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Application of the Continuum damage mechanics model in the three point bending test of Ti-6Al-4V titanium alloy specimens

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Abstract. One of the most important and challenging activities in the simulation of the mechanical behaviour of materials is the prediction of the failure phenomena. If well calibrated, damage models can simulate and predict the failure of materials in a generalized way allowing the replication of not only the calibration tests themselves but also of different loading cases. Generally damage models can be categorized into three different groups including phenomenological models, porosity models and continuum damage mechanics (CDM) models. Different CDM models have been proposed by researchers and these models have been applied in diverse loading conditions, geometries and materials. However the limitations and advantages of the CDM models are still not completely explored in the application areas. In this paper, a CDM model, (previously calibrated with round smooth specimen) has been applied in a three-point bending test model in order to simulate the correlated experiment. Specifically, the CDM framework has been applied in a finite element model and the obtained results have been compared with the experimental data. The tested material is Ti-6Al-4V titanium alloy, which is a widely used material in the aerospace industry because of its high strength and low density. Load-displacement data in the experiments and numerical simulations are the main results, which have been compared. Therefore, the ability of the CDM model to simulate the three point bending test has been investigated and the results are discussed.

1 INTRODUCTION

Failure phenomena are of great importance in the design process and intense research has been carried out in the field of damage. A high number of damage models have been proposed based on different concepts. However, neither of these models is comprehensive enough to be used in all of the loading conditions and for all materials. Generally each model has its advantages and limitations. Therefore in order to use a proper model for each case, comprehensive knowledge about the abilities of the models is necessary and each model has to be tested in the different loading conditions and on the different materials. Continuum damage mechanics (CDM) models are considered as one of the main categories of damage models. In 1985 Lemaitre [1] proposed the first CDM model and different CDM models have been proposed since that time [2, 3, 4 etc.]. Lemaitre's model was initially proposed for ductile damage, this application of the CDM model has however been extended over the decades. Yang et al [5], A.Pires et al [6] and Bonora et al.[7] have proposed some models for cyclic loadings and compressive loads. The application of the CDM models in creep has raised a lot of interest and some CDM models have been proposed for creep [8, 9, 10]. Further models consider the anisotropic distribution for damage which in the initial model of Lemaitre has been considered as an isotropic variable [11, 12, 13].

The calibration of the CDM models is the first step in the application process. Model parameters have to be obtained for each material and these parameters are supposed to be identical for all geometries and loading conditions. It has, however been shown that there is not a complete geometry transferability in the damage models and that each model predicts some cases well but fails to predict other cases [14, 15, 16, 17]. It is therefore necessary to have a comprehensive understanding of the geometry transferability of each damage model. In order to check geometry transferability of damage models they should be investigated in different loading conditions. Stress triaxiality as one of the most important parameters which affects the damage models behaviour can be considered as an indicator of the loading condition. Therefore, damage models have to be investigated in different stress triaxiality regions. The three point bending test of a notched specimen is an interesting case for the application of the damage models. The stress triaxiality is generally very high in the notch and the stress state differs from the normal tensile tests. In fact the estimation of the failure point in the notched specimens is complex due to the presence of high triaxiality and high gradient stress. Mashayekhi et al. [18] have studied the application of the Lemaitre's model on the three point bending test of A533-Bl alloy steel. Pourmodheji et al. [19] have further combined the CDM model with XFEM theory and have analysed the prediction of the crack growth in the three point bending test. Xue and Wierzbicki [20] have also applied their new model in the three point bending test of the 2024-T351 aluminium alloy with some good results. Although some research has considered the application of the damage models in the three point bending test, more comprehensive studies are needed to investigate the damage models in this loading condition, especially for those materials which have not been tested yet. In this research, Lemaitre's damage model has been applied in the three point bending test of Ti-6Al-4V titanium alloy which is an important material for the aerospace industry. Ti–6Al–4V is a multiphase alloy considered as the 'workhorse' of the titanium industry. This material has been previously investigated [21, 17, 22, 23] but the aim of this research is specifically to verify the modelling behaviour in the CDM framework when subjected to high gradient stress.

