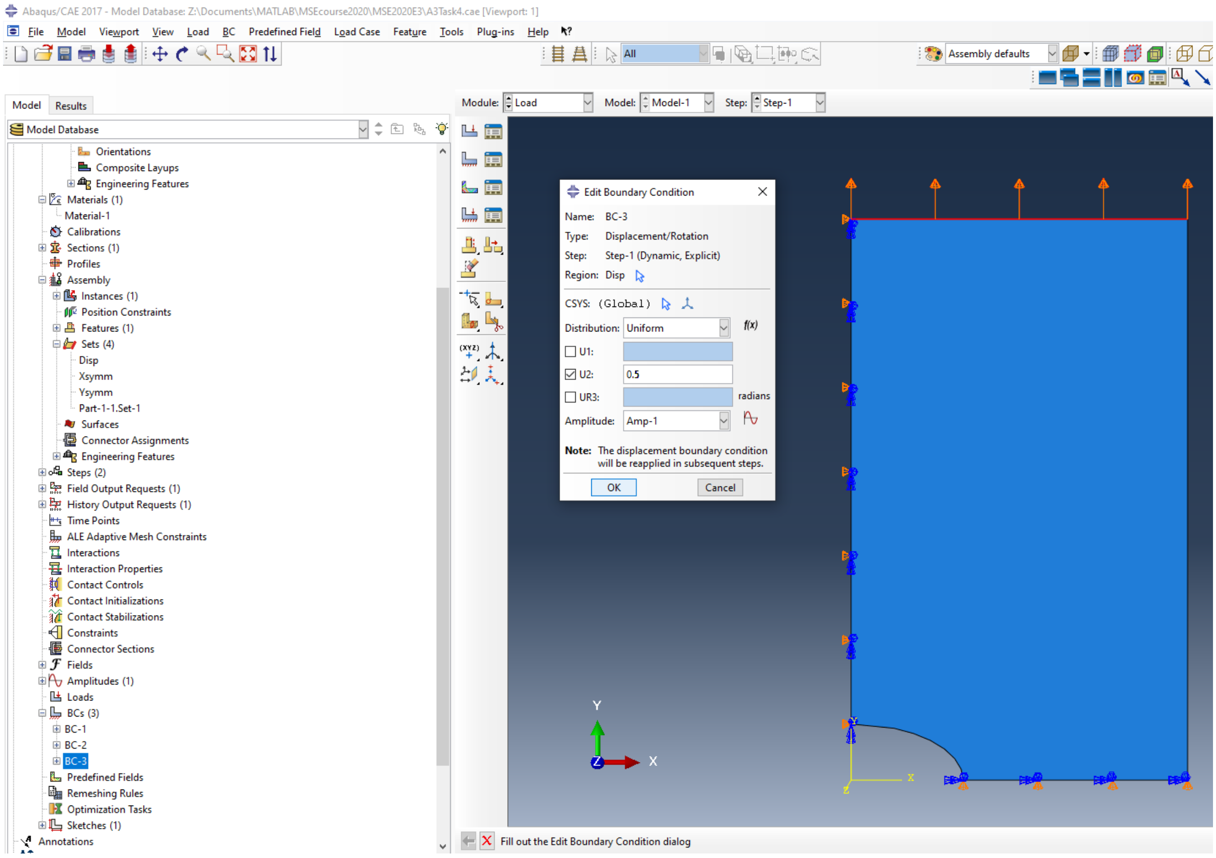
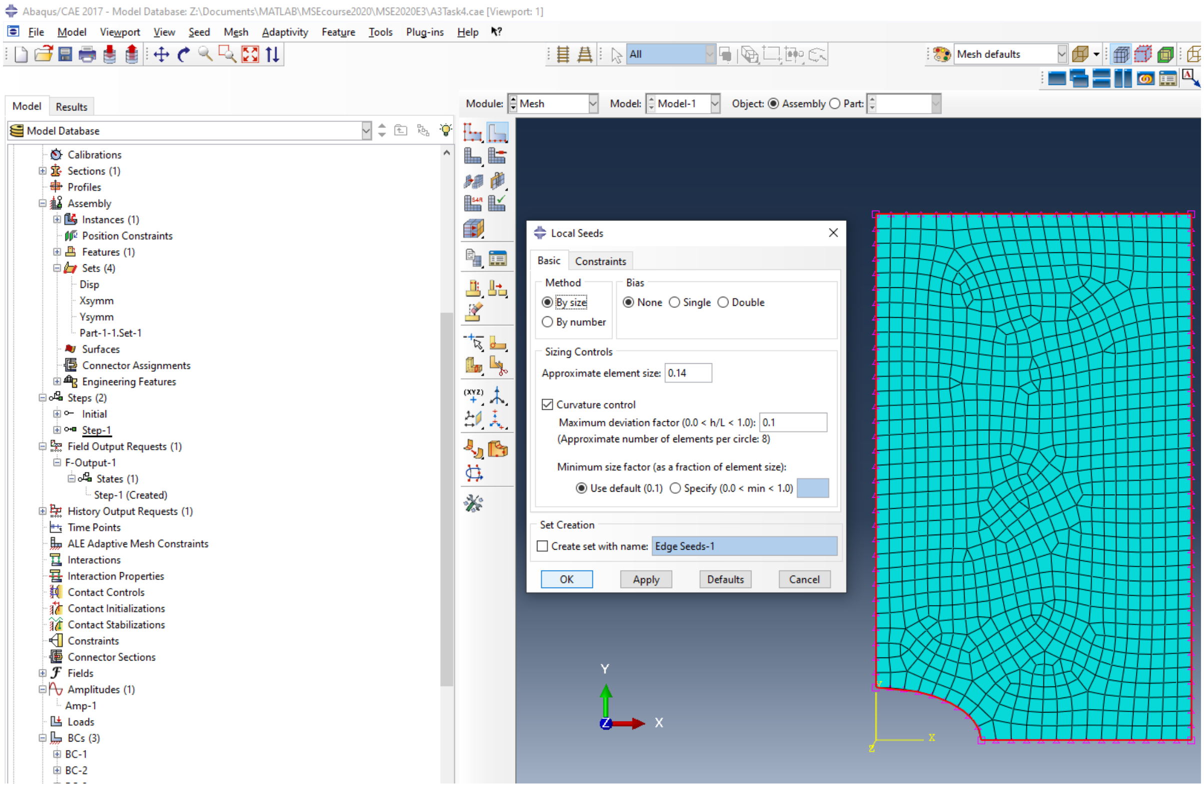
3. For BC-3, displacement-controlled loading, with the initial specimen length 10 mm, 10% global engineering strain related to an elongation of 1 mm. For half model along the y-direction, 0.5 mm is applied.



4. The mesh size is the same as the Exercise setting:



Any process figures to show actions on Abaqus modeling: 5 points
Boundary condition setting: 5 points
von Mises stress/strain patterns: 5+5 points
Predicted force–displacement curve: 5 points
-2 points if the wrong displacement is defined, -1 point if only 1/4 pattern is shown, -2 points if half/double/wrong force–displacement values are presented.

Task 5. Self-assessment (15 points)
Thank you for your feedback!

Reference

[1] W. Bleck, *Materials Science of Steel*, Department of Ferrous Metallurgy, RWTH Aachen University, 2013.
[2] W. D. Callister and D. G. Rethwisch, *Materials Science and Engineering: An Introduction, 8th Edition*, Wiley, 2009.

Due date: 18:00, 21.11.2021.
Contact: MyCourses 'General discussion' channel

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