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A mechanism of fatigue in salt under discontinuous cycle loading

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1. Introduction

The fatigue properties and their relationship with material deformation, damage and failure is an important topic in geotechnical engineering field, including rock cutting, drilling and blasting, underground openings, supports and rock pillars.[1–6] In recent years, the Chinese Government has constructed many underground oil gas storages in rock salt layer to ensure energy supplies and reserves. Owing to the influence of periodic injection-production action and seasonal temperature variation, understanding the fatigue behavior of rock salt becomes crucial for ensuring safety and stability of storage caverns.[6] In recent years, much research has focused on the effects of various factors on fatigue in salt and other rocks. Song et al.[6] and Fuenkajorn and Phueakphum[7] studied the effects of cyclic loading on mechanical properties and acoustic emission for Pakistan salt and Maha Sarakham salt, respectively. Grgic and Giraud[8] studied the influence of different fluids on the static fatigue of a porous rock and the mechanical-chemical coupling effect. Erarslan and Williams[9,10] examined the damage mechanism of rock fatigue and its relationship to the fracture toughness of rocks using Brisbane tuff disc specimens. Le et al.[11] reported a comprehensive set of size effect on fatigue crack kinetics for Berea sandstone. Mellouli et al.[12] studied the impact of thermal fatigue damage on hardness effect for hot-working tool steel. These references provided a number of ways to interpret and characterize the fatigue behaviors, such as residual strain, elastic module evolution and acoustic emission.

A salt mine in Jintan, Jiangsu province, China, composed of sixty-three underground salt caverns (USCs) serves as a gas storage group since 2007. Fig. 1 shows its periodical variation in gas pressure within one year.[13] As the gas pressure maintains the maximal value for three months (from sixth month to ninth) until the gas production, the storage wall/pillar rock around USCs will be subjected to a relatively smaller deviatoric stress to ensure that USC capacity loss by creep action is slow[14–17] This equivalently brings storage wall rocks combined stress composed of cyclic pressure and intervals of non/small deviatoric stress. However, the investigation into this essential factor (intervals) has rarely been made. This work experimentally explores the impact of non-stress interval on the fatigue in salt. The results would contribute to enriching the knowledge comprehensiveness of the factors that impact the safety of gas storage and the accuracy in designing and estimating fatigue life of gas-storage facilities.

2. Experimental conditions

2.1. Samples and experimental techniques

The loading equipment used in the tests was a conventional mechanical rigid testing machine, which was developed and manufactured in the State Key Laboratory for Coal Mine Disaster Dynamics and Controls. The rock salt samples were collected from the Khewra salt mine in Pakistan. The rock salt consists of a high purity of NaCl (greater than 96%), small amounts of K_2SO_3 (around

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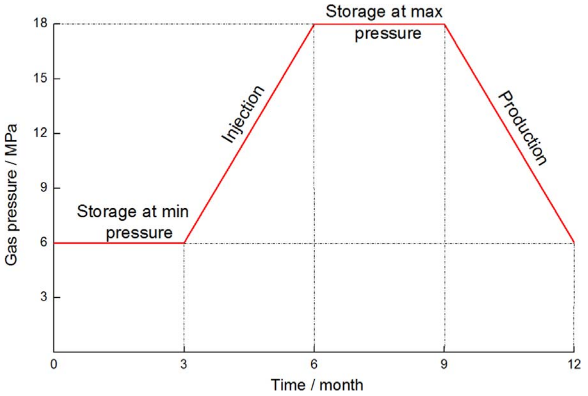

Fig. 1. Working path of gas pressure of underground salt cavern in one year.

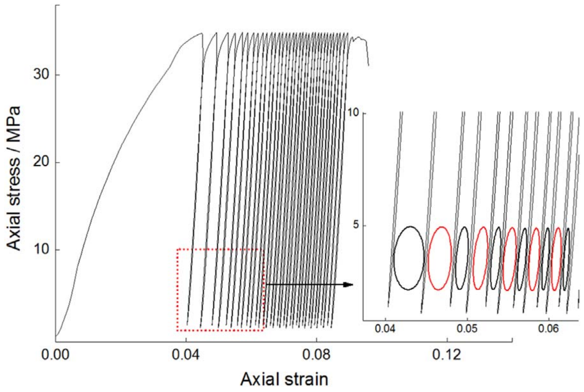

Fig. 2. Entire strain–stress curve of interval fatigue test with 5 min intervals. The red ovals represent the strain increments from the S cycles; the black ovals represent the strain increments from the N cycles.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.1%), some mud and other undissolved substance (less than 0.9%). The samples were shaped into standard cylindrical blocks of 50 mm diameter and 100 mm length. Duplicate tests were conducted to enhance the reliability of the results.

