Based on Micromechanical Damage of Q345 Specimen's Acoustic Emission Quantitative Assessment in Tensile Process

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Abstract To further reveal the mesomechanical damage behavior of the plastic material, quantitative evaluation the micromechanical damage state of material use acoustic emission characteristic parameters. Based on the Gurson-Tvergaard-Needleman micromechanical damage model, establish the quantitative evaluation model of acoustic emission cumulative hits, taking void growth ratio as the damage variable. Taking steel Q345 notched bar specimens tensile process as example, using acoustic emission testing technology, get the AE information from yield to fracture process. Using ABAQUS finite element analysis software, analyze the meso-damage process during tensile process of steel Q345 notched bar specimens, and get the numerical solution of meso-damage parameters. Based on AE testing and Finite Element Simulation, get the quantitative evaluation formula of void growth ratio based on AE cumulative hits N during Q345 steel notched bar specimens tensile process. Result shows that, in the tensile process of Q345 steel from yield to fracture damage, the function relationship of N and V_G is divided into two stage, linear damage stage and nonlinear damage stage, and when the N reaches 128, the material is at the transition state from linear damage stage to nonlinear damage stage. This critical transition area value could be used as steel Q345 damage fracture of acoustic emission recognition feature and safety evaluation threshold value.

Keywords Acoustic emission, Void growth ratio, Cumulative hits, Gurson-Tvergaard-Needleman model, steel Q345

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1. Introduction

Acoustic emission refers to the material or components rapid release of strain energy and the transient stress wave phenomenon when stress exceeds yield stress into the irreversible stage of plastic deformation or crack initiation, growth and fracture. There is consistent correspondence relationship between acoustic emission and material interior damage. Acoustic emission cumulative hits directly correspond to different material damage state and the new damage must be accompany with the release of stress wave, which is the basis fundamental to the direct measurements and modeling of acoustic emission[1-3].Generally micro-void nucleation, growth and coalescence is a typical mechanism of microstructure damage and failure for metal plastic material. Gurson-Tvergaard-Needleman (GTN) model[4-6]is regard as a significant progress in meso-damage mechanics. Because it was well descript the metal plastic damage in the process of plastic deformation caused by the evolution of micro-voids and had been developed and applied in many fields[7,8]. Based on voids nucleation controlled by the stress triaxiality and equivalent plastic strain, Zheng Changqing[9]proposed the concept of critical void ratio V_{GC}.V_{GC} is an micromechanics parameters which built on the micro-void damage mechanism when metals got into the plastic deformation, and it contacts the meso-damage parameters and macro-mechanical behavior. The variation of void growth ratio V_G directly reflects the damage state of the materials. Therefore, established the relationship between the characteristics parameters of acoustic emission and the void growth ratio can be deeply understanding the macroscopic and micromechanics behavior in the process of metal plastic damage, and achieving quantitative evaluation materials micromechanical damage state used acoustic emission testing technology.

This paper from micro-void damage mechanisms of metal plastic materials, used acoustic emission testing the steel Q345 round notch specimen in tensile process, obtained of material's release of the stress wave from yielding to the fracture process. Using ABAQUS analyzed the changes of steel Q345 round bar notched specimen micromechanics parameters in tensile fracture process, obtained numerical solution of void growth ratio in different damage states. Based on acoustic emission testing result, establish acoustic emission characteristics parameters of tensile process and quantitative evaluation formula of void growth ratio, in order to achieve Q345 quantitative evaluation of micro-damage state.

2.The relationships between AE and material micro-damage parameters

2.1. GTN model

Based on the previous work, Gurson researched the response under the axisymmetric triaxial stress state in limited large matrix of cylindrical or spherical with void. He constructed material damage yield function to describe the effect of micro-void damage to the metal plastic deformation behavior. After further amended to the Gurson model by Tvergaard and Needleman[5,6], the model's prediction accuracy has greatly improved[8,10].The GTN model yield function φ is expressed as follows:

$$\phi = (\frac{\sigma_{eq}}{\sigma_s})^2 + 2fq_1\cosh(q_2\frac{3\sigma_m}{2\sigma_s}) - (1+q_3 f)^2 = 0 \tag{1}$$

