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Experimental and numerical investigation on fracture behavior of CTS specimen under I-II mixed mode loading

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ABSTRACT

Experimental and numerical investigations are both performed to study the fracture behavior of CTS specimen of CP-Ti under I-II mixed mode loading. The results show that crack growth path and loading capability of CTS specimen are dependent on both loading angle and crack length. Or rather, crack length effect of CTS specimen on the loading capability and crack growth path (except for pure mode I) becomes more remarkable, as the component of mode I increases. Opening stress from mode I loading is the main reason, the applied mode (tensile and bending opening stress) of which is associated with the crack length of CTS specimen. It is due to the opening stress applied on the specimen, crack length effects on the transition from ductile to brittle fracture and plastic zone (except for pure mode I) ahead of crack tip are more obvious when the component of mode I is dominant, which also explain the results of loading capability and crack growth path (except for pure mode I) respectively. In addition, critical *J*-integrals J_c are analyzed, the results show that constraint effect on J_c of mode I dominant crack is much more remarkable than that of mode II dominant crack, which is also because of the applied style of opening stress on the specimen.

1. Introduction

Considerable fracture work has been done on both brittle and ductile materials under tensile loading or mode I loading, since this mode was thought to be the most dangerous and was also the easiest to test in the laboratory. Most structures do not experience just one type of loading but the combination of tension and shear loading, which is commonly known as mixed mode loading. Investigations of mixed mode fracture have generally been restricted to linear elastic materials, since the theoretical analyses are more fully understood than those for elastic-plastic materials. The existed theoretical criteria of linear elastic materials can be classified into three major categories, the energy based, strain based and stress based. Strain energy density (SED) criterion (Sih, 1974) and *R* criterion (Khan Shafique and Khraisheh Marwan, 2004) are energy based. Maximum tangential strain criterion (Chang, 1981) is strain-based, and maximum tangential stress (MTS) criterion is stress-based (Erdogan and Sih, 1963). *T*-stress, the second order term of linear elastic stress field ahead of crack tip by Williams (1957), affects not only the plastic zone ahead of crack tip (Nazarali and Wang, 2011; Miao et al., 2017; Smith et al., 2001), but also the fracture toughness of elastic material (Miao et al., 2017; Smith et al., 2001). It is regarded that *T*-stress can be taken as the elastic constraint parameter. The results of fracture criteria referred above would be different when considering *T*-stress. It was concluded that SED criterion was less be affected by *T*-stress as compared with MTS criterion (Shahani and Tabatabaei, 2009). The authors have associated the *R*-criterion with *T*-stress, the size and geometry of plastic yielding zone were both affected by *T*-stress (Ayatollahi, 2010).

Different from linear elastic fracture, a large scale of plastic zone occurs ahead of crack tip during the elastic-plastic fracture process, and for which brittle fracture criteria are not suitable any more. Even though numerous studies have been done on I-II mixed mode ductile fracture, no unified guideline has been established so far. Laboratory tests of I-II mixed mode fracture are much more difficult compared with mode I fracture tests. For example, the uncertainty of crack growth, the effect of specimen geometry and output of fracture parameter and so on. These factors all hinder the development and standardization of I-II mixed mode ductile fracture. There have been several common set-ups for I-II mixed mode fracture tests, i.e., four point bending specimen, Arcan specimen with its fixture, compact tension shear (CTS) specimen with an S-shape grip, and plate with an inclined crack at the center. Combinations of the applied shear force and bending moment on the crack plane enable the specimen to reach an anticipated mode-mixity ranging from pure mode I to pure mode II condition. Qian and the co-authors (Yang and Qian, 2012a, 2012b) have studied the I-II mixed mode fracture behavior of aluminum alloy, including crack initiation

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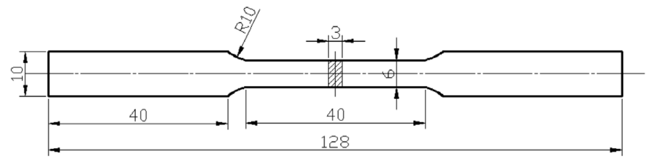
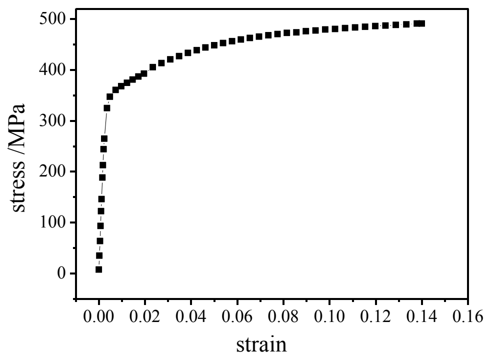


(a) Coupon specimen (unit: mm)



(b) Uniaxial stress-strain curve

Fig. 1. Specimen and mechanical properties.