2.2. Experimental methods

The loading path used in our experiments combined cyclic stress and intervals. The experiments were performed at a loading velocity of 2kN/s. The upper and lower stress are set at 34.8 MPa (85% of the compression strength 41 MPa)[6] and nearly 0 MPa, respectively. The first loading and unloading period (or cycle) is marked as the *F* cycle, the normal stress cycle (immediately following a cycle) is the *N* cycle, and the spaced cycle (immediately following an interval) is the *S* cycle. The stress path in tests is: *F–N–interval–S–N–interval–S–N–interval–S…to failure*. Each fatigue test has a given interval duration; tests with durations of 5, 10, 15, and 20 min were run (Table 1). No significant effect of working order of the *S* and *N* cycles was observed via a confirmatory test (stress path: *F–interval–S–N–interval–S–N–interval–S–N…to failure*).

3. Experimental results

3.1. The accumulation of the irreversible deformation

Under normal/conventional conditions, the spacing closeness of every cycle's strain-stress curve will undergo three phases, sparse-dense-sparse.[6,13,14] Three phases correspond to three phases of deformation-evolution, respectively. Fig. 2 shows the axial stress-axial strain curve and the typical phase feature. The width of the ovals among the curves represents the distance between loading lines and unloading lines, namely, the strain increment in each cycle. The black ovals are obviously narrower than the red, which implies a difference in deformation characteristics compared to normal/conventional fatigue stress-strain curves.

Sample deformation can be decomposed into reversible and irreversible components. The reversible component is induced by the elasticity of rock, while the irreversible component can be induced by plasticity or fatigue behavior of rock. In this study, the irreversible component is termed residual strain, which is calculated by subtracting each strain value that corresponds to lowest stress. Fig. 3 shows the residual strain accumulation with the stress cycle number. The compressive strain is defined to be positive, whereas the extension strain (expansion) is negative. As shown by the enlarged local region, in *S* cycles, the speed of accumulation is faster. This phenomenon indicates that a distinct difference in deformation evolution exists between *S* and *N* cycles. For a clear presentation of the difference, the residual strains from *S* and *N* cycles are summed separately (Fig. 4), excluding *F* cycle. The accumulation of residual strain from *S* cycles is notably faster than that from *N* cycles. From Table 1, it can be found that the total residual strains keep constant with a negligible float; the average residual strain from *S* cycle is larger 18–60% than *N* cycle.

3.2. Variation of residual strain ratio

The development of residual strain can reflect the damage progress inside the rock salt. We define the ratio of residual strain and total strain to track the dynamic development of irreversible deformation, based on the axial deformation. The calculated

Table 1
Residual strain and fatigue life of samples from tests carried out with intervals of different duration. Numerical values in some blanks are axial deformation, radial deformation, and volumetric deformation. For the test that combines different intervals, parameters of the first six cycles are excluded from the average of the residual strain. The last cycle is not concluded in the fatigue life.

Tests	Interval duration	Total irreversible deformation/ $\times 10^{-2}$	*N* cycle/ $\times 10^{-3}$	*S* cycle/ $\times 10^{-3}$	Ratio of *S/N*	Fatigue life
Test with constant intervals	0	8.08/-/-	1.37/-/-		-/-/-	58
	5 min	8.31/−8.39/−8.35	1.14/−1.60/−2.06	1.49/−1.98/−2.50	1.31/1.24/1.21	34
	10 min	8.18/−7.76/−7.35	1.48/−1.88/−2.28	1.74/−2.26/−2.78	1.18/1.20/1.22	24
	15 min	7.16/−7.69/−8.22	2.33/−3.47/−4.61	2.84/−4.82/−6.58	1.22/1.39/1.43	13
	20 min	8.44/−8.35/−8.26	1.70/−2.48/−3.26	2.52/−3.86/−5.21	1.48/1.56/1.60	20
Test combining with different intervals	0	8.19/-/-	0.86/-/-	–	–	39
	5 min		–	0.93/-/-	1.08/-/-	
	10 min		–	1.00/-/-	1.16/-/-	
	15 min		–	1.03/-/-	1.20/-/-	
	20 min		–	1.15/-/-	1.34/-/-	