Where q_1, q_2, q_3,is revision coefficient; σ_{eq} is Misses stress; σ_m is macro hydrostatic stress; σ_s is flow stress of the base material in the unit; f is the percentage of void volume. In GTN model damage variable is considering as isotropic, which comprises two parts:

$$f = (f)_{growth} + (f)_{nucleation} = (1-f)\varepsilon_{ij}^p + A\langle R_\sigma\rangle\eta^p \tag{2}$$

Assumed the nucleation void mechanism by strain controlled and the void follows normal distribution. The voids nucleation intensity function A is expressed as:

$$A = \frac{f_N}{hs_N\sqrt{2}}\exp\left[-\frac{1}{2}(\frac{\eta^p-\varepsilon_N}{s_N})^2\right] \tag{3}$$

where $(f)_{\mathrm{growth}}$ indicates the void-volume fraction caused by the void growth;$(f)_{\mathrm{nucleation}}$ is the void-volume fraction caused by the nucleation of a void; ε_{ij}^p is macroscopic plastic strain rate tensor; R_σ is stress triaxiality ($R_\sigma=\sigma_m/\sigma_{eq}$); η^p is equivalent plastic strain of the matrix material; $\langle x\rangle$ Macauley operator; f_N for the nucleation of micro-voids volume percentage of the two-phase particles; h is material constants; S_N is void nucleation average strain standard; ε_N is void nucleation average strain.

2.2. The relationships between AE and material damage

The emergence and development of inside damage (micro-cracks and micro-voids) in the metal plastic material generates the acoustic emission, so there is inevitable relation between acoustic emission parameters and material damage variable. C.A.Tang etal.[11] obtain damage model which based on damage mechanics theory characterized by AE parameters, the relationship was written as:

$$D = \frac{A_d}{A} = \frac{N}{N_m} \tag{4}$$

Where the damage variable D represents the damage state of the material, Kachanov defined it as ratio of the instant all the area of the bearing surface defects A_d and sectional area when initial nondestructive; N_m is the total number of acoustic emission cumulative hits when material entire cross section A destructed, N is the instant acoustic emission cumulative hits.

Base on the microcosmic architectural feature, Gurson proposed that make the void-volume percentage f as a micro-mechanical damage variable for metal-plastic material. Zheng Changqing[9] used an electron microscope to observe micro-void nucleation, growth, and coalescence of plastic deformation when metal stretching, necking as well as instability in the fracture process. Combined experiment and numerical simulation and analyzed the relations between the strain and stress, make the fracture strain ε_f and stress triaxiality $R_{\sigma 0}$ as critical void growth ratio V_{GC} when material fractured. Micromechanics fracture criterion was $V_G \geq V_{GC}$,V_G is the void growth ratio under the conditions of forcing. For notched specimen was the following relationship:

$$V_G = \varepsilon_p \exp(1.5 R_\sigma) \tag{5}$$

Where ε_p is the equivalent plastic strain. The nucleation of micro-void controlled by the triaxiality stress and equivalent plastic strain. Also they were the function of void growth ratio V_G. The void growth ratio is the micromechanics parameters which establish on the micro-voids growth and coalescence in metal plastic materials. It is the bridge of contacting microscopic damage characteristic and micromechanics parameter. The change of V_G directly reflected the material damage of macro-micro state changes in real time, so make the void growth ratio V_G as the new damage variable of material deterioration state.

Considering formula (4) and (5), the void growth ratio V_G and acoustic emission cumulative hits N can be used as parameters which describe the damage state of the metal plastic materials. Therefore established the quantitative evaluation of the formula between the void growth ratio and acoustic emission cumulative hits:

$$V_G = f\,(N) \tag{6}$$

According to the formula (6), used the acoustic emission testing technology obtained the Q345 notched bar specimen's information in tensile process. Using ABAQUS finite element analysis software to obtained the numerical solution of void growth ratio in different damage state. Then establish quantitative evaluation formula between the acoustic emission characteristics parameters and void growth ratio when steel Q345 in stretch process. Finally realized use acoustic emission quantitative evaluation the material's microscopic damage state.

