Damage Factor Analysis of Q235A Steel Based on Acoustic Emission Test

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Abstract. To analyse the damage of Q235A steel during axial tension, tensile experiments were carried out on several Q235A sheet specimens, the acoustic emission (AE) signals were collected at the same time. The properties of cumulative ringing counts of sheet specimens were analysed during tension process, the load-cumulative ringing counts curves were fitted, and the expression of steel damage factor was obtained by polynomial cumulative ringing counts. The cumulative ringing counts calculated by this expression under different loads are close to the experimental values, which prove that it is feasible to use the cumulative ringing counts of acoustic emission to represent the damage factors of Q235A steel during tensile process.

1. Introduction
Q235A steel is widely used in engineering for its good performance such as good ductility, toughness and machinability. Degree will occur to steel in the course of service, so how to detect the damage degree of steel safely and accurately is of great significance to the engineering structure. Acoustic emission (AE) is a physical phenomenon that defects in materials release energy and produce transient elastic waves under load. AE detection technology can collect elastic waves generated by defects in materials under load, which is widely used for the merits of dynamic real-time, free from material shape restrictions, and does not destroy the original structure. In order to obtain the AE characteristics of different defects, Q345 steel specimens with different welding defects were stretched[1]. Intact and welded Q235B steel plate specimens were stretched, the results show that AE parameters can describe the effect of welding on the mechanical properties of materials well[2]; 16Mn steel specimens tensile tests were carried out, the results show that AE characteristics were agree well with material damage[3]; To analyse the AE characteristics at different loading speeds, Q235A steel specimens were stretched[4]. The plates with V-shape notch were loaded in tension-tension fatigue with AE activity monitoring, the results showed the time history of RA is similar to the crack propagation rate curve[5]; Ferrite-martensite dual-phase steels with various microstructures were investigated, the results showed that AE monitoring and sentry function were efficient tools to detect failure micromechanisms[6]. To investigate the hydrogen embrittlement phenomenon in the electrolytically charged mild low-carbon steel, tensile testing coupled with in situ AE measurements were adopted[7,8]. AE control results for cyclic tests of metal samples with a notch were presented. The results shown that the boundaries of clusters remain unchanged irrespectively to the differences in the kinetics of damage development[9]. To investigate the Piobert-Lüders band propagation and the development of necking for a low alloyed and low carbon steel, the axial tensile tests monitored by speckle interferometry and acoustic emission were carried[10]. The pitting corrosion characteristics of low carbon steel specimens are studied by AE
and electrochemical techniques\cite{11}. Most of the studies above focus on the acoustic emission signal characteristics of materials during tensile process, to analysis the relationship between AE signal and damage factor of Q235A steel, Q235A steel specimens were stretched in this study.

2. Test Results

Q235A low carbon steel is selected in the tests, the specimens were processed into dumbbell shape with a thickness of 3 mm\cite{12}. The specific size is shown in Figure 1.

![Figure 1. Geometry dimension of specimen(Unit: mm).](image)

2.1. Test Results

The specimens were investigated during tensile testing coupled with in situ AE measurements, the sound velocity in steel was determined by in situ lead-breaking test before loading. The sound velocities of each group were measured three times, and the average value was chose. The specimens were divided into three groups and 3 in each group. In each group, loading speed of two specimens is 3 mm/min and the others is 5 mm/min. The experimental setup is shown in Figure 2. The acoustic emission ringing counts and stress diagrams of the specimen during loading were shown in Figure 3-Figure 6.

![Figure 2. Experimental setup.](image)

![Figure 3. AE amplitude and stress history under different load speed.](image)
3. Result Analysis
The internal structure of the material changed in the process of tension, which lead to damage and sent out sound signals at the same time. The ringing counts in AE signals were analysed in this paper. In the elastic stage, many acoustic signals were collected, which is caused by the friction between the clamped ends of the specimen and the fixture of the tension machine, not caused by the internal damage of the material. In the yield stage, the internal structure of the material changed greatly, deformation generated due to the dislocations moved along the slip plane, local stress concentration generated along the dislocations, which lead to more dislocations and strong acoustic signals, and the ringing count and intensity were proliferated. In the hardening stage, the acoustic emission changed steady, the ringing count decreased, and even there is no acoustic signal at the later stage of the hardening stage, but instantaneous high signals produced in few parts of materials, which was due to the more rapid dislocation of the internal grains of the material after yielding. At the later stage of hardening, the dislocation between grains has been effectively released, so the cracks development tend to mature. In the necking stage, the plasticity of the material decreased, the intergranular gap in
material developed relatively perfect, so the AE signals were relatively flat. The AE signals generated instantaneously at the moment when the materials were pulled off, and the ringing count produced a more obvious peak value (Figure 3-Figure 6).

