3.1 THERMOMECHANICAL DAMAGE OF TUNGSTEN UNDER TRANSIENT PLASMA HEAT LOADS — T. Crosby and N. M. Ghoniem (University of California, Los Angeles)[1]

OBJECTIVE

The objective of this work is the development of a computational model to determine the relation between the thermo-mechanical loading conditions and the onset of damage and failure of tungsten surfaces.

SUMMARY

Tungsten is a primary candidate for plasma facing components (PFCs) in fusion energy systems because of its superior thermophysical properties. International efforts are focused on the development of tungsten surfaces that can intercept ionized atoms and high heat flux in the divertor region of magnetic fusion confinement devices. Designing a robust interface between thermonuclear plasma and the heat sink material in the divertor remains a major challenge to the success of future fusion power reactors. In this report, we present a multiphysics computational model to determine the extent of thermomechanical damage in tungsten under type-I edge localized modes (ELMs). The model is formulated in a finite element framework, and is based on a multiphysics approach that combines elastoplastic mechanical analysis and thermal heat conduction. The model is coupled with a reaction-diffusion model of material swelling and grain boundary degradation due to helium bubbles resulting from the plasma flux. Contact cohesive elements are used to model grain boundary sliding and fracture. The present results establish the connection between plastic deformation and the onset of material damage.

PROGRESS AND STATUS

Introduction

In nuclear fusion reactors, plasma facing components (PFC) (e.g. divertor) are subjected to high fluxes of energetic neutrons, hydrogen and helium ions. The impingement of these energetic atom fluxes leads to rapid and transient surface heating. Bombardment by helium isotopes leads to helium-induced damage accompanying micro-structural evolution, such as material swelling and the formation of blisters [1], dislocation loops and helium holes or bubbles [2]. Several recent experiments (see references [3] and [4]) have shown that the damage in the surface region and inside the material degrades the thermo-physical properties as well as the optical reflectivity of tungsten.

The divertor in fusion reactors are subjected to transient plasma events characterized with high thermal energy for a short time. One of these transient events is the Edge Localized Mode (ELM) which is a highly nonlinear magneto-hydrodynamic event and which is accompanied by a periodic expulsion of particles and high thermal energy (3-10% of the core thermal energy). ELM energies deposited at the divertor plates a substantial fraction of the total plasma energy content. Typical values for ELM energy

[1] Formatted from the original paper "**THERMOMECHANICAL DAMAGE OF TUNGSTEN UNDER PLASMA HEAT LOADS**", T.Crosby and N.M. Ghoniem, to be published in "Journal of ASTM International"

densities are 0.1-0.5 (MJ/m^2) for JET and 1-5 (MJ/m^2) for ITER. The duration of the ELM events are relatively short, 0.1-1 ms, causing material damage like melting, ejection of clusters and droplets and release of hydrogen isotopes. ELM events have also long-term effects such as degradation of thermo-physical properties due to cyclic heat loading [5], [6].

Experimental observations of cracks developing in tungsten subjected to transient heat loads exist in the literature, for example the results of experimental observations shown in Fig. 1, [7, 8].