2 LEMAITRE'S CDM MODEL

Damage is a thermodynamic state variable which characterizes the deterioration of the material. During the evolution of damage, the number and size of the voids and microstructural defects within the material increases. As a matter of fact, the load bearing capacity of the material decreases with the progression of the damage. Generally, by considering a reference volume element at a given point, the damage variable can be defined by equation 1:

$$D_n = 1 - \frac{A_{ef}^n}{A_0^n} \quad (1)$$

Here D_n is the damage variable in the direction of the normal vector n of the plane which intersects the reference volume, A_0^n is the nominal intersection area of the plane and the reference volume before damage and A_{ef}^n is the effective resisting area of the intersection plane which is reduced because of the damage.
Lemaitre's model assumes that the distribution of damage in the material is isotropic. Therefore, the value of the damage in all directions is the same and can be shown by the scalar factor D instead of D_n. In most of the applications this is an acceptable assumption. It is also supposed that the value of the strain in the damaged material is equal to the value of the strain in the undamaged material with the stress value, known as the effective stress, defined by the following equation:

$$\sigma_{eff} = \frac{\sigma}{1-D} \quad (2)$$

Where σ_{eff} is the effective stress and σ is the stress value in the damaged material.
It can be proven that there is a relationship between the damage dissipation energy and the damage evolution:

$$D^{\cdot} = -\lambda \frac{\partial F_D}{\partial Y} \quad (3)$$

According to the definitions above, the damage evolution equation can be derived for Lemaitre's model:

$$\dot{D} = \dot{\gamma} \frac{1}{1-D} \left(\frac{-Y}{r}\right)^S \quad , \quad Y = \frac{-q^2}{6G(1-D)^2} - \frac{P^2}{2K(1-D)^2} \quad (4)$$

Where D is the damage parameter, γ is the plastic multiplier, Y is the damage energy release rate and q, G, K, P are respectively von Mises equivalent stress, shear modulus, bulk modulus and hydrostatic stress. It is therefore necessary to solve a set of equations which include the damage evolution and the plasticity equations in order to apply the CDM models.

3 EXPERIMENTAL TEST

A three point bending experimental test has been performed on the Ti-6AL-4V titanium alloy notched specimen. Figure 1 shows the geometry of the tested specimen. The configuration of the test has been shown in the figure 2. The testing machine is a mono-axial hydraulic machine and a laser sensor (MEL Mikroelektronik GMBH, M5L/20, range 20mm) is used to measure the displacements of the pusher.

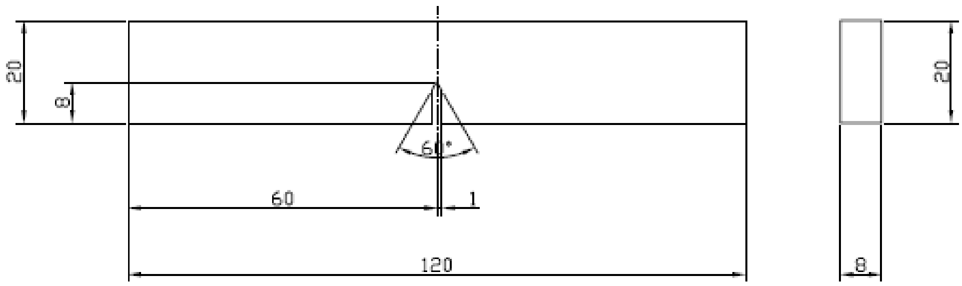


Figure1: Geometry of the specimen.

