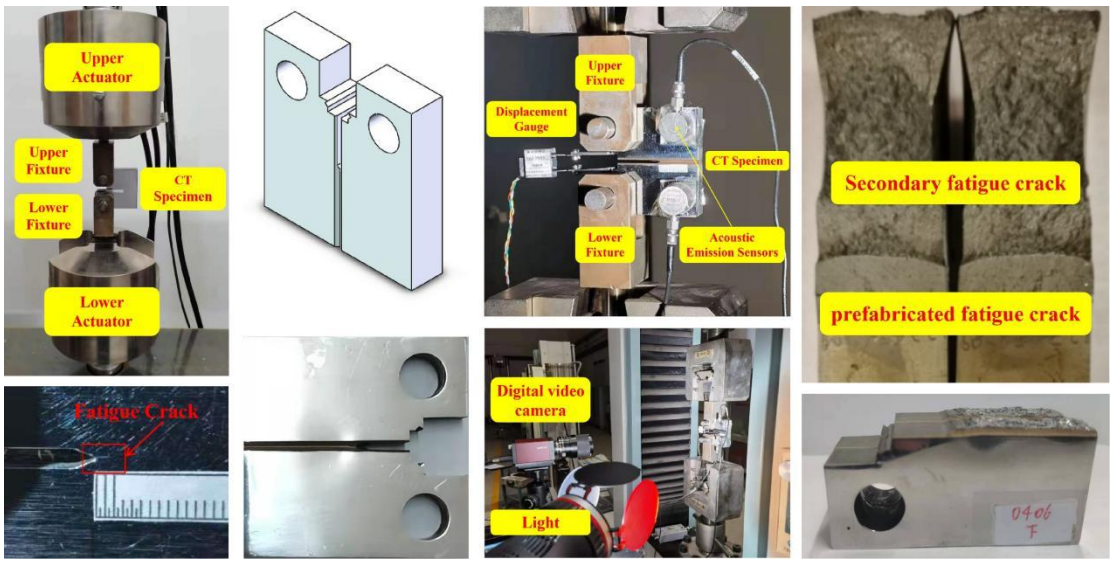
SUMMARY

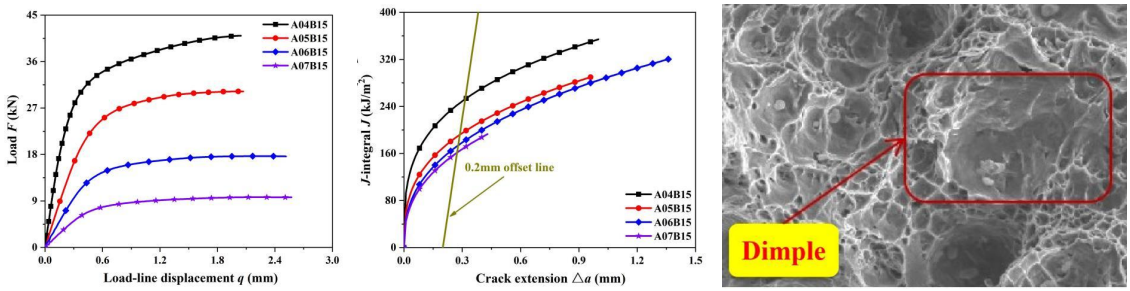
Fracture toughness is a measure of the fracture resistance of materials, which is significantly affected by the constraint of crack tip. Constraint is the hindrance of material or structure on the plastic deformation at the crack tip. The constrained fracture theory has been developed for decades, single parameter, two parameter, three parameter and unified parameter theories have been proposed to characterize in-plane constraints, out-of-plane constraints and their composite constraints. However, these theories can only describe the stress or strain field at the crack tip and their calculation process is complicated. Therefore, how to put forward a unified constraint parameter that can characterize the in-plane and out-of-plane constraints and accurately describe the stress-strain field at the crack tip is the key of structural safety design and integrity evaluation.

In this paper, the effects of in-plane and out-of-plane constraints on the fracture toughness of G20Mn5QT cast steel were investigated by means of theoretical analyses, tests and numerical simulations. A new unified parameter A_{EES} that can characterize in-plane and out-of-plane constraints was proposed, and the correlation line between A_{EES} and dimensionless characteristic value J_{IC}/J_{ref} was established. Through introducing image processing and acoustic emission (AE) technique, the stage analyses of fracture toughness test were carried out. The main research contents and conclusions are as follows:

(1) The fracture toughness tests of compact tensile (CT) specimens with varying in-plane constraints were carried out. *J*-R curves of G20Mn5QT cast steel were firstly measured by Normalization Method. The characteristic values, namely initiation toughness J_i and engineering initiation toughness J_{IC} , were calculated according to ASTM E1820 and ISO 12315. The results show that with the strengthening of in-plane constraints, *J*-R curves drop and characteristic values decrease. The fracture morphology was analyzed by Scanning Electron Microscope (SEM). The fracture mechanism can be revealed from ductile fracture through mixed ductile and brittle fracture to brittle fracture with the enhancement of in-plane constraints.