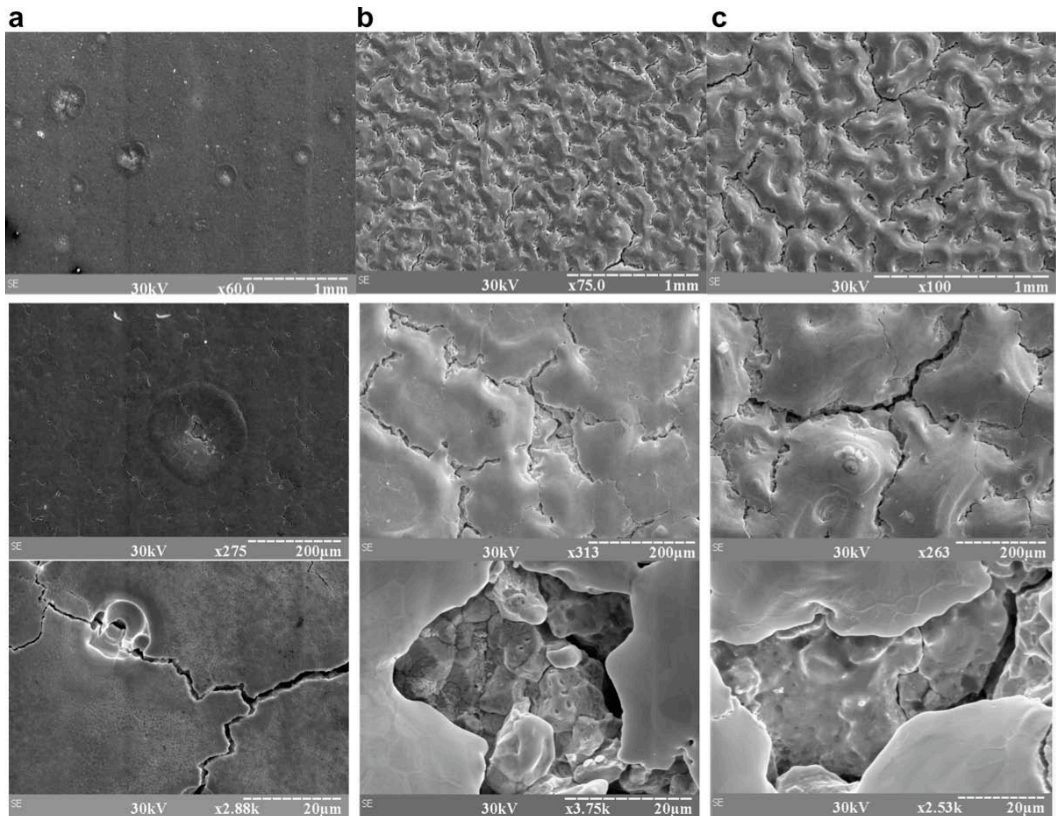

Figure 1. SEM images of the tungsten surface after 100 (a), 210 (b) and 350 (c) pulses (Q = 0.75 MJ/m^2) with different magnification [8].

Components (PFC) because it has good thermo-physical properties, a high melting point, a low sputtering rate, and a low tritium inventory [9]. Models that describe and study the change in tungsten structure and the damage that takes place as a result of its interaction with the plasma edge are critical in determining the limits for its operating conditions in environments with extreme heat flux. Recent experiments have shown that under helium and hydrogen ion bombardment conditions, some near-surface grains are ejected from the bulk to the surface region [10]. The main objective of this report is to develop a computational model for the development of thermo-mechanical damage in W under energetic ion bombardment conditions.

Coupled Thermal and Mechanical Models

In Tokomak-type plasma applications, such as in JET and ITER, the divertor is subjected to transient high heat loads that propagate inside the divertor material by heat conduction. This is described with the heat conduction equation given by:

$$\rho c_p \frac{\partial T}{\partial t} + \nabla\cdot(-k\nabla T) = Q - \rho c_p \mathbf{u}\cdot\nabla T \quad (1)$$

where Q is a heat source, and k is the thermal conductivity.

To simulate transient conditions of the plasma, the tungsten surface is subjected to a heat flux of the from:

$$-\mathbf{n}\cdot\mathbf{q} = q_o + h(T_\infty - T)$$

(2)

where q_o is the inward heat flux normal to the boundary and $\mathbf{q}$ is the total heat flux vector :

$$\mathbf{q} = -k\nabla T + \rho c_p \mathbf{u} T \quad (3)$$

In order to perform thermo-mechanical analysis, a boundary value problem (BVP) is formulated for an elastic material response. The BVP is constructed by substituting the constitutive equation for linear elasticity:

$$\sigma_{ij} = C_{ijkl}\epsilon^e_{kl} \quad (4)$$

into the strong form of the equilibrium equation:

$$\sigma_{ij,j} + f_i = 0 \quad (5)$$

The total strain is the sum of elastic, plastic and thermal strains, i.e.:

$$\epsilon_{ij} = \epsilon^e_{ij} + \epsilon^p_{ij} + \epsilon^\theta_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i}\right) \quad (6)$$

where σ is the symmetric stress tensor and f is body force, ϵ^e is the elastic strain tensor, and ϵ^θ is the strain tensor due to thermal expansion.

$$\begin{cases} \sigma_{ij}n_j = t_i \text{ on } \partial\beta_t \\ u_i = \bar{u}_i \text{ on } \partial\beta_u \end{cases} \quad s.t. \quad \partial\beta_u \cup \partial\beta_t = \beta, \qquad \partial\beta_u \cap \partial\beta_t = \varnothing \quad (7)$$