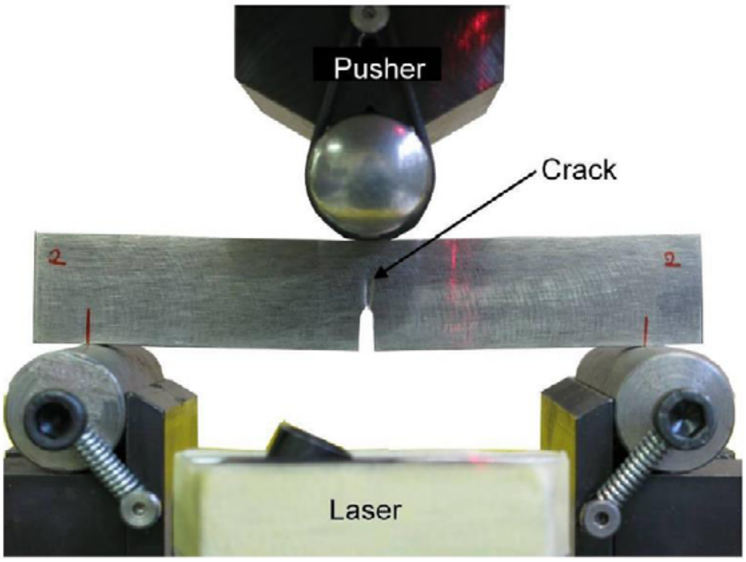


Figure 2: Test configuration.

4 FINITE ELEMENT MODEL

A three dimensional finite element model of the specimen and the experimental test configuration has been made in Ls-Dyna commercial software. C3D8R elements have been used in the simulations. In the presence of high stress triaxialities, due to a sudden change of the stress field generally the numerical results of the FE simulations are very sensitive to the element size. Giglio et al.[21] has shown that for Ti-6Al-4V titanium alloy, the results of the finite element simulation using Bao-wierzbicki's damage model is so sensitive to the element size. In order to investigate the sensitivity of the CDM model to the mesh size three different mesh sizes with an approximate length of 0.2, 0.1 and 0.075 mm in the critical region have been used in the FE models. Figure 3 shows the finite element model.

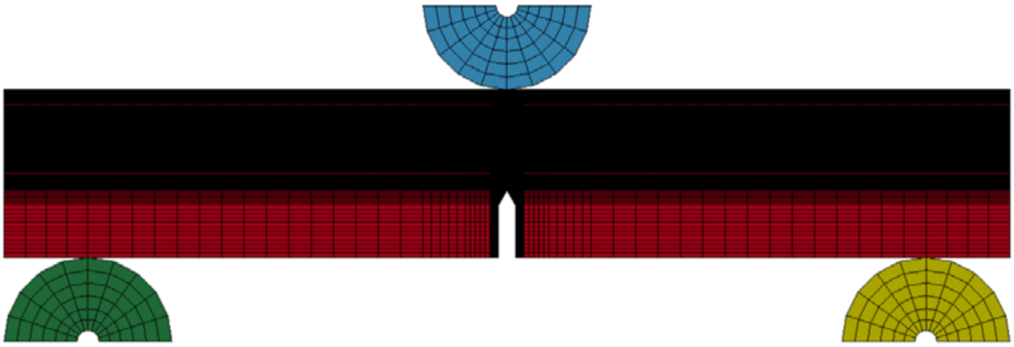


Figure 3: Finite element model of the test configuration.

5 RESULTS AND DISCUSSION

The authors have recently calibrated the model parameters for Ti-6AL-4V titanium alloy [17] according to experimental results of the round smooth specimen and have shown that these parameters has a good geometry transferability when applied on flat notched specimens. A plasticity model with five parameters also has been calibrated. Equation 5 shows the general form of the calibrated plasticity model. The plasticity and damage model parameters are shown in table1.

$$\sigma = \sigma_0 + Q_1\left(1 - \exp\left(-C_1\varepsilon_p\right)\right) + Q_2\left(1 - \exp\left(-C_2\varepsilon_p\right)\right) \tag{5}$$

The stress gradient near the notch in the three point bending test is remarkable and is therefore a point of interest to check the ability of the calibrated model in this case. The calibrated model parameters have been used in the finite element models with different mesh sizes. Generally the load-displacement behaviour of the specimen under the test has been used as the main investigator of the models predictions and has been compared with the experimental data. Figure 4 shows the load displacement data obtained from the experimental test and the numerical simulations. As mentioned above three different mesh sizes have been used in the finite element models. Figure 4 shows the high mesh sensitivity in the results. Decreasing the mesh size significantly affects the failure displacement and decreases its value.