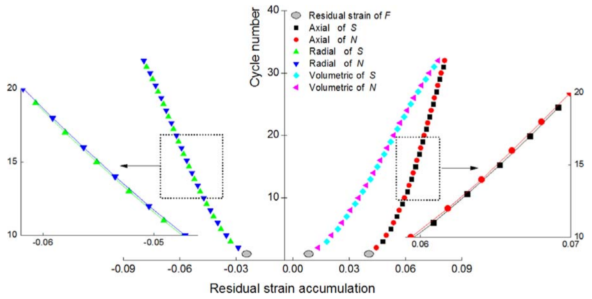

Fig. 3. Accumulation curve of residual strain from interval fatigue tests for time intervals of 5 min Two selected local regions are enlarged on the right. To avoid the overlap of radial strain accumulation lines and volumetric strain accumulation lines, the sign of the volumetric strain is reversed.

results are plotted in Fig. 5. This ratio is very large in the first cycle, declines slowly and fluctuates at a certain level, then rise slightly when the failure is approaching. During the fluctuation, the ratios of *S* cycles are markedly larger than those of *N* cycles, suggesting that the plastic strain develops more in *S* cycles.

3.3. *The features of fracture*

Fracture types of samples from the interval fatigue tests are similar to those from uniaxial tests.[6] As the cyclic stress proceeds, the sample just deformed progressively, but no visible fracture appeared. When the sample approached failure (in the last one to two cycles), a visible fracture on the surface initiated in the centre of samples, then extended rapidly to the edges of two ends, formed X-like cracks, and eventually samples were separated into two cone-shaped bodies with some fine fragments. The fracture was defined mainly by mixed pattern of splitting and shear slide, which are typical for rock salt, one kind of soft rock. Cracks forming inside the samples principally include shear cracks and tensile cracks. The characteristic sample cross section (perpendicular to axial direction) of samples was examined by scanning electron microscope. Parallel intragranular cracks, which may be caused by the rupture of grains under tensile stress, stretch into the internal of rock salt (see Fig. 6). Fine fragments around the cracks may result from shear damage, which induces micro-fractures and frictional kneading of the grains.

4. Discussion

4.1. *The impact of interval on fatigue life*

Samples under the same conditions (including stress and environmental condition) have the similar total residual strain at the time of their failures.[18] If the residual strain of each stress cycle is extended, the fatigue life should decline. The total residual strain, fatigue life and related parameters of samples are listed in Table 1. The fatigue life tends to decrease with increasing interval. Owing to the discreteness of samples on the mechanical behavior, some data slightly deviate from the tendency. We therefore conducted one extra test, in which different durations of interval were combined on one single sample, thereby avoiding the discreteness. The loading path was as follows: *F–N–interval (5 min)–S–interval*