4. Damage Factor Analysis

According to Huang's research\[13\], the material damage correspond to the cumulative ringing counts of rock acoustic emission signals. In order to quantitative analysis the damage of low carbon steel, the damage factor of material was represented by the cumulative ringing counts, which are used to evaluate the damage status of low carbon steel under tensile load. Damage degree of material is expressed by damage factor $D$:

$$D = \frac{N}{N_0}$$  \hspace{1cm} (1)

Where $N$ is the accumulated ring counting of AE under Load, $N_0$ is the accumulated ring counting of AE under maximum load.

The load-cumulative ringing count data corresponding to the front part of the ultimate load in the AE test results are extracted, the load- cumulative ringing count curve were fitted by polynomial fitting, power function fitting and Gauss fitting. Four data fitting curves are shown in Figure 7.

![Figure 7. Load-cumulative Ringing Count fitting Curve.](image)

Four sets of fitting curve parameters were extracted and listed in Table 1 to Table 4, where SSE represents the square sum of the error of fitting data and corresponding points of original data; R-Square (determinant coefficient) represents the quality of fitting by data change, the closer to 1, the stronger the explanatory power of equation variables to data was, the better the fitting effect was; Adjusted R-square refers to the coefficients determined after correction, which are consistent with the determined coefficients in single variable linear regression; RMSE (root mean square) refers to the sum of all the square values.
Table 1. Fitting parameter table of specimen 1.

| Parameter     | Polynomial function fitting | Power function fitting | gauss function fitting |
|---------------|-----------------------------|------------------------|-----------------------|
| SSE           | 4.503e+09                   | 1.676e+10              | 6.653e+09             |
| R-Square      | 0.9921                      | 0.9706                 | 0.9883                |
| Adjusted R-square | 0.9921                  | 0.9706                 | 0.9883                |
| RMSE          | 990.1                       | 1909                   | 1204                  |

Table 2. Fitting parameter table of specimen 2.

| Parameter     | Polynomial function fitting | Power function fitting | gauss function fitting |
|---------------|-----------------------------|------------------------|-----------------------|
| SSE           | 1.387e+10                   | 6.385e+10              | 3.518e+09             |
| R-Square      | 0.9845                      | 0.9285                 | 0.9961                |
| Adjusted R-square | 0.9844                  | 0.9285                 | 0.996                |
| RMSE          | 2060                        | 4417                   | 1040                  |

Table 3. Fitting parameter table of specimen 3.

| Parameter     | Polynomial function fitting | Power function fitting | gauss function fitting |
|---------------|-----------------------------|------------------------|-----------------------|
| SSE           | 7.778e+09                   | 1.345e+10              | 5.714e+09             |
| R-Square      | 0.9865                      | 0.9766                 | 0.9901                |
| Adjusted R-square | 0.9844                  | 0.9766                 | 0.99                |
| RMSE          | 1613                        | 2118                   | 1385                  |

Table 4. Fitting parameter table of specimen 4.

| Parameter     | Polynomial function fitting | Power function fitting | gauss function fitting |
|---------------|-----------------------------|------------------------|-----------------------|
| SSE           | 2.24e+10                    | 8.479e+10              | 2.832e+10             |
| R-Square      | 0.9962                      | 0.9857                 | 0.9952                |
| Adjusted R-square | 0.9962                  | 0.9857                 | 0.9952                |
| RMSE          | 1872                        | 3640                   | 2107                  |

It can be seen that the polynomial function fitting curve is most consistent with the actual load-cumulative ringing count curve from Figure.7 and Table.1 to Table.4. The coefficient of determination is closest to one, and the sum of variance and root mean square are relatively small. Therefore, the fitting of load-cumulative ringing count curve by polynomial function has better reliability and smaller relative error. The polynomial function equation is:

\[
f(x) = p_1x^7 + p_2x^6 + p_3x^5 + p_4x^4 + p_5x^3 + p_6x^2 + p_7x + p_8
\]  