Damage Crack Formation Model

Grain boundary sliding and motion result in stress concentrations along grain boundaries, which are generally weak regions in the material susceptible to crack initiation and propagation. We consider here a crack equilibrium model to describe crack damage formation along weak grain boundaries. From force equilibrium on the crack faces and using a stress equation for the field similar to that of a dislocation, an expression for the equilibrium crack length is found to be [12]:

$$2L = \frac{F^2(1-\nu^2)}{\pi\mu E} \tag{8}$$

As a simple constitutive damage model, we take the grain boundary thermally induced forces in the crack surface to be simply proportional to the internal strain at the grain boundary during the transient:

$$F = \nabla\cdot(\mathbf{C}:(\varepsilon^{F}+\varepsilon^{\theta})) \tag{9}$$

The thermal force exhibits spatial and time dependence, as a result of the spatial dependence and time dependence of the temperature field and locality of grain boundaries.

COMPUTATIONAL MODEL

A multiphysics computational model has been developed within a finite element framework in order to investigate the synergistic effects of transient high heat loads and helium ion irradiation. The implementation of the model utilizes the capabilities of the COMSOL multiphysics platform in which a transient heat conduction analysis, coupled with a large deformation quasi-static elastic structural mechanics analysis with contact elements along the grain boundaries were solved in a segregated fashion. The simulated model is a 10 mm x 10 mm, two-dimensional block, which was divided into a random distribution of grains using an algorithm based on the Voronoi diagram as shown in Fig. 2.

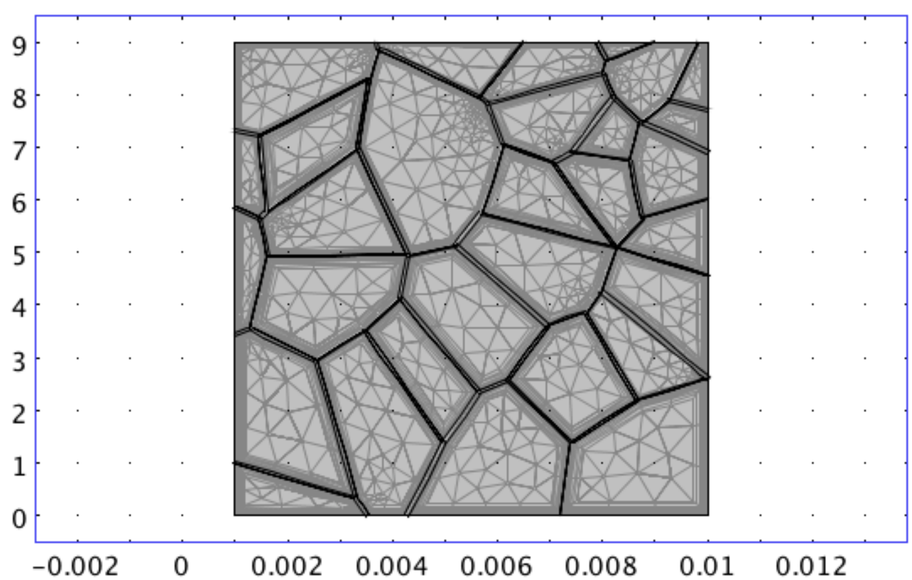

Figure 2. Initial configuration of the random distribution of grains with boundary layer mesh [mm].

The grain boundaries were replaced with cohesive contact elements to better simulate sliding and opening between the grains, as a result of He bubble formation along grain boundaries causing the grains to open up and form micro-cracks. A boundary layer mesh was utilized along the grain boundaries, as can be seen in the figure.

Thermal boundary condition were prescribed as an inward heat flux, q_o, on the left side. The heat flux pulse was taken to be 10 x 10^3, 2 x 10^3, 1 x 10^3 (MW/m^2), for the duration of 0.1,0.5 and 1 ms, respectively, as shown schematically in Fig [3]. These heat flux profiles are similar to conditions expected in ITER during ELM transient heat loads. A convective heat flux boundary condition was applied on the other side of the W plate, representing helium cooling. The mechanical boundary conditions were taken as free surface on the left side, while the right side was fixed. Periodic boundary condition for both the displacement and the temperature field were used on the top and bottom boundaries of the model. The simulation duration was taken to be 0.1 s, with time steps of 0.1 ms using a segregated solver that combines transient thermal analysis with the quasi-static mechanical analysis.