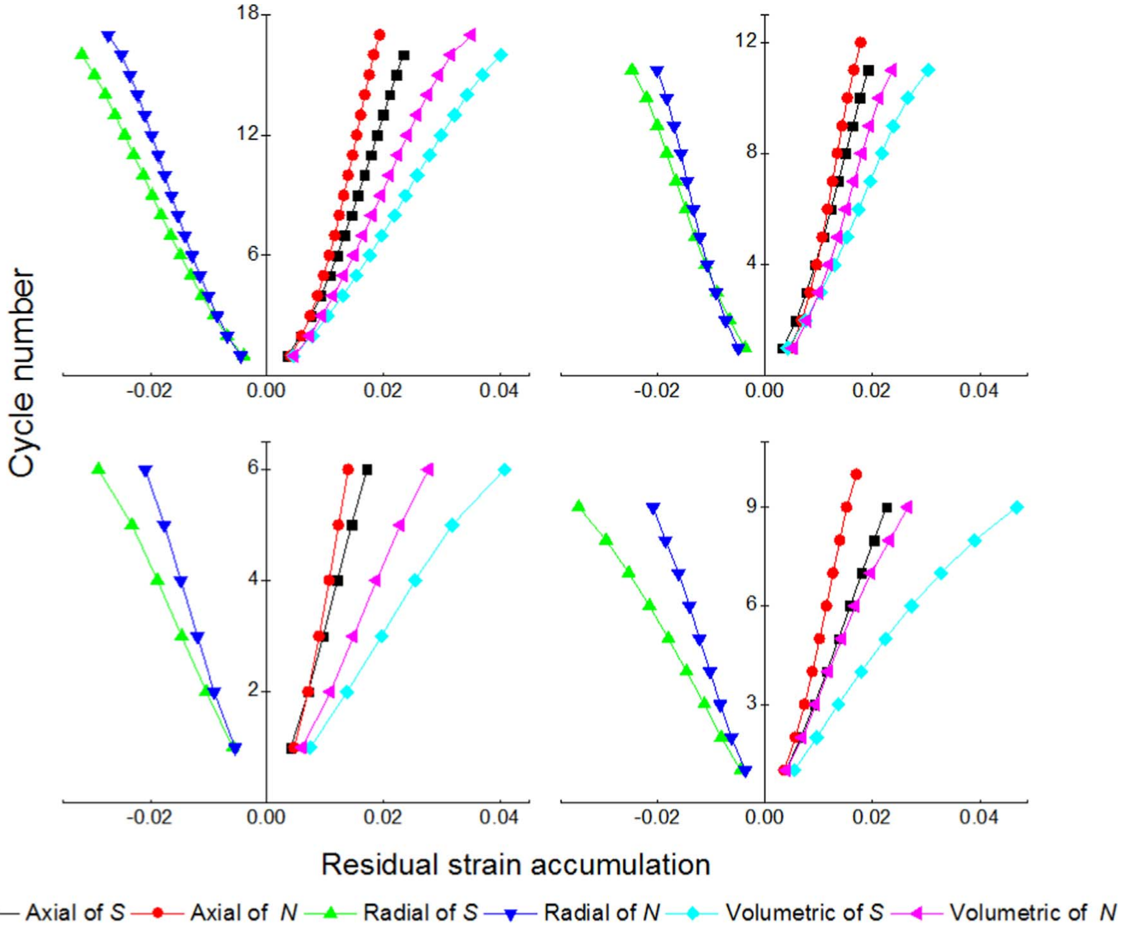

Fig. 4. Separated residual strain accumulation of S cycles and N cycles for interval fatigue tests for (a) 5-, (b) 10-, (c) 15-, and (d) 20-min intervals. For a clear presentation, volumetric strain is reversed.