3. Steel Q345 notched specimen tensile process acoustic emission testing experiment

3.1. The Steel Q345 notched specimen size and mechanical properties

The size of Steel Q345 tensile specimen is shown in Figure 1. There are eight specimens, numbering from#1 to #8.

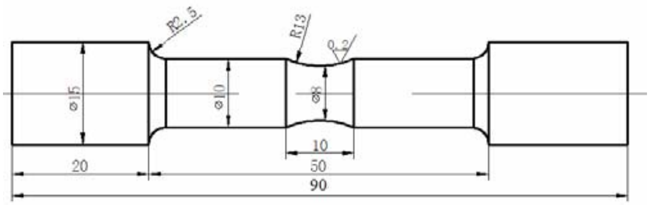

Fig.1 The shape and size of notched tensile specimens

Experiment mechanical properties and chemical composition of the steel Q345 are shown in Table 1.

Table 1 Steel Q345 mechanical properties and chemical composition

mechanical properties						chemical composition %				
σ_s MPa	σ_b MPa	E GPa	γ	Ψ %	Φ %	C	Mn	Si	P	S
408	533	200	0.3	4.58	60.58	0.17	1.42	0.019	0.020	0.031

3.2. Experimental equipment and methods

The tensile test was on the SANS electronic universal testing machine, adopted displacement loading, axial tensile in constant speed, loading rate was 0.3mm/min. Acoustic emission data acquisition system was the U.S. PAC PCI-2 acoustic emission system, and the sensor was WD broadband sensor, the frequency range of 100~1000kHz. The preamplifier was PAC2/4/6 produced in PAC. The sensors were installed at the end of the specimen, and coupled by vacuum grease. To calibrated the sensitivity of each channel used HB pencil(Φ=0.5mm) breaking signals as sound simulate source. In order to collect the acoustic emission signal that generated from material's microscopic damage during tensile stretched, need to lower the threshold value. In order to testing the experiment environment, environmental noise and electromagnetic noise of AE signal distribution levels under no-load operation, finally set threshold value is 30dB. Acoustic emission testing system parameter settings were shown in Table 2.

Table 2 Acoustic emission detection system parameter settings

Parameter category	Setting value	Parameter category	Setting value
Threshold value /dB	30	Peak definition time PDT/μs	200
Sampling rate /MB	2	Hits definition time HDT/μs	600
Sampling length /K	4	Hits lockout time HLT/μs	1000

3.3. Experimental results and analysis of acoustic emission testing

Table 3 shows the results of eight specimens' acoustic emission testing experimental. It listed axial displacements and acoustic emission cumulative hits and corresponding mean value of separately yield point B and yield end point C, tensile strength point D and breaking point E. Studies[11,12] indicated that acoustic emission cumulative hit can reflect the changes in the material damage state, so selected the acoustic emission cumulative hits combined with the amplitude to analyze different damage stage of Steel Q345 in tensile process. The amplitude of the #1 specimen's AE vs. the cumulative hit vs. stress increases with the experiment time is shown in Figure 2.

Table3 Steel Q345 axial tensile displacement and acoustic emission cumulative hitting statistics

		1#	2#	3#	4#	5#	6#	7#	8#	average
B	displacement /mm	1.79	0.98	1.86	2.28	1.91	1.92	1.82	1.76	1.79
	Accumulate strike count	20	23	18	24	20	22	19	22	21
C	displacement /mm	2.24	2.10	2.06	2.61	2.45	2.31	1.96	2.43	2.28
	Accumulate strike count	104	99	110	103	100	107	104	109	104.50
D	displacement /mm	4.33	4.45	4.01	4.45	4.66	4.51	4.41	4.57	4.42
	Accumulate strike count	148	150	165	150	160	162	150	160	155.62
E	displacement /mm	6.15	5.49	6.21	6.25	5.99	5.39	5.53	6.03	5.88
	Accumulate strike count	157	160	176	156	164	171	162	171	164.63

