An Impact Fatigue Life Prediction Model of Metal Materials Based on Damage Mechanics

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Abstract. This article proposes a metal material impact fatigue life prediction model based on damage evolution laws. This model describes the damage evolution process of metal materials as a gradually increasing process over time, and by monitoring the changes in damage parameters, the lifespan of materials can be predicted. Meanwhile, considering the influence of the microstructure of metal materials on their fatigue performance, this paper also introduces the microscale characteristics of material parameters, further improving the accuracy and precision of the model. By comparing and verifying with relevant experimental results, it is shown that the combination of continuous damage mechanics and finite element analysis method can effectively evaluate the impact damage and subsequent fatigue life of metal structures.

Keywords: damage mechanics; Metal; Impact; Life prediction

1 Introduction

Deterministic life cannot fully reflect the probabilistic statistical characteristics of fatigue life, such as probability distribution types and standard deviations, kurtosis, and skewness. Probabilistic fatigue life should be able to characterize its probability distribution and corresponding distribution parameters. At present, most studies are based on the improvement of these models, such as Bai Enjun, who equates the fatigue life of different levels of stress to the highest level of stress, achieving the fitting of p-S-N curves under small sample sizes. Liu et al. predicted the fatigue life at the bolt holes of the turbine disc using an improved average stress formula. Luo et al. constructed a functional function for bridge fatigue damage based on the S-N curve and Miner's criterion, which is used for fatigue reliability evaluation of simply supported beam bridges. Ma Yu'e established S-N curves through fatigue experiments on glass fiber aluminum alloy laminates (FMLs), providing material properties and information for predicting their fatigue life. Doudard et al. proposed a probabilistic dual scale model under the framework of the weakest link theory for predicting the dispersion of S-N curves. Due to the complexity of impact fatigue testing methods and material impact fatigue performance description, there is currently no systematic theory, standard testing methods, and rich experimental data to guide material selection and structural design of components subjected to repeated impacts. This article relies on damage mechanics and finite element analysis methods to explore the fracture mechanism and behavior of metal materials, establish a prediction model for the impact fatigue life of metal materials, and evaluate and correct the accuracy of the model through experimental verification [1].

2 Deformation Characteristics of Metal Materials in Impact Fatigue

When studying the impact fatigue deformation characteristics of metal materials, the first step is to study the deformation characteristics of the material under a single impact load, and then study the deformation characteristics of the material under an impact fatigue load. The following will be elaborated in sequence [2].

2.1 Single Impact Load

Compared with nonimpact stress, the duration of impact stress under a single impact load is very short, only about 0.1% to 1% of the nonimpact fatigue stress under one cycle. The typical stress characteristics of metal materials under tensile impact load are shown in Figure 1.

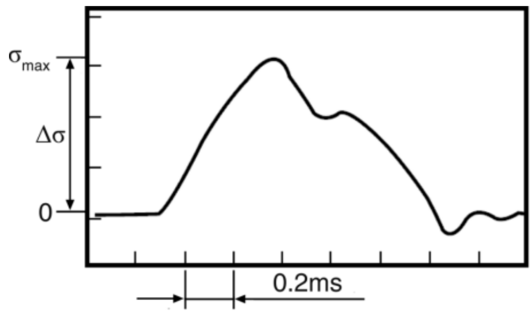


Fig. 1. Stress variation during a single impact.

2.2 Impact Fatigue Load

Due to the higher dynamic yield strength of medium carbon steel under impact fatigue loading (see Figure 2), the same maximum stress intensity factor is applied $K_{\max}$. The plastic deformation zone at the crack tip under impact fatigue is smaller than that under nonimpact fatigue (see Figure 2). Multi-system slip under impact fatigue is also more complex than under nonimpact fatigue. The measurement results of dislocation density at the fatigue crack tip also indicate that under the same conditions $K_{\max}$, horizontally, the dislocation density of nonimpact fatigue is greater than that of impact fatigue. This trend can be attributed to the susceptibility of multiple system slips under nonimpact fatigue [3].