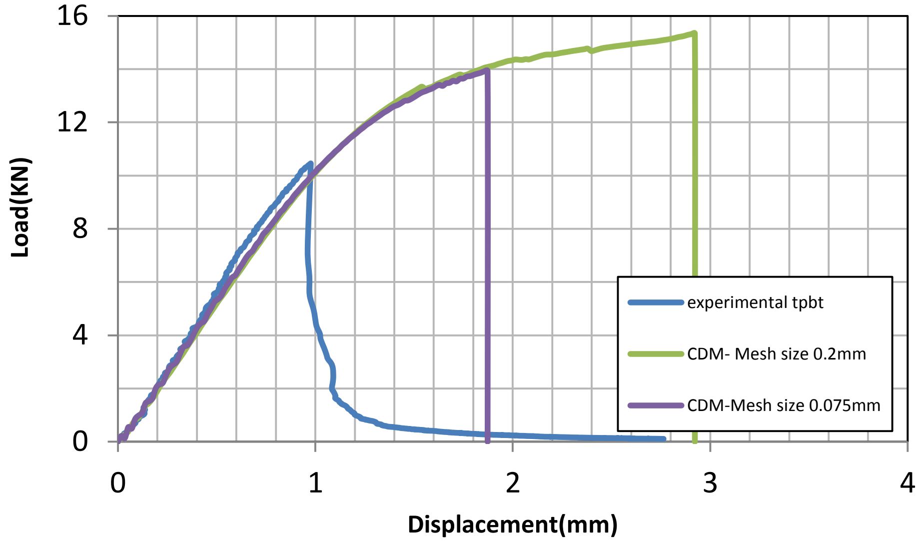


Figure4: Experimental and numerical load displacement data. First series model parameters.

The calibrated model fails to exhibit good geometry transferability. Although the predicted failure point for the finite element model with a 0.075mm mesh size is closer to the experimental data than with a 0.2mm mesh size element model, there is still a sufficiently high difference between the numerical and experimental failure displacements. Therefore a new series of damage model parameters has been chosen and another series of finite element simulations has been performed with these new model parameters. Table 1 shows the old and new damage model parameter values. Changing the threshold strain (ε_{th}) strongly affect the behaviour of the Lemaitre's damage model. Physically, ε_{th} indicates the value of the strain at which damage starts. In the first series of the damage model parameters the value of the ε_{th} is 0.35, which is high for the three point bending test. Generally the value of the failure strain decreases whit the increment of the triaxiality. Therefore the value of 0.35 for the threshold strain means that the failure stain will be greater than 0.35 which according to the existence of the high triaxiality in the notch tip is not very exact. According to this fact, the value of the threshold strain has been reduced in the new model parameters, to 0.1. The value of the parameter S has also been reduced according to the reduction of the ε_{th}. The aim of the application of the second series of the model parameters is to show that with appropriate model parameters Lemaitre's model is able to better predict the failure point in the three point bending test. The experimental and numerical load-displacement results obtained with new damage model parameters are shown in figure 5. The numerical results are closer to the experimental values with the new series of the model parameters. Therefore, even though Lemaitre's model fails to include geometry transferability from smooth specimen to the three point bending test Lemaitre's model is still able to predict the failure point in the three point bending test with a new calibration for the material parameters. Each calibration is valid for some loading conditions and when the loading conditions are very different from the initial case which has been used for the calibration, new calibrations are necessary.

Table 1: Material model parameters.