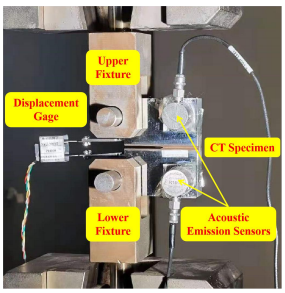


Fatigue precracking Side groove machining Fracture toughness test Macroscopical fracture surface

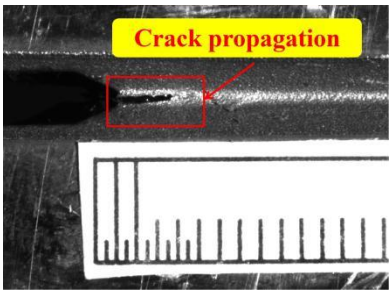


Load-displacement curves *J*-R curves SEM

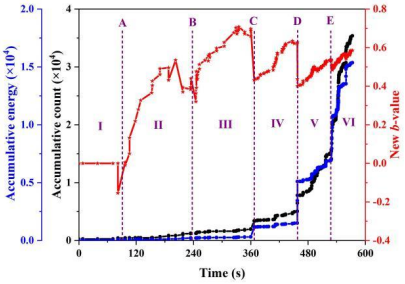
(2) Image processing and AE technique were introduced to conduct stage analyses of fracture toughness tests. The crack evolution process and damage accumulation process of CT specimens are analyzed through using image processing and AE technique respectively. The fracture toughness test process changes from fatigue precracking through crack initiation, then slow, stable and rapid crack propagation to finally instability. The characteristic values at critical points are calculated through the synergistic analysis of AE parameters-time curves and load-displacement curves. J_B and J_C corresponding to the crack initiation (point B) and the onset of stable crack propagation (point C) determined by stage analyses represent the initiation toughness and engineering initiation toughness obtained from image processing and AE technique. It is found that J_B is 10% ~ 30% smaller than J_i , and J_C is 8% ~ 40% smaller than J_{IC} , proving that the characteristic values estimated through using the combination of image processing and AE technique are more conservative.



CT specimen and AE equipment

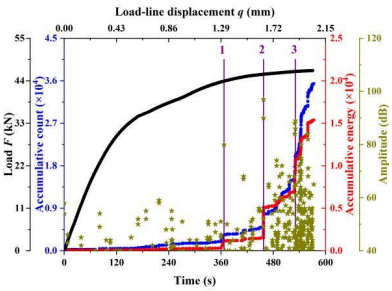


Crack evolution process analyzed by image processing

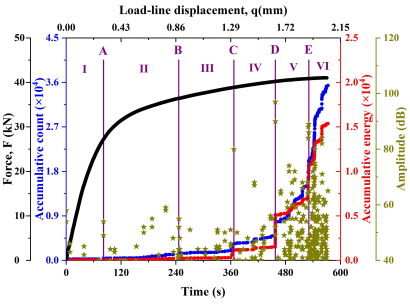


Stage analysis based on *b*-value

Industrial camera

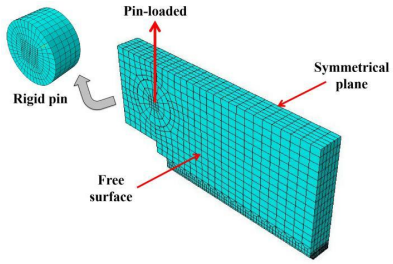


Damage accumulation process analyzed by AE technique

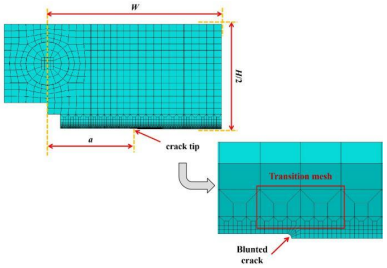


Stage analysis based on AE technique and image processing

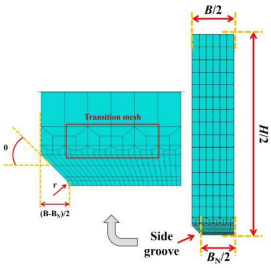
(3) The GTN model embedded in ABAQUS finite element software was used to predict *J*-R curves of G20Mn5QT using CT specimens with different in-plane and out-of-plane constraints. The effects of f_0 , f_N , f_c and f_F in GTN model on load-displacement curves, *J*-R curves and crack evolution process were studied in detail for calibrating GTN model parameters precisely. It is demonstrated that the numerical results using the calibrated GTN model are in good agreement with the experimental measurements, which proves that GTN model is an convenient and effective tool for evaluating the fracture toughness of materials. The increase of in-plane or out-of-plane constraints makes *J*-R curves descent. There exists interaction between the in-plane and out-of-plane constraints. The lower in-plane constraints strengthen the out-of-plane constraints effects, while the higher in-plane constraints are not sensitive to the out-of-plane constraints.