Figure 2 shows Steel Q345 tensile damage process is divided into four phases, i.e., AB, BC, CD, and DE, respectively corresponding to the elastic deformation stage, the yield phase, strengthening phase and necking stages of the specimen. (1) The elastic deformation stage (0~320s, 0~408MPa). There are few acoustic emission signals in the stage and acoustic emission cumulative hit change is also very small. Amplitude are less than 35dB, most of the which are from mechanical noise caused by the loaded the initial specimen two ends of the fixture bite and friction; (2) Yield stage (321~496s, 408~432MPa),which are also known as the stage of plastic flow. After the specimen entering this phase, the acoustic emission signal was significantly increased, and then the acoustic emission yield effect appears. Signal amplitude between 30~54dB, the cumulative hit - time curve appears apparent inflection in the vicinity of the point B, and rapid raised. The micro-voids generally nucleation at lower strain in the vicinity of the inclusions or second phase particles itself broken, or produced in the detachment of the inclusions and matrix interface[9,13].This stage acoustic signal reflects the sensitive to metal plastic material micro-voids nucleation process; (3) strengthening stage (497~931s, 432~533MPa). The specimen was in the uniform state of strain and begun to produce plastic deformation, the damage of micro-void continued to develop. The amount of AE signals reduced significantly and accompanied by a little amount of high-amplitude signal, the amplitude range between 30~55dB. The curve of accumulation hits vs. time rising trend was becoming slowly;(4) Necking stage(932~1230s,533~441MPa).When the stress reaches to the point D, since strength increase insufficient to compensate for size contraction caused by the work hardening, resulting in the phenomenon of necking. Since then, the deformation of the material became non-uniform. In this stage the amount of acoustic emission signals continued to reduce, the amplitude below 50dB, the curve of cumulative hits substantially in the horizontal direction.

Based on the above analysis, the acoustic emission amplitude and the slope of cumulative hits have obvious stage characteristics from yielding to plastic deformation then to the stages of the fracture process of steel Q345. The relationship between simulation and experiment with the load and time curve were fit well, which illustrates the changes of acoustic emission cumulative hits can reflect the different processes of the development of material damage state.

Fig.2 Accumulated hit-amplitude-stress vs. time for specimen 1.

4 The tensile process micro-damage of Steel Q345 notched specimen: simulation and analysis

4.1 The establishment of the Steel Q345 notched micro model and parameter selection

The voids growth ratio VG of Steel Q345 notched specimen are obtained with numerical simulation method in tensile process. Take GTN as the micro-damage model, using the ABAQUS finite element analysis software, we analyzed Steel Q345 notched specimen and observed micro-damage evolution, then obtain the numerical solution of the micro-damage parameters. Voids growth ratio V_G is a function of the stress triaxiality and equivalent plastic strain, so using the finite element software ABAQUS/Explicit can calculate stress triaxiality, equivalent plastic strain, void volume percent distribution and changes with the load in notched specimen. First, modeling of the notched specimen, due to the geometric axis of the specimen, took the modeling of the test piece of 1/4 which shown in Fig.3. The element type is CAX4R. Meshing principle is that the more close to the notched root the meshing was more dense, the minimum mesh size of the front notched is about 80μm. The number of nodes of the model was 496, the number of units was 328. The boundary conditions are consistent to the former experimental conditions, loading mode is displacement loading. Loading amount of displacement of eight specimens at the point B~E which listed in Table 2 is displacement average. Choice of the steel Q345 GTN model parameters are as follows: q_1=1.5， q_2=1.0， q_3=2.25， f_N=0.02， S_N=0.1， ε_N=0.25.