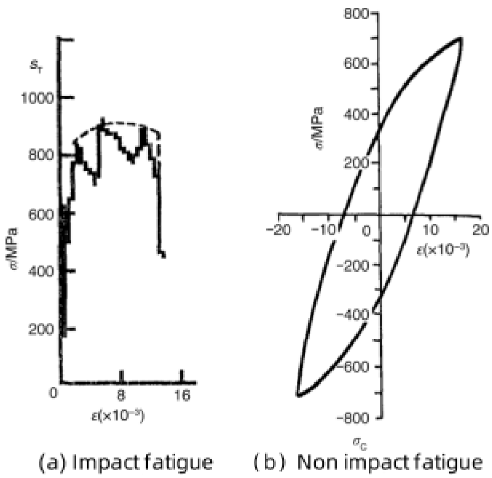


Fig. 2. Stress-strain curve of carbon steel under low cycle impact fatigue load and hysteresis loop under nonimpact low cycle fatigue load.

3 Theoretical Model

3.1 Plastic Damage Model

The uniaxial effective tensile stress and compressive stress are used as the basis for determining the yield and failure surfaces:

$$\bar{\sigma}_t = \frac{\sigma_t}{(1-d_t)} = E_0 - \left(\varepsilon - \varepsilon_t^{pl}\right) \tag{1}$$

$$\bar{\sigma}_c = \frac{\sigma_c}{(1-d_c)} = E_0 - \left(\varepsilon - \varepsilon_c^{pl}\right) \tag{2}$$

where d_c and d_t are plastic damage factors during compression or tension, respectively; ε_c^{pl} and ε_t^{pl} are the plastic strain of concrete under uniaxial compression and tension, respectively.

The mathematical expression of the D-P strength criterion includes intermediate principal stress and hydrostatic pressure, and there is no singularity caused by sharp edges and corners. Therefore, it has been widely applied and promoted after its proposal and is widely used in various large-scale numerical calculation software. The flow potential function G used in the model is the Drucker Prager function, i.e.

$$G = \sqrt{(\kappa\sigma_0 \tan\psi)^2 + \bar{q}^2} - \bar{p}\tan\psi \tag{3}$$

where the displacement of the flow potential κ approaches zero, the flow potential function approaches a straight line; σ_0 is uniaxial stress during material failure; ψ is under high lateral pressure $\overline{p}-\overline{q}$ shear dilation angle on the plane; $\overline{p}$ is the average hydrostatic pressure; $\overline{q}$ is the average equivalent effective stress.

3.2 Fatigue Damage Model

Chaboche and Lesnes proposed a nonlinear uniaxial stress fatigue damage model:

$$\dot{D}=\frac{dD}{dN}=\left[1-(1-D)^{\beta+1}\right]^{\alpha}\left[\frac{\sigma^{\alpha}}{M(\sigma_m)(1-D)}\right]^{\beta} \tag{4}$$

where N is the number of cycles; σ_a and σ_m are the stress amplitude and average stress of fatigue load, respectively; β is the material constant; α and $M(\sigma_m)$ are as follows:

$$\alpha=1-a\left\langle\frac{\sigma_a-\sigma_0}{\sigma_b-\sigma_a}\right\rangle \tag{5}$$

$$M(\sigma_m)=M_0(1-b\sigma_m) \tag{6}$$

where σ_b is the ultimate tensile strength of the material; σ_0 is the fatigue limit of the material; a, M_0 are both material constants. For metallic materials, Dattoma et al. obtained a = 0.0801; $\langle\sigma\rangle$ is Macquarie brackets (Macaulay brackets).

Lin Youzhi and others revised the above model based on the theory of distortion energy density to consider the situation of multi-axial stress

4 Prediction of Impact Fatigue Life of Aluminum Alloy

4.1 2A12 Impact and Fatigue Testing of Aluminum Alloy Plates

The shape and dimensions of the test piece are shown in Figure 3. Using a drop hammer device to produce impact pit defects, a pit with a radius of r = 3 mm and a depth of d = 0.4 mm was obtained through calibration. Then, a high-frequency fatigue machine was used to conduct two sets of fatigue tests on the sample with pit defects, with a stress ratio of R = -1 and a maximum nominal stress of 200 MPa and 230 MPa, respectively. The test results are listed in Table 1 [4].