Plasticity parameters					Damage model parameters					
					Old calibration			New values		
$\sigma_0(MPa)$	$Q_1(Mpa)$	C_1	$Q_2(MPa)$	C_2	ε_{th}	$S(MPa)$	D_{cr}	ε_{th}	$S(MPa)$	D_{cr}
912.712	499.715	3.627	103.215	146.212	0.35	25	0.1356	0.1	7.5	0.1356

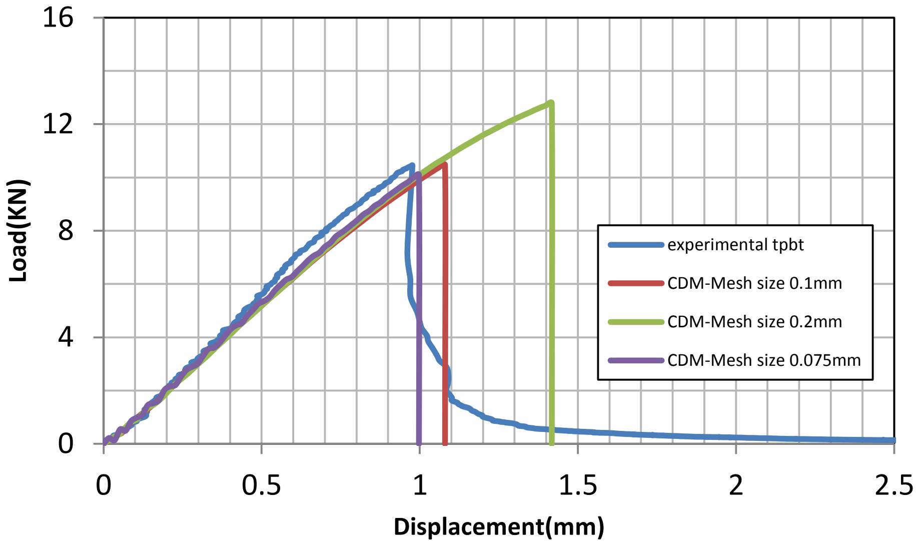


Figure5: experimental and numerical load-displacement data- Second series model parameters.

Also with the new series of the damage model parameters the results are significantly affected by the mesh size. The failure displacement of the 0.2mm mesh size still has 50% difference with the experimental data. However, the 0.1mm and 0.075 mesh sizes gives acceptable results. Figures 6 and 7 show respectively the accumulative equivalent plastic strain (PEEQ) and the triaxiality evolution with the displacement in the models with different mesh sizes. The values of the PEEQ and the triaxiality have been obtained from the critical elements in the model (the element which fracture starts from) and the value of the displacement represents the total displacement.

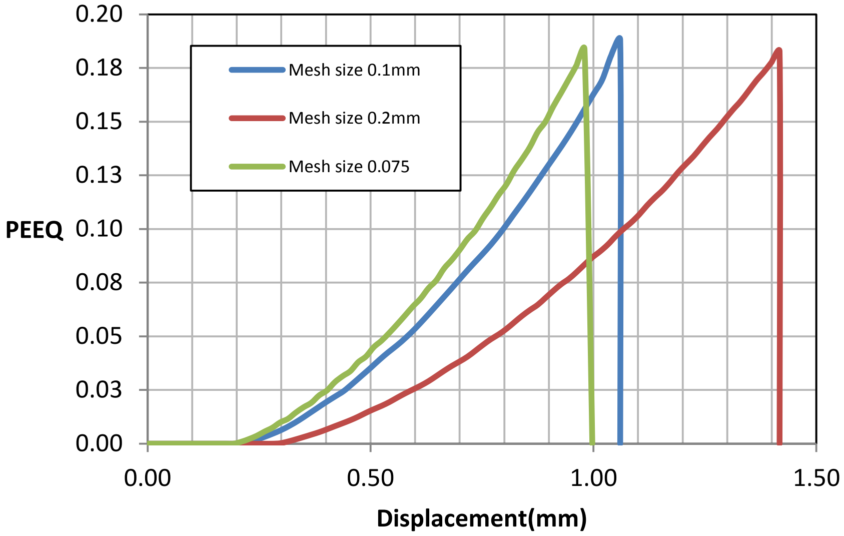


Figure 6: PEEQ-displacement evolution in the finite element models with different mesh sizes.