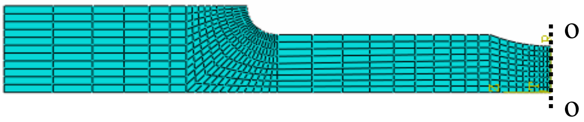

Fig.3 1/4 finite element model of notched tensile specimens

4.2 The numerical simulation results and analysis

Figure 4 is a numerical simulation proceeds that steel Q345 axial tensile stress-displacement curve compared with the specimen 1 of the experimental curves. The highest stress point D and the yield point B obtained by the numerical simulation agree with the experiment results, which are proved the GTN model parameter selected reasonable. These can truly reflect the macro-mechanics and micro-mechanics behavior of Steel Q345 axial tensile experiment. Figures 5~7 are respectively different loading stage of model notched o-o, they are the curves of stress triaxiality R_σ, equivalent plastic strain ε_p and the void volume percentage f versus x. x represents the specimen o-o surface center (x=0mm) to the distance of the notched root(x=4mm). To express the micro-damage parameters changes with the loading clearly, the middle of the loading process should select appropriately. Concluded from Fig.5, the R_σ of the specimen notched center is bigger than the value of the root of the specimen and the maximum R_σ always at the center of the specimen during the loading stage, and increasing with the loading. Fig.6 and Fig.7, ε_p and f change similar with x, but in the loading process they change different with R_σ , and can be divided into two stages. Stage I: Hardening stage (B~D point), the stage is the material yield and enhanced stage, ε_p and maximum f appear at the root of the notched, and they rise with the loading increase. Stage II: Necking stage (D~E point). When the material loaded to the strength limit point D, for the influence of R_σ intensified, ε_p at the middle of the specimen change greater than the growth of the roots. Micro voids move from the notched root to the core part. After plastic zone extends to the core part, stress triaxiality at the core part is much larger than the value of the root, ε_p and f at the core part of the specimen is far greater than the value, which lead to the occurrence of fracture of the specimen from the core part.