(2)

Where \( p_1, p_2, p_3, p_4, p_5, p_6, p_7, p_8 \) are constant that related to the stress state and size of materials. Polynomial parameters of four groups of specimens were extracted, which were shown in Table.5.
Table 5. Polynomial parameter values of specimens.

| Parameter | Specimen 1   | Specimen 2   | Specimen 3   | Specimen 4   |
|-----------|--------------|--------------|--------------|--------------|
| $p_1$     | 1.52e-26     | 4.71e-25     | 2.25e-26     | 6.43e-25     |
| $p_2$     | -5.05e-21    | -5.24e-20    | -2.17e-21    | -7.41e-20    |
| $p_3$     | 3.73e-16     | 2.29e-15     | 7.72e-17     | 3.36e-15     |
| $p_4$     | -1.12e-11    | -4.99e-11    | -1.25e-12    | -7.57e-11    |
| $p_5$     | 1.58e-07     | 5.69e-07     | 1.28e-08     | 8.93e-07     |
| $p_6$     | -0.00109     | -0.00333     | -0.00017     | -0.00538     |
| $p_7$     | 4.336        | 10.07        | 2.096        | 16.85        |
| $p_8$     | -1792        | -5172        | -1121        | -1274        |

The expression of cumulative ringing count $N$ under different load conditions can be deduced from Equation (2):

$$N = p_1 x^7 + p_2 x^6 + p_3 x^5 + p_4 x^4 + p_5 x^3 + p_6 x^2 + p_7 x + p_8$$

Substituting Equation (3) into Equation (1), we obtain:

$$D = \frac{N}{N_0} = \left( p_1 x^7 + p_2 x^6 + p_3 x^5 + p_4 x^4 + p_5 x^3 + p_6 x^2 + p_7 x + p_8 \right) / N_0$$

The respective damage factor values can be obtained through the maximum cumulative ringing count $N_0$ of each specimen, the damage factor values of each specimens under different loads were list in Table. 6.

Table 6. Damage factor values of under different loads.

| Load    | Specimen | specimen 1 | specimen 2 | specimen 3 | specimen 4 |
|---------|----------|------------|------------|------------|------------|
| 5000N   |          | 0.1075     | 0.1209     | 0.1190     | 0.1167     | 0.1160     |
| 15000N  |          | 0.1797     | 0.1925     | 0.1799     | 0.2040     | 0.1890     |
| 25000N  |          | 0.3082     | 0.3184     | 0.3441     | 0.3725     | 0.3358     |

As seen in Table.6, the values of damage factors of specimens obtained from the tests are relatively close, and the cumulative ringing counts calculated from the fitted damage factors of each specimens under different loads are relatively close to the experimental values. Therefore, it is feasible that the damage factor of low carbon steel in the tensile process can be represented by the cumulative ringing count of acoustic emission.

5. Conclusion

This work aimed at the analysis of AE signals during low carbon steel tensile tests, the main conclusions of the present study can be summarized as follows:

1. The AE signals during low carbon steel tensile tests were analysed. In the elastic stage, acoustic signals were produced by the friction between the clamped ends of the specimen and the fixture of the tension machine; In the yield stage, strong acoustic signals produced due to the dislocations moved along the slip plane, the ringing count and intensity were proliferated; In the hardening stage, the acoustic emission changed steady, but instantaneous high signals produced in few parts of materials due to the more rapid dislocation of the internal grains of the material after yielding; In the necking stage, the plasticity of the material decreased, the intergranular gap in material developed relatively
perfect, so the AE signals were relatively flat. The AE signals generated instantaneously at the moment when the materials were pulled off, and the ringing count produced a more obvious peak value. The AE signals are in good agreement with the mechanical characteristics of specimens during the test process.

2. The load-cumulative ringing count curve was fitted by several functions, the results show that the polynomial function has the best fitting results. The expression of damage factor is expressed by the cumulative ringing counts, the cumulative ringing count calculated by this formula is close to the experimental ringing count, so it is feasible to express the damage factor of low carbon steel by the cumulative ringing count.

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