RESULTS

The high heat flux applied to the surface of tungsten cause the temperature on the surface of the material and inside it to increase causing thermal expansion and contraction during the thermal transient, forcing the grains to slide relative to each other. This relative motion between the grains leads to their separation between them, forming inter-granular micro-cracks. The cracks propagate inside the material forming networks of cracks of different resolutions, which can be categorized into primary (relatively larger) cracks, and secondary (relatively smaller) cracks. Typical results at the end of the simulation that show the onset of cracks of different sizes are shown in Figs. 4, 5, and 6, as well as contour plot for the plastic strain in Figs. 7, 8, and 9.

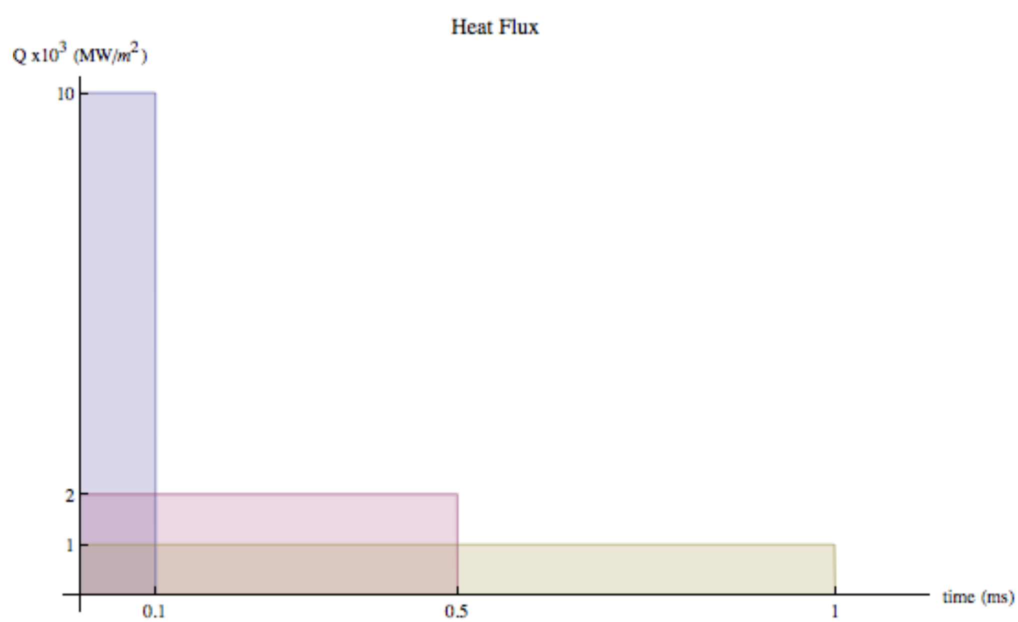

Figure 3. Incident heat flux profile: values of the heat flux (MW/m^2) vs. duration of application (ms) for the three cases considered.

It's noted that the temperature rises to very high values exceeding the melting point for the case when the heat flux is 1 $x10^4$ (MW/m^2). Our model doesn't directly address the ensuing evaporation of W from the surface in such severe conditions, as experimentally observed, for example in references [11] and [12]. The temperature of the surface at the end of the simulation is shown in Fig [10].

We note the difference in the distribution and in the size of cracks for the different applied heat fluxes. Thus, we see from the results that the cracks have larger sizes for the case when the heat flux is 1 $x10^4$ (MW/m^2), but they closer to the surface, while for the case when the heat flux is 1 $x10^3$ (MW/m^2), the cracks are smaller in size and formed at deeper distances from the surface of tungsten. This is due to the difference in transient heat transport for the different heat fluxes profiles.

Another aspect of the tungsten surface damage is grain ejection, which has been experimentally observed in tungsten subjected to He irradiation [10]. When the W surface is subjected to He and D^+ bombardment at high temperature, helium and vacancies diffuse to the grain boundaries forming grain boundary bubbles. When the surface is subsequently subjected to a transient heat load, He bubbles grow and expand rapidly along grain boundaries, causing substantial pressure on grain faces. When the pressure exceed a critical value greater than the cohesive forces on grain boundaries, causing the grains to completely separate resulting in the phenomenon called grain ejection.