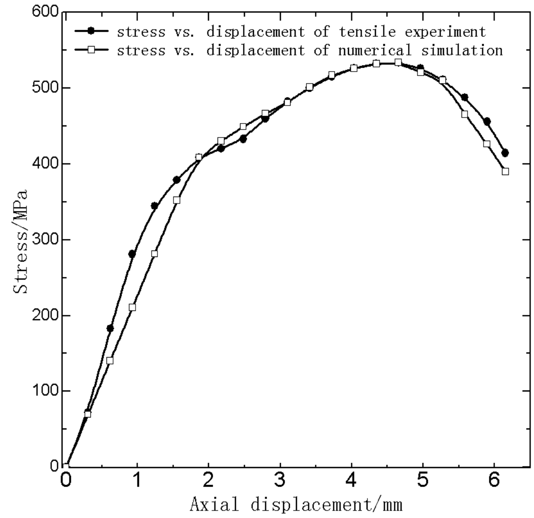

Fig.4 Numerical simulation and experimental results

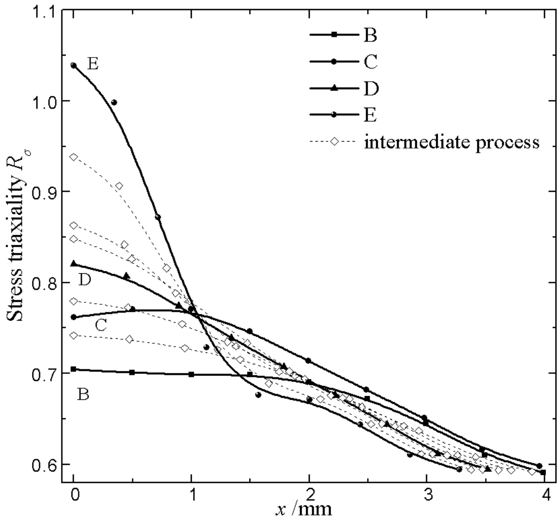

Fig.5 Distribution of Rσ on notch tip

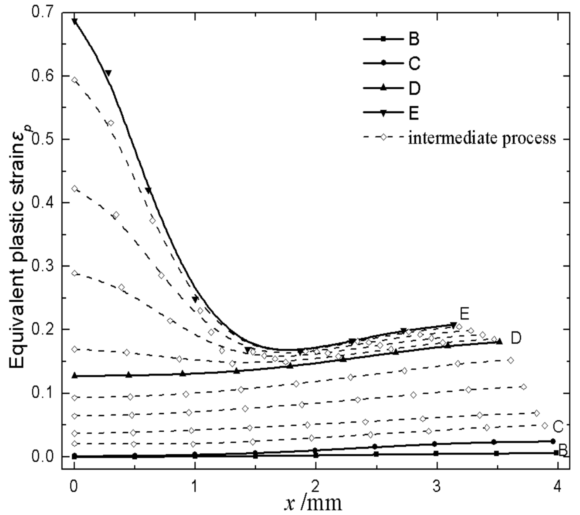

Fig.6 Distribution of εp on notch tip

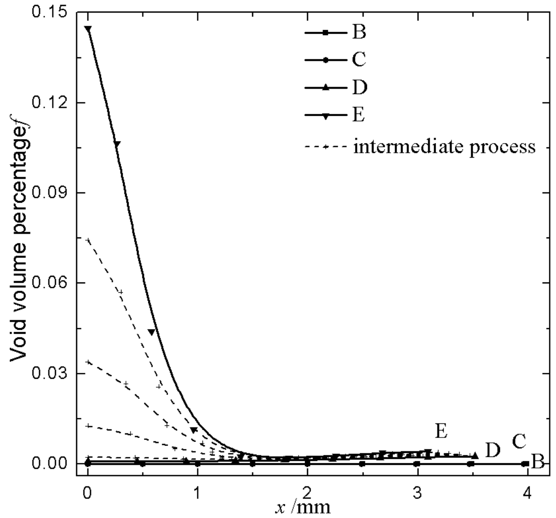

Fig.7 Distribution of f on notch tip

4.3 The numerical simulation of Steel Q345 notched specimen voids growth ratio

Concluded from the simulation results, the final fracture first occurs at o-o surface, so R_σ and ε_p at point B~E which located at model integrator x=0 from o-o surface, and select the appropriate middle point in the loading process. According to equation (6), the numerical simulation results of steel Q345 notched specimens in tensile process are showed in Table 4.

Table 4 Table of voids growth ratio calculation

	stress triaxiality	equivalent plastic strain	voids growth ratio
B	0.704	0	0
C	0.762	0.00104	0.00326
D	0.820	0.128	0.437
E	1.22	0.687	4.29

5. The quantitative evaluation formula between AE cumulative hits and the void growth ratio VG

Selecting the critical point B~E in the tensile process, so do the intermediate process in the loading process, the acoustic emission of each point in the cumulative hit average and numerical simulation of the void growth ratio V_G are showed in Figure 8. From Figure 8, the relationship between $\overline{N}$ and

V_G can be divided into two stages:

Stage I: point B~D, steel Q345 is in the yielding and hardening process. This stage is an important period of the material within the nucleation and growth of micro-voids, the void growth and acoustic cumulative hit are linear growth, and the growth trend is relatively slow. Therefore, this stage is defined as the stage of the linear damage of the material. By numerical fitting:

$$V_{G\,\mathrm{I}} = 0.0021\overline{N} - 0.109 \tag{7}$$

Where $21 \leqslant \overline{N} \leqslant 155$.

Stage II: point D~E, steel Q345 is in the necking stage. This is the development of late damage, micro-void confluence occur in the material internal. With the cumulative hit increases, void growth ratio is increasing rapidly. Contrast to stage I, this stage increase evidently in exponential form. Therefore, the stage is defined as a nonlinear damage stage. By numerical fitting:

$$V_{G\,\mathrm{II}} = 0.058(\overline{N} - 153.05)^{1.75} \tag{8}$$

Where $155 \leqslant \overline{N} \leqslant 164$.

Fig.8 The diagram of AE average cumulative hit vs. void growth ratio

The intersection point F (147.28, 0.26) was obtained by simultaneous the equation (7) and (8), it revealed that steel Q345 notched specimen begins to transform from linear damage stage to nonlinear damage stage. Taking the uniformity of experimental material , the micro-voids distribution and mechanical noise impact in acoustic emission testing experimental process into consideration, the safety factor n range was 0.9~0.95. Material transform from linear damage to the next stage, the critical acoustic emission cumulative hits take $[N^*]=N_F \times n$. When n=0.9, acoustic emission cumulative hit is 128, which can be taken as the critical value of steel Q345 notched specimen in plastic damage. This is the evident to certify the transformation of steel Q345 notched specimen from linear damage stage to nonlinear damage stage.