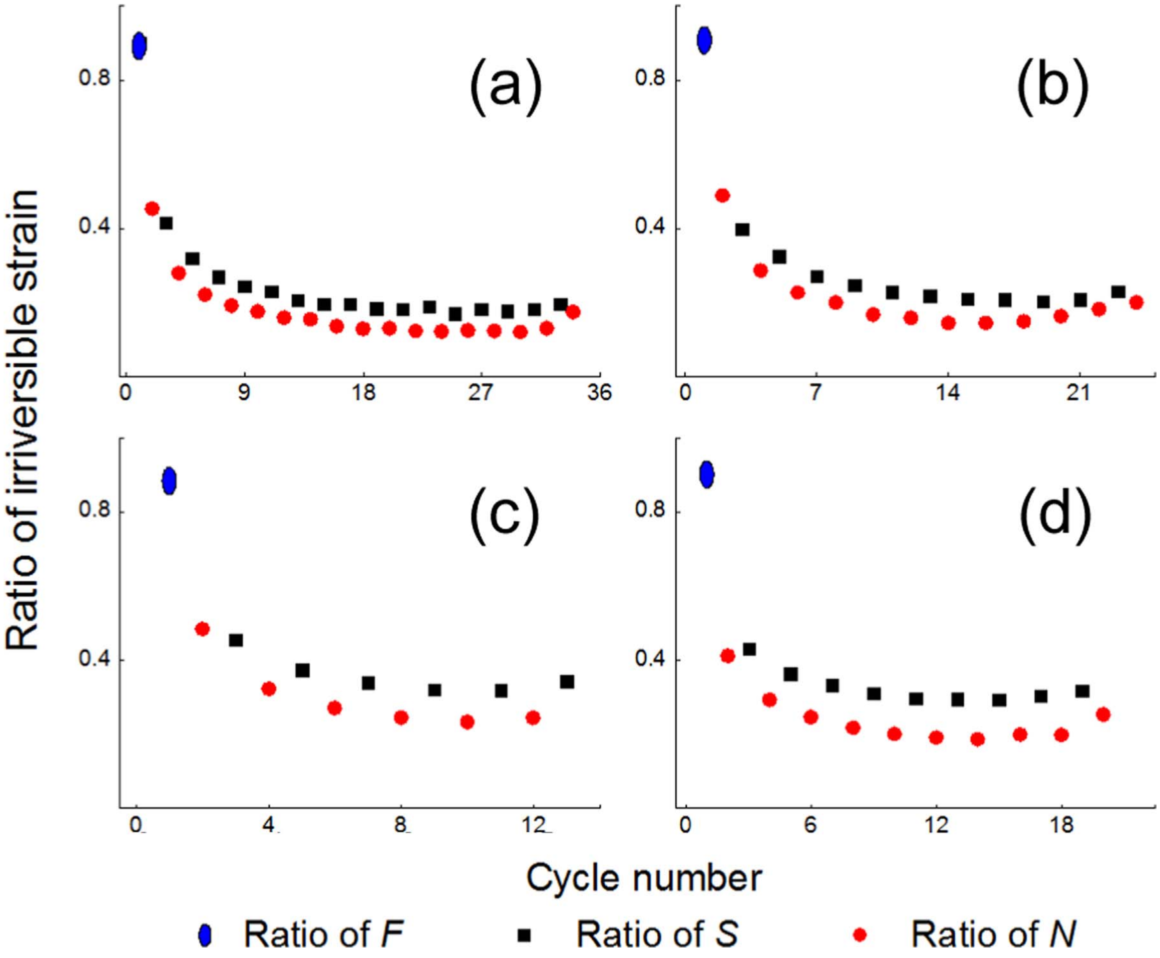

Fig. 5. Ratio of residual strain and total deformation of interval fatigue tests for (a) 5-, (b) 10-, (c) 15-, and (d) 20-min intervals.

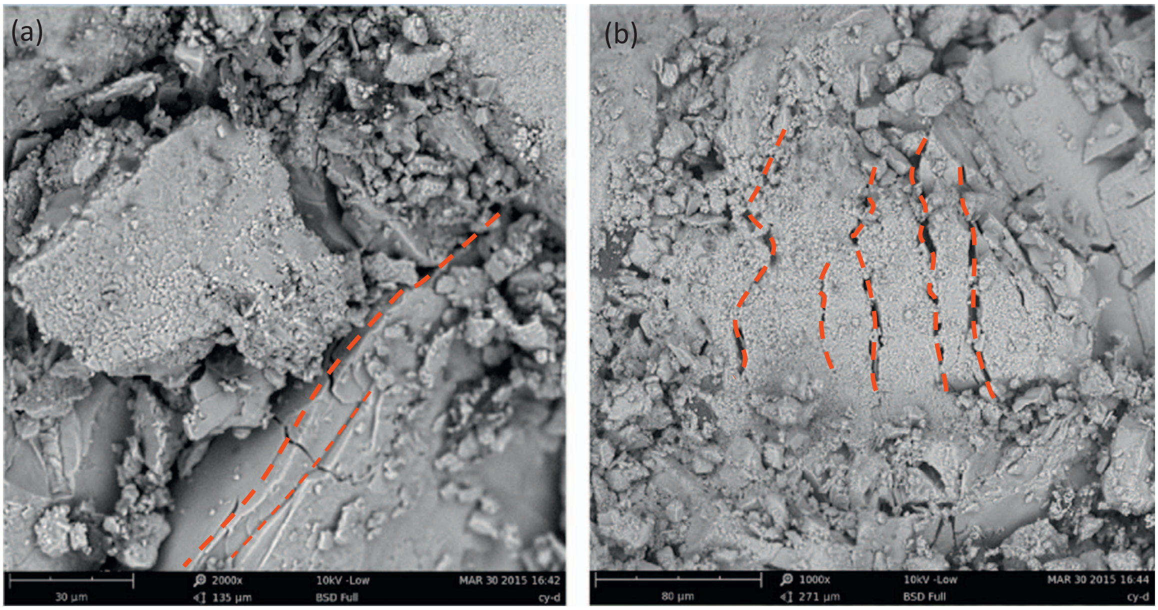

Fig. 6. Scanning electron microscope images of a cross section from interval fatigue tests for 5-min intervals.