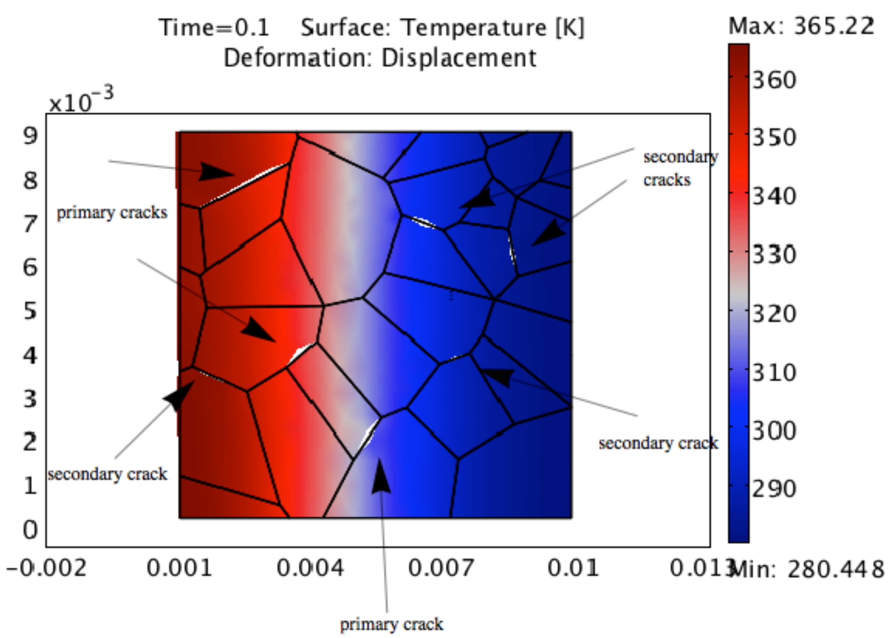

Figure 4. Temperature and damage distribution in [K] and tungsten grain boundary damage due to differential thermal expansion/contraction and crack formation when subjected to Q = $1x10^3$ (MW/m^2).

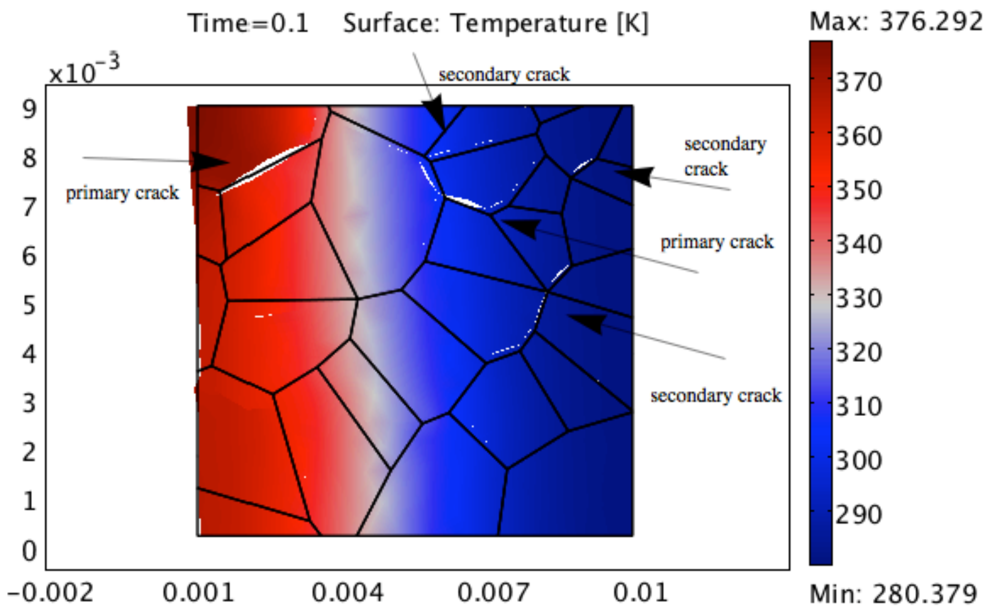

Figure 5. Temperature and damage distribution in [K] and tungsten grain boundary damage due to differential thermal expansion/contraction and crack formation when subjected to Q = 2x10^3 (MW/m^2).