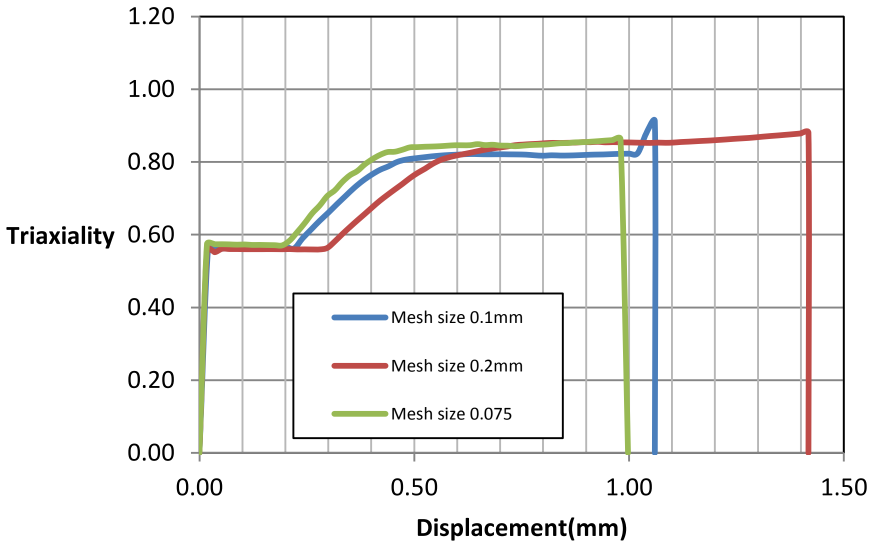


Figure7: Triaxiality-displacement evolution in the finite element models with different mesh sizes.

Figures 6 and 7 clearly show the general trend of the evolution of PEEQ and triaxiality are identical. However, with an increase of the mesh size, at a constant displacement, the model with the smaller mesh size predicts higher values for the PEEQ and the triaxiality, which explains the earlier occurrence of the failure in the models with a smaller mesh size. In fact, there is a delay in the results of the models with bigger element size with respect to the models with smaller elements. Due to the high stress state fields in the small areas around the notch tip and the sudden changes of the stress value, bigger elements are unable to simulate these situations as well as smaller elements. Figure 8 shows the PEEQ-Stress triaxiality curve obtained from the critical element in the models with the different element size. In this case there is no significant effect of the mesh size. The comparison of figures 6 and 7 with figure 8 shows that to obtain the same value for the triaxiality and PEEQ in the model with the bigger element size, higher values for the load (displacement) are needed. However, the trend of the triaxiality and PEEQ is the same.

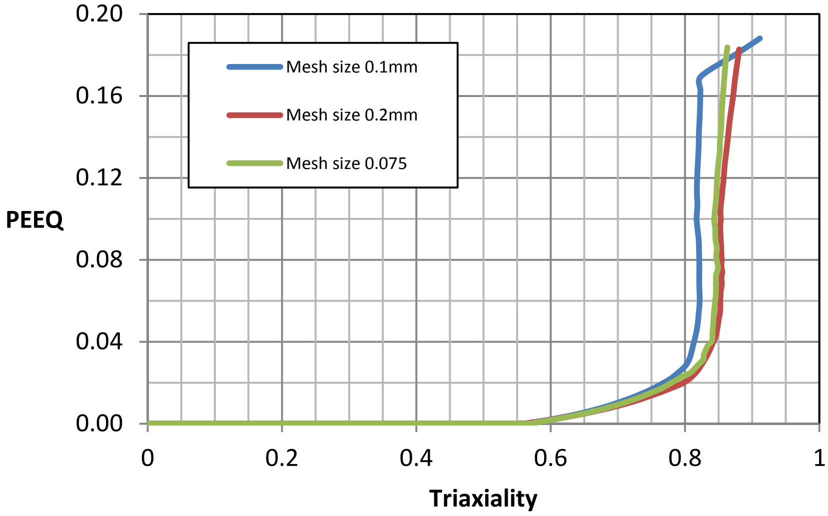
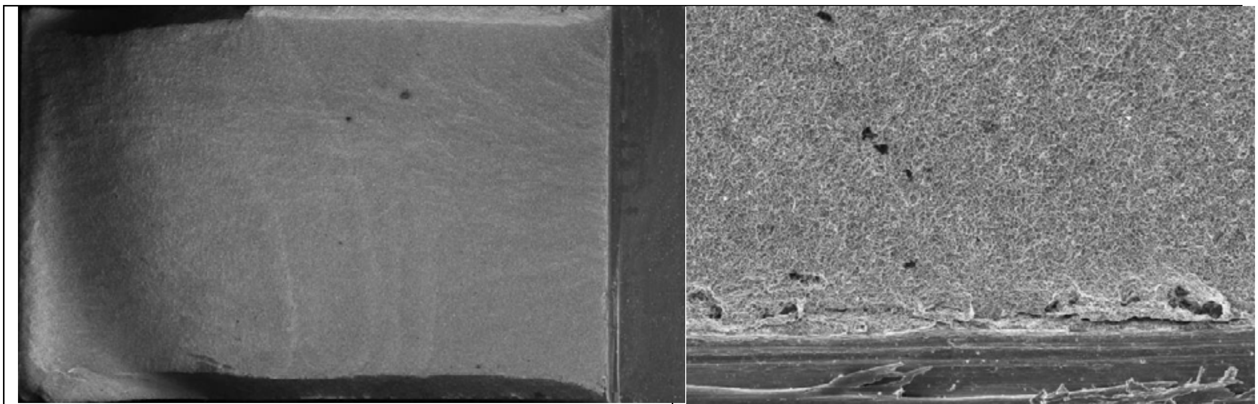