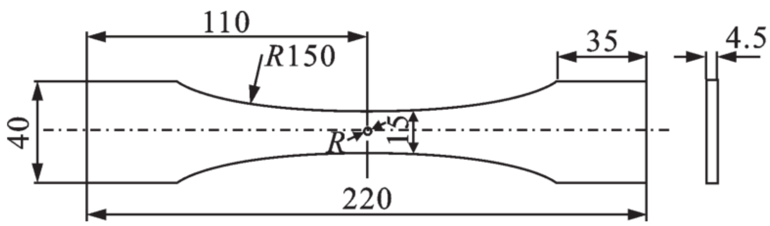


Fig. 3. Schematic diagram of geometric dimensions and impact positions of 2A12 aluminum alloy specimen.

Table 1. Fatigue test results.

Nominal stress/MPa	Number of test pieces	Fatigue life/cycle	Average lifespan/cycle	Standard deviation
230	3	56, 100 81, 300 81, 100	72, 833	11, 833
200	5	220, 200 232, 000 287, 500 220, 500 301, 500	252, 340	34, 967

Figure 4 shows the cross-sectional view of the 2A12 test piece with a 0.4 mm impact pit defect after fatigue failure.

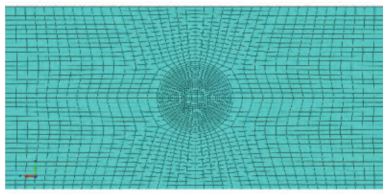
Fig. 4. The fatigue fracture surface of the 2A12 aluminum alloy test piece.

The cyclic action of impact load forms impact fatigue, and impact fatigue load has impact load characteristics. Due to the short-term and strong load characteristics of impact loads, the interior of metal materials is in a dynamic equilibrium process that rapidly changes over time. The mechanical properties of the material are determined by both external loads and internal responses. The dynamic response behavior of metal materials determines their unique impact fatigue characteristics. The rheological stress of the material is significantly higher than that of conventional fatigue, the cyclic hardening ability and fatigue strength are lower than those of conventional fatigue, the crack propagation rate is higher, and the fatigue life is relatively lower [5].

4.2 Finite Element Simulation of the Impact Process

We establish a finite element model corresponding to fatigue testing using ABAQUS software, as shown in Figure 5, mechanical performance parameters are shown in Table 2. When the impact energy is 2.64 J, the simulated pit depth obtained is consistent with the experiment. There is significant local deformation and residual stress at the impact crater, therefore the stress relaxation effect has been considered [6].The distribution of their local deformation and residual stress are shown in Figure 6 and Figure 7.

(a) Whole grid



(b) Local grid

Fig. 5. Finite element model for impact simulation of 2A12 aluminum alloy specimen.

Table 2. 2A12 mechanical property parameters of aluminum alloy.

E/MPa	ν	σ_y / MPa	σ_b / MPa	$\rho / (kg \cdot m^{-3})$
68, 000	0.33	410	547	2, 780

The distribution of equivalent plastic strain near the pit is shown in Figure 8. The equivalent plastic strain is mainly concentrated inside the pit and reaches its maximum at the bottom of the pit.

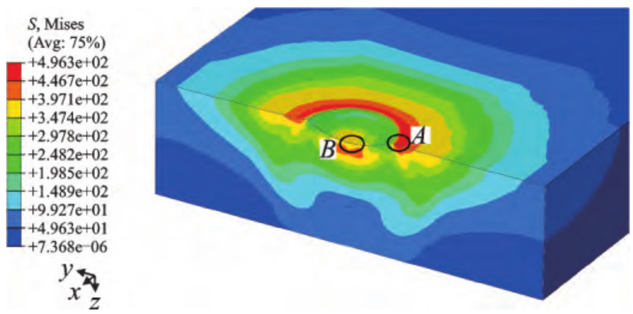


Fig. 6. Cloud map of residual stress distribution near the impact crater.

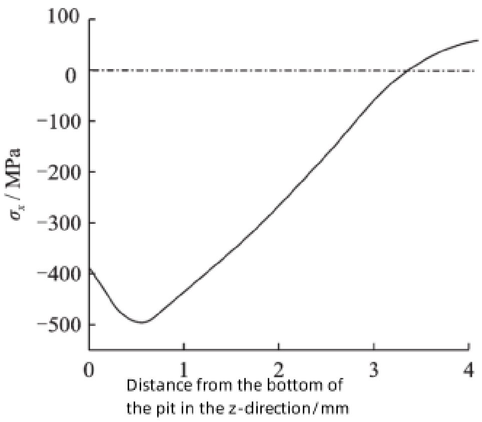


Fig. 7. The distribution curve of residual stress σ x along the z-direction (thickness direction) at the bottom of the pit.