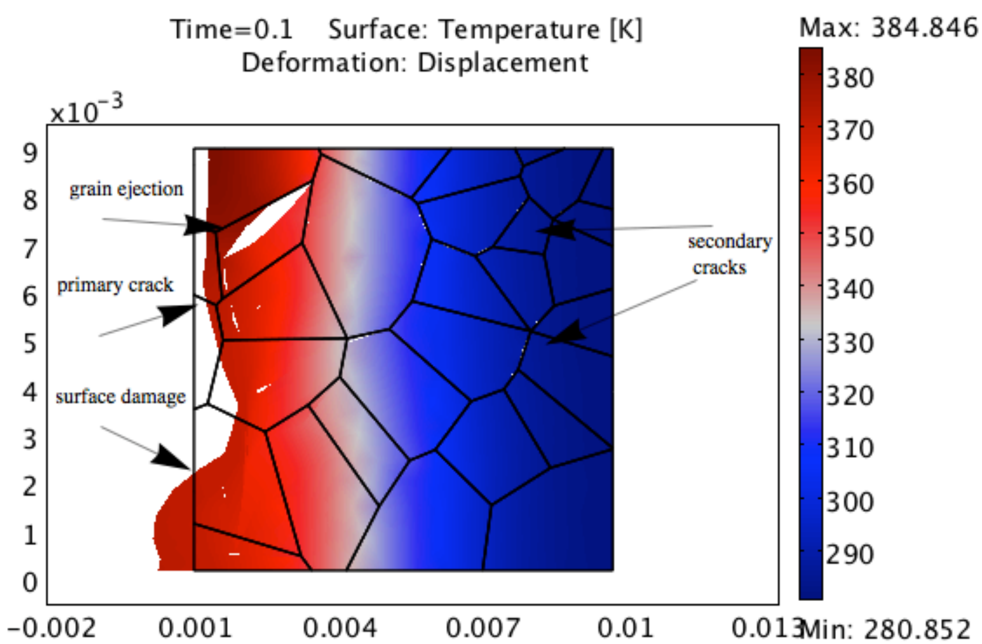

Figure 6. Temperature and damage distribution in [K] and tungsten grain boundary damage due to differential thermal expansion/contraction and crack formation when subjected to Q = 10x10^3 (MW/m^2).

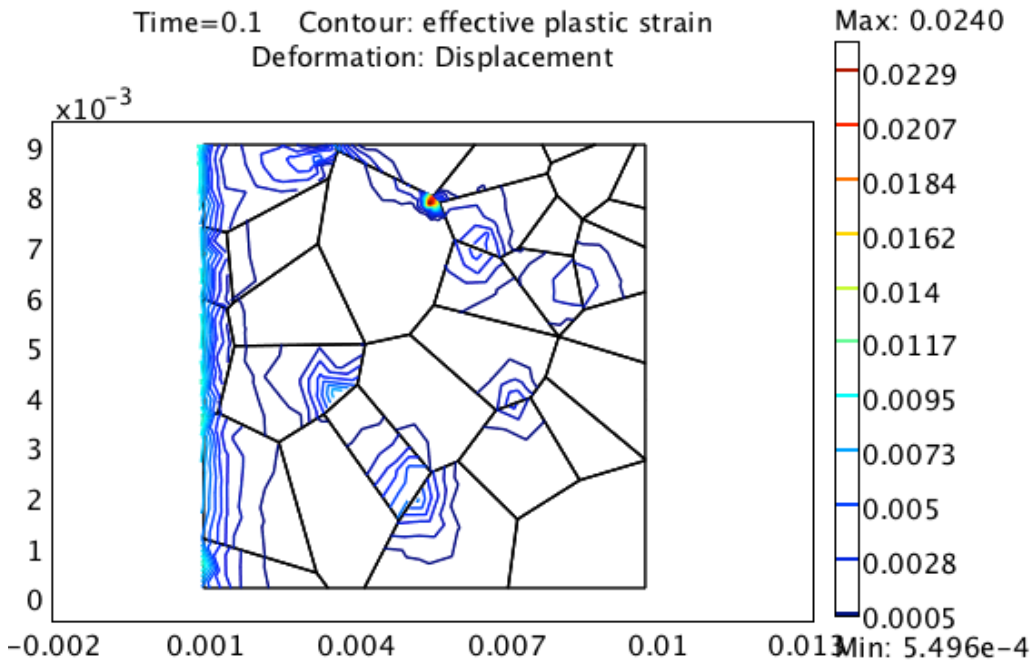

Figure 7. Contour plots of the effective plastic strain (Dimensionless) Q = 1x10^{3} (MW/m^{2}).