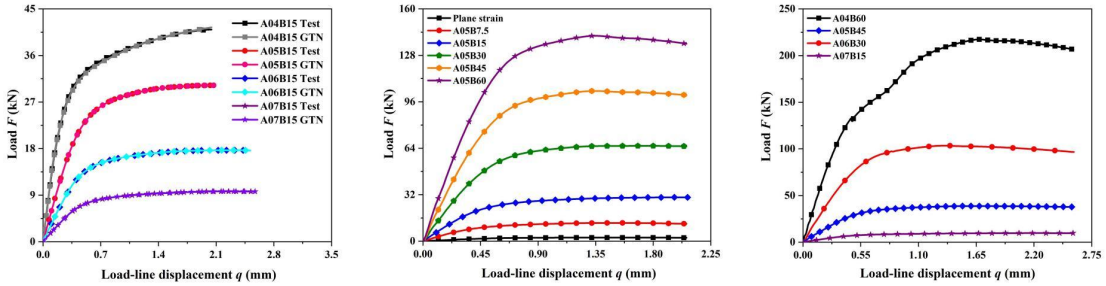
GTN model



Crack tip

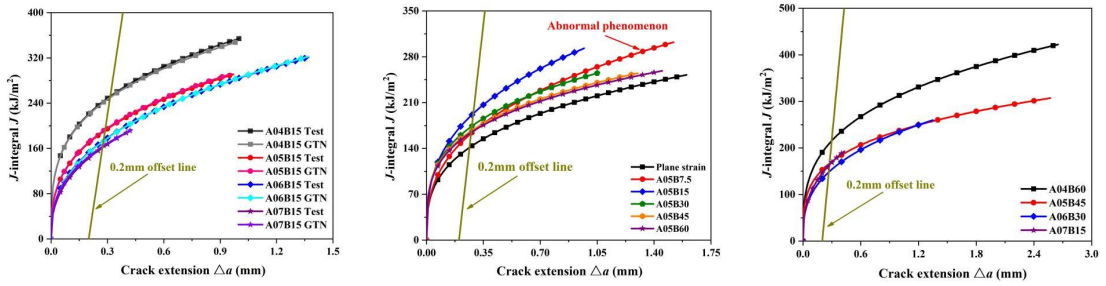


Side groove



In-plane constraints　　Out-of-plane constraints　　In and out-of plane constraints

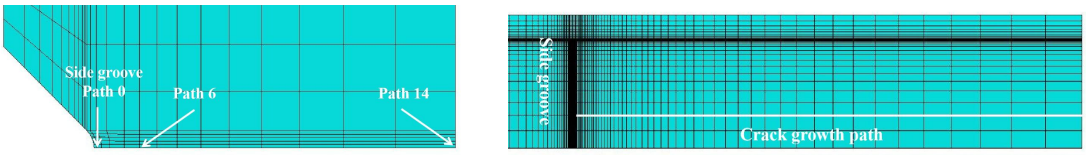
Load-displacement curves



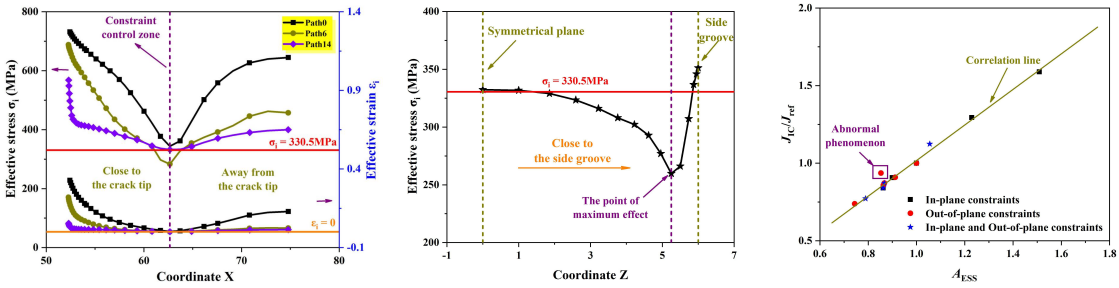
In-plane constraints　　Out-of-plane constraints　　In and out-of plane constraints

J-R curves

(4) The static crack tip stress-strain field of CT specimens with different in-plane and out-of-plane constraints was analyzed through using ABAQUS. Based on the area under the equivalent stress-strain curve in the yield range of the constraint control zone on the crack growth path, a new in-plane and out-of-plane unified constraint parameter A_{ESS} can be defined. There exists a sole linear relation between A_{ESS} and the dimensionless characteristic value $J_{\mathrm{IC}}/J_{\mathrm{ref}}$ regardless of in-plane or out-of-plane constraints or both. $J_{\mathrm{IC}}/J_{\mathrm{ref}}$ can be used to characterize the effect of in-plane and out-of plane constraints on the fracture toughness of G20Mn5QT. It provides calculation parameters and theoretical guidance for the safety design and integrity evaluation of practical engineering components or structures.



Side view of crack growth path　　Front view of crack growth path



The effective stress/strain of different crack growth paths　　The effective stress on the boundary of constraint control zone　　The correlation line $A_{\mathrm{EES}}-J_{\mathrm{IC}}/J_{\mathrm{ref}}$