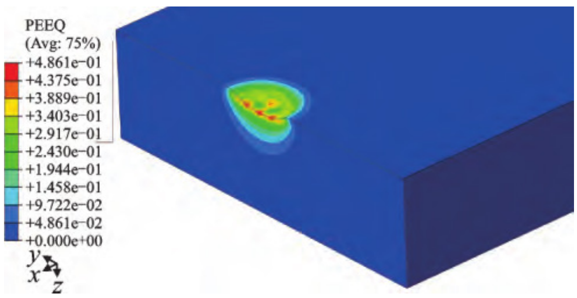


Fig. 8. Cloud map of equivalent plastic strain distribution near the impact crater.

4.3 Local Stress Simulation and Fatigue Life Prediction of Pits under Fatigue Loads

By substituting the equivalent stress, equivalent plastic strain, and other data during the impact process of Points A and B into Formula (4), the initial plastic damage of the dangerous point can be obtained, as shown in Table 3. The material parameters in the plastic damage model and fatigue damage model refer to Chen et al.'s research, and the relevant parameter values are shown in Table 4. The comparison of the fatigue test results and the prediction results of the injury model is shown in Table 5. Figure 9 shows the stress distribution of the impact pit under the subsequent fatigue maximum tensile load.

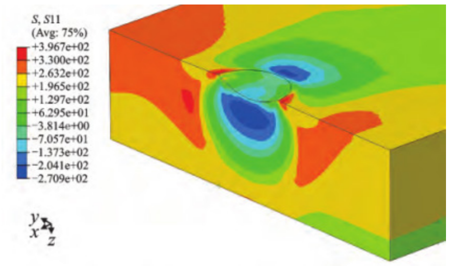
Table 3. Calculation of initial plastic damage at risk points of impact pit defects.

Dangerous points	σ_{eq} / MPa	R_v	Δp	D_0
A	496.196	0.887	0.109	0.094
B	384.606	1.409	0.486	0.362

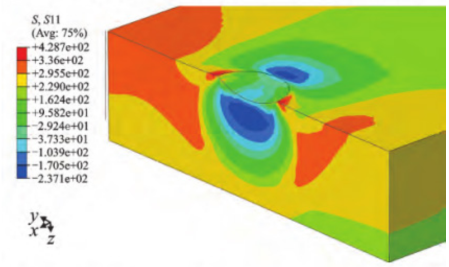
Table 4. Relevant material parameters in plastic damage and fatigue damage models.

S_0 / MPa	S_0	σ_0 / MPa	α	β	M_0	b
1.69	3	137	0.0801	1.95	114, 339	0.003

By comparing the theoretical predicted values with the experimental results, it can be seen that the predicted life based on the continuous damage mechanics model is consistent with the experimental results.



(a) Stress nephogram under consequent load of 200 MPa



(b) Stress nephogram under consequent load of 230 MPa

Fig. 9. Stress distribution of impact pits under subsequent fatigue maximum tensile load.

Table 5. Comparison between fatigue test results and damage model predictions.

Nominal stress/MPa	Test average life/cycle	Predicting lifespan/cycle	Error/%
200	252, 340	309, 193	22.53
230	72, 833	83, 108	14.11

5 Conclusion

Based on the theory of continuous damage mechanics, we research the impact of 2A12 aluminum alloy.

The impact damage and subsequent fatigue life were evaluated, and combined with fatigue testing, the accuracy of life prediction results was verified.

(1) Considering the initial damage and residual stress caused by the impact comprehensively, the influence of various factors such as stress and stress concentration on fatigue life, and prediction, the location of the measured fatigue source is consistent with the test results, and the fatigue life is consistent with the test.

The value matching proves the combination of damage mechanics theory and finite element analysis method. We can effectively evaluate the impact damage and subsequent fatigue of metal material life.

(2) Research has found the risk of fatigue fracture caused by impact pit defects points at the edge of the pit, where tensile stress dominates during the loading process, and the bottom of the pit is rushing. During the impact process, significant residual compressive stress is generated, which has an impact on fatigue failure.

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