Figure8: PEEQ-triaxiality evolution in the finite element models with different mesh size.

Using a scanning electron microscope(SEM), photos have been taken from the failure surface of the specimen. Figure 9 shows two photos taken from the fracture surface. The damage distribution contour at the failure point also has been shown in figure 10. In the numerical models fracture starts from the central point beneath the notch.



Fracture surface-20X.	Microcrack in the fracture surface-250X

Figure 9:SEM photos of the fracture surface of the specimen.

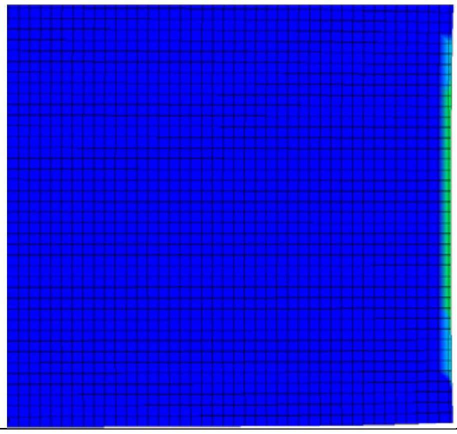
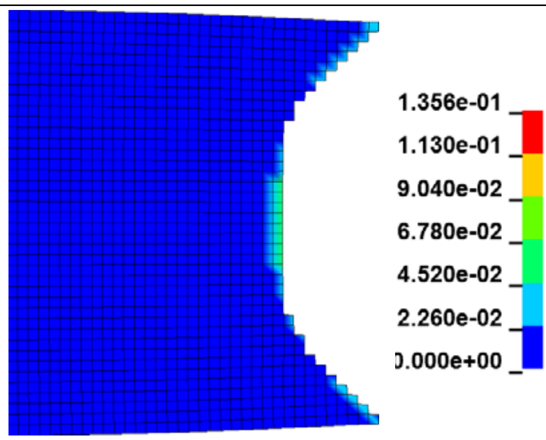
	
Damage contour in the failure surface at the initiation of fracture.	Crack growth in the failure surface.

Figure 10: Failure surface.

CONCLUSION

A three point bending test has been performed on Ti-6AL-4V titanium alloy. A CDM model previously calibrated for round smooth specimen has been applied in the finite element models of a three point bending experimental test. It has been shown that the model fails to have suitable geometry transferability from the smooth tensile to the three point bending test. The CDM model is able to simulate the experimental test only with a dedicated series of damage model parameters. In both cases the mesh size has a significant effect on the finite element results for the failure displacement.

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