(10 min)–S–interval (15 min)–S–interval (20 min)–S–N–interval (5 min) –…… – failure. The axial residual strain is shown in Fig. 7.

The statistical results of the average residual strains suggest that a longer duration of the intervals results in a larger residual strain. According to the limit strain criterion,[18] if intervals of different duration (from 5 min to 20 min) were combined with every stress cycle, the fatigue life would reduce approximately 1-(1/1.08)=7.4%, to 1-(1/1.34)=25%, for the sample in the extra test. Therefore, we confirm the trend that the time interval reduces the fatigue life of rock salt by increasing residual strain. A longer

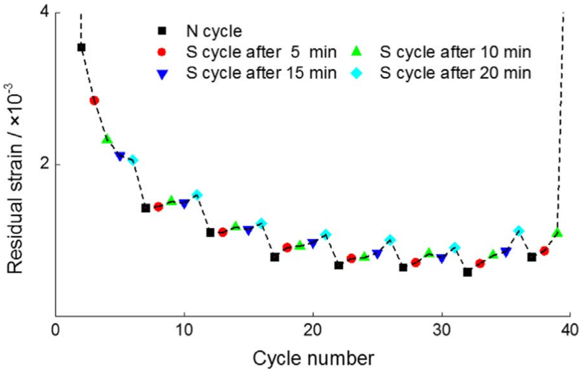

Fig. 7. Axial residual strain from the extra test. This parameter for the first and last cycles is 38.9 and 7.3, respectively. To ensure a clear presentation, they are not shown.

duration of intervals causes a diminishing fatigue life.

4.2. Internal residual stress

Understanding the larger residual strain in *S* cycles (or the reduced fatigue lives) involves two questions. First, what governs the irreversible deformation of materials? The irreversible deformation of materials could arise from a variety of inelastic deformation activities, such as dislocation slipping, grain decohesion (or grain rupture), microcracks and fractional sliding.[19–23] The rock salt used in the tests can be considered as a kind of polycrystalline material, whose inelastic deformation is strongly correlated to dislocation motion.[24] Another question is what affects the dislocation motion and how this occurs. Because the plastic action of rock salt is defined by dislocation slipping, its deformation regime and behavior are similar with metal, to some extent. In the field of metal welding,[25] spray coating layer[26] and so on,[27,28] internal residual stress (IRB) was identified as the reason in weakening the fatigue life of machine part and coating layer, which serve as an important reference value. IRB usually arises and develops when uncoordinated deformation of crystal grains or elements is induced by different swell-shrink parameters or non-uniform mechanical responses.[29] The following paragraph will explain the generation of IRB in rock salt and its influence to fatigue life.

Crystal dislocations are produced in loading period, they slip and are impeded by obstacles inside the rock salt. During the unloading period, most of the dislocations attempt to return to their original sites under the interaction of the stacks of crystal dislocations. Normally, if all material parts are intact, the internal stress will release with unloading stress. However, on account of fatigue damage, the mechanical parameters of materials in different stress-concentrated areas will change with plastic action. Materials of different mechanical properties would have uncoordinated mechanical responses like metal welding and spray coating layer. Internal stress cannot be release completely, then IRB results. During intervals, the IRB will reverse the dislocations. Longer intervals will yield longer backtracking distances. Bauschinger effect[24] will make it easy for dislocations to slip back and surmount the obstacles. After intervals, the longer backtracking distance enhances the Bauschinger effect, and results in a larger increment of plastic deformation in the next stress cycles (*S* cycles). As a consequence, fatigue lives are shorter.

5. Conclusions

This paper reports the evidence that intervals have a strong impact on the rock salt fatigue performance. All results suggest that intervals can accelerate the development of residual strain accumulation in cyclic stress. The residual strain of *S* cycles (the cycles after intervals) is notably larger than that of *N* cycles (the cycles before intervals). Plastic deformation is in a greater proportion within total deformation for the *S* cycles compared with *N* cycles. The fatigue lives of the samples in interval fatigue tests are lower than normal/conventional values and decline with the duration of intervals. The reason for this decrease is identified as the internal residual stress caused by uncoordinated mechanical response in different concentrated stress regions.

Acknowledgments

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