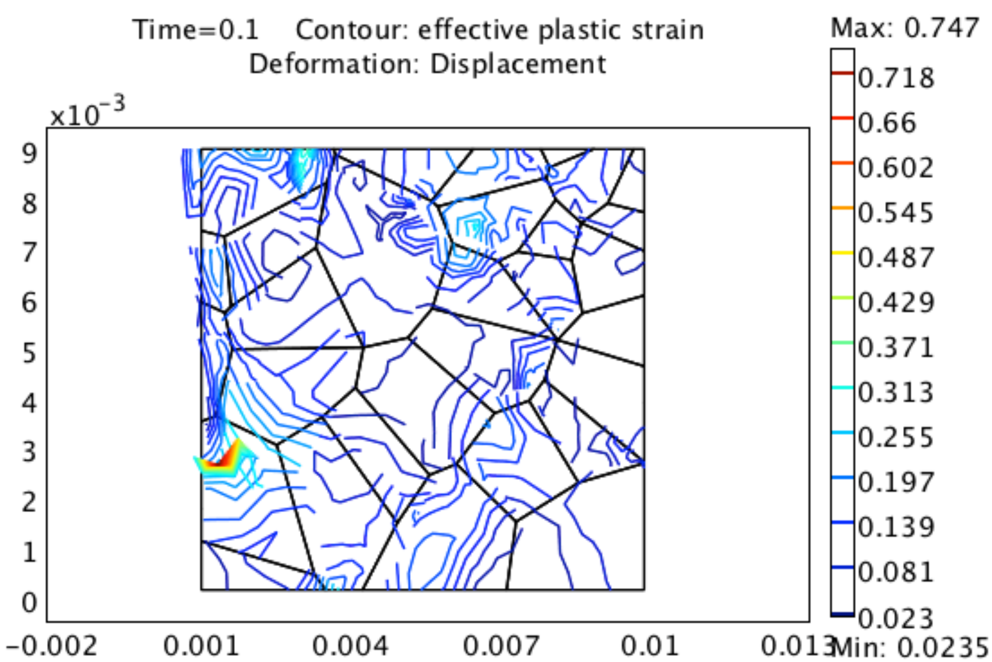

Figure 8. Contour plots of the effective plastic strain (Dimensionless) Q = 2x10^{3} (MW/m^{2}).

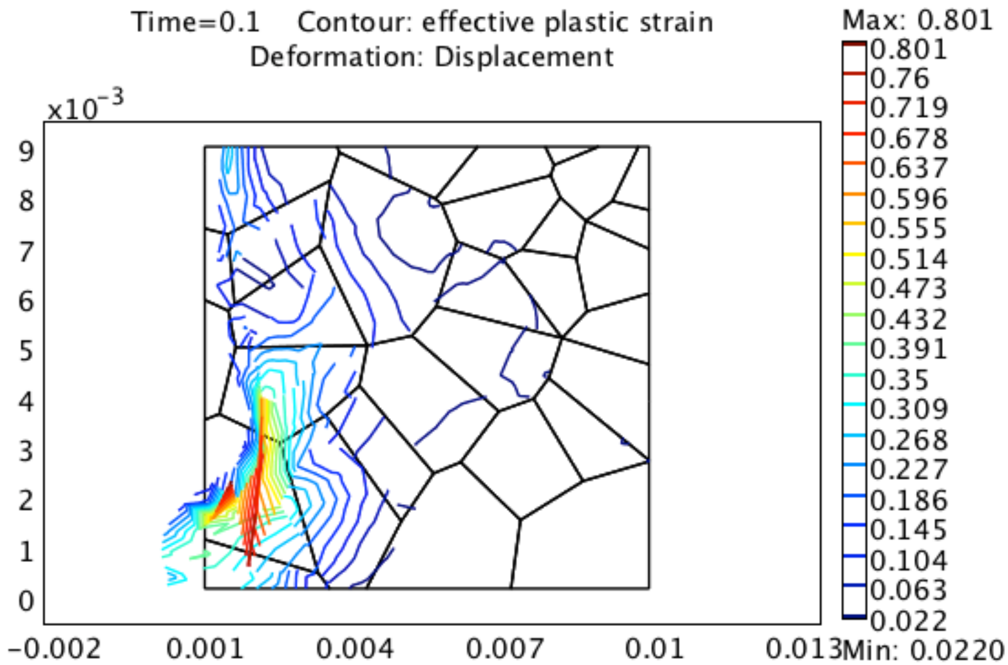

Figure 9. Contour plots of the effective plastic strain (Dimensionless) Q = $10x10^3$ (MW/m^2).