6. Conclusions

(1) The meso-damage mechanism of metal-plastic material is micro-void nucleation, growth and coalescence. Steel Q345 notched specimen in tensile process shows that AE and micro-voids of metal plastic material have the consistent corresponding relationships, which the changing of AE cumulative hits directly corresponds with the different damage stage of material.

(2) Based on the micro-void damage theory of metal plastic materials, the micromechanics parameters of void growth ratio V_G is the bridge with which combined micromechanical

characteristics and macro mechanical parameters. The changes of V_G directly reflects the state of deterioration of the material. Applying GTN model to calculate the changes of V_G on tips of Steel Q345 notched specimen combined with AE testing experiment, and finally established the quantitative evaluation formulas between acoustic emission cumulative hits and void growth ratio.

(3) The quantitative evaluation formulas between acoustic emission cumulative hits and void growth ratio can be divided into two parts: linear damage stage and nonlinear damage stage. From the function of cumulative hits and void growth ratio, when the acoustic emission cumulative hits is larger than 128, the steel Q345 damage transform from linear damage stage to nonlinear damage stage.

References

[1] Wang Huijing, Lin Zhe, Zhao Deyou. Application and prospect of acoustic emission technology in engineering structural damage monitoring [J]. Journal of Vibration and Shock, 2007, 26(6): 157—191. (in Chinese)

[2] D.E. Lee, I. Hwang, C.M.O.Valente, J.F.G. Oliveira, etal. Precision manufacturing process monitoring with acoustic emission[J]. International Journal of Machine Tools and Manufacture, 2006,46(2):176—188.

[3] C. Ennaceur, A. Laksimi, C.Herve, etal. Monitoring crack growth in pressure vessel steel by the acoustic emission technique and the method of potential difference[J]. International Journal of Pressure Vessels and Piping, 2006,83(1):197—204.

[4] Gurson A L. Continuum Theory of Ductile Rupture by Void Nucleation an Growth: Part I—Yield Criteria and Flow Rules for Porous Ductile Media[J]. Transactions of ASME: Journal of Engineering Materials and Technology,1977, 8(1):1—15.

[5] Tvergaard V, Needleman A. Analysis of the Cup–Cone Fracture in a Round Tensile Bar[J]. Acta Metal, 1984, 32(1):157—169.

[6] Needleman A, Tvergaard V. Numerical Modeling of the Ductile-brittle Transition[J]. International Journal of Fracture, 2000, 101 (1/2):73—97.

[7] M. Abbasi, B. Bagheri, M. Ketabchi, D.F. Haghshenas. Application of response surface methodology to drive GTN model parameters and determine the FLD of tailor welded blank[J]. Computational Materials Science,2012, 53 (12):368—376.

[8] CHAE D, KOSS D A. Damage accumulation and failure of HS-LA-100 steel[J]. Materials Science and Engineering, 2004,A366(2) : 299—309.

[9] Zheng Changqing, Zhou Li, Zhang Keshi. Micromechanical research and application for the ductile fracture of metal. [M]. Beijing: National Defense Industry Press, 1995.(in Chinese)

[10] KIM J, GAO Xiaosheng, SRIVAT SANT .Modeling of void growth in ductile solids effects of stress triaxiality and initial porosity[J]. Engineering Fracture Mechanics, 2004, 71 (6):379—400.

[11] Tang C A，Xu X H. Evolution and propagation of material defects and Kaiser effect function[J]. Journal of Seismological Research,1990,13(2):203—213.

[12] Long Xianhai, Yang Nengjun, Wang Hangong. Fracture mechanism for 30CrMnSi steel based on acoustic emission technology [J] Materials Engineering, 2011,20(1):17—22.(in Chinese)

[13] Zhu Hongping, Xu Wensheng, Chen Xiaoqiang, Xia Yong. Quantitative concrete-damage evaluation by acoustic emission information and rate-process theory [J] Engineering Mechanics, 2008, 25 (1): 186—191. (in Chinese)

[14] Xu Jinquan. Strength of materials science. [M]. Shanghai: Shanghai Jiaotong University Press, 2009:133-135.(in Chinese)