and fracture resistance, using four point bending specimen. The total measured fracture toughness showed a minimum value for the pure mode I case, a maximum for the pure mode II case and an oscillated trend over the I-II mixed-mode load. Fracture toughness tests of I-II mixed mode fracture have also performed using CTS specimen by researchers. The results showed that the fracture toughness decreased as the mode II component increased (Arun Roy et al., 1999; Smith et al., 2008), and fracture toughness increased firstly then decreased as the mode II component increased (Smith et al., 2008). Arcan specimen with its fixture was firstly proposed by Arcan, which has been used frequently for mixed-mode crack growth (Hallback., 1997). Due to several similar configurations of Arcan specimen, discussions on the configuration of Arcan testing have been conducted (Greer et al., 2011). Cracked plate with a central inclined crack (CCP), was the specimen firstly used to study the I-II mixed mode brittle fracture. Elastic and elastic-plastic *J*-integrals of CCP under biaxial loading were analyzed

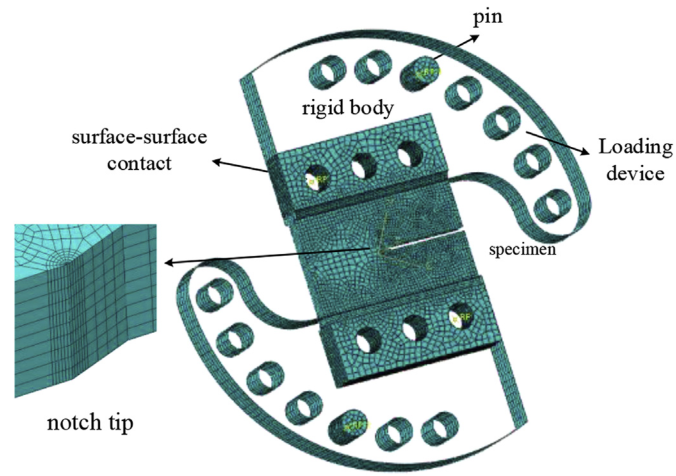
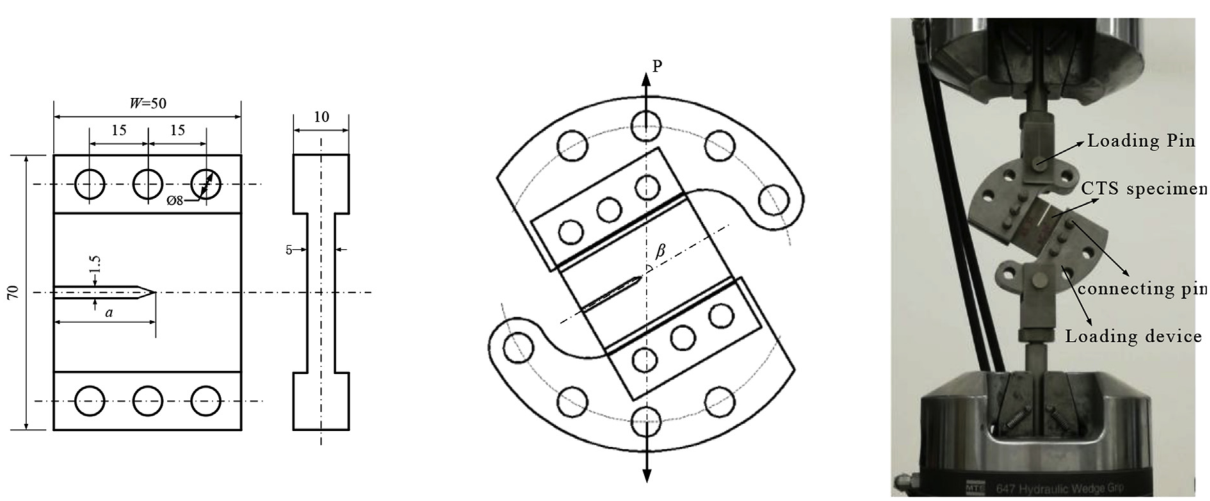


Fig. 3. Three dimensional finite element model.

and compared with each other (Miao et al., 2016).

For ductile fracture, constraint at crack front can be defined as the resistance against plastic deformation, which is affected mainly by specimen's geometry and loading condition. The level of constraint at crack front plays an important role in the fracture behaviors of cracked components. Constraint effect of ductile mode I fracture has been studied a lot by researchers, and a great deal of achievements have been made. For I-II mixed mode ductile fracture, studies of constraint effect are relatively fewer. Experiments have been performed to investigate the constraint effect on mixed mode ductile fracture by changing the crack length of specimen (Arun Roy et al., 1999) and specimen's size (Smith et al., 2008). Results showed that the effect of crack length on fracture toughness decreased as mode II crack approached, and specimen size also had effects on the fracture toughness of mixed mode crack. Out-of-plane constraint is affected usually by thickness. Experiments of CTS specimens with various thicknesses under mixed-mode loadings at room and elevated temperatures have been performed (Zhang et al., 2011). It was concluded that thickness and temperature both had effects on the loading capability, fracture toughness and crack initiation angle.

Although investigations of I-II mixed-mode ductile fracture have gained a lot of insights, a universally agreed standard of I-II mixed-mode ductile fracture test is lacked, which partially resulted in contradicting conclusions of I-II mixed mode ductile fracture resistance



(a) Specimen geometry (b) Specimen with its fixture (c) Fracture test device

Fig. 2. Geometry of CTS specimen and test devices.