Evaluation of the Cumulative Fatigue Damage on the Spot Welded Joints using 590 MPa-class Steel under Random Loading Conditions

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Abstract

In this study, fatigue tests were carried out under constant and random loading conditions using the spot welded joints whose base metal was 590 MPa-class automobile steel in order to investigate about fatigue properties of joints under practical loading conditions. Fatigue tests were carried out under some kinds of load ratio because general automobiles have been taken the loading with various mean load. As the result, fatigue life is decreased involved with the increase of the mean load. Then, the effect of the mean load was found to be arranged using the equivalent load amplitude based on the modified *Goodman*'s diagram. In this study, the estimation method of the cumulative fatigue damage was proposed based on modified fatigue test results mentioned above. As the result, the proposed method satisfied with the typical standard in automobile industry on the cumulative fatigue damage under random loading conditions. Furthermore, more precise estimation is expected in this method to account for the additional mean load effect involved with the deformation near the welded spot.

Introduction

Spot welding used in various industrial fields is the typical technology on thin structures because it has some advantages such as high workability, low running cost or easiness of the automation. Especially, spot welding technology accounts for approximately 90 percentages on the joint method of the car body in the automobile industry[1]. Therefore, the spot welding technology has played an important role on the joint of thin structures.

Recently, technologies which lighten the automobile weight have been developed using the high strength steel for the solution of global environment problems like global warming in automobile industries. Involved with the application of the high strength steel, many studies about fatigue properties of the spot welded joints under constant loading conditions have been reported from the viewpoint of the strength design [2-7]. However, a few reports are published about fatigue properties of the joints under variable loading conditions nevertheless the automobile construction has been taken the loading which varies randomly on service [8]. Especially, few study has considered about the effect of random loading condition on fatigue characteristics of the spot welded joints[9].

In this study, fatigue tests were carried out under random loading conditions using the spot welded joints which has 590 MPa-class high strength steel applied in general automobile in order to examine the effect of the random loading on fatigue properties of that joints. In addition, the quantitative evaluation method was proposed on the cumulative fatigue damage of the spot welded joints from experimental results under random loading conditions.

Specimen and Experimental Method

Cold-rolled 0.8-mm-thick high-strength steel, JIS SPFC590Y, with a low yield ratio was used as the base metal in this study. This material has been used in automobile body in general. Table 1 and 2 show the chemical composition and mechanical properties of this material respectively. On the preparation of specimens, the spot welding was conducted using two thin plates which were machined into the shape presented in Fig.1. The welding conditions were unified so that the nugget in the welded spot, which was the welded area of the spot, had the diameter of 4.7 mm.

Static tensile and fatigue tests were conducted using a servo-hydraulic testing machine (Shimadzu Corporation). At this point, the unique jigs which enable to move toward thickness direction were used for the attachment of specimen so that the specimen had no initial bending stress on the welded spot before the fatigue tests. Then, fatigue tests were conducted at 5~20 Hz, with a load ratio of 0.05 at room temperature under constant loading conditions. Moreover, the discontinued cyclic number was defined as $N=10^7$ cycles on running out of fatigue tests. It is mentioned later about details of fatigue test under random loading conditions.

Table1 Chemical composition of JIS SPFC590Y (mass%)

C	Si	Mn	P	S	Fe
0.06	0.63	1.61	0.009	0.004	Bal.

Table2 Mechanical properties of JIS SPFC590Y

0.2% proof stress (MPa)	Tensile stress (MPa)	Elongation (%)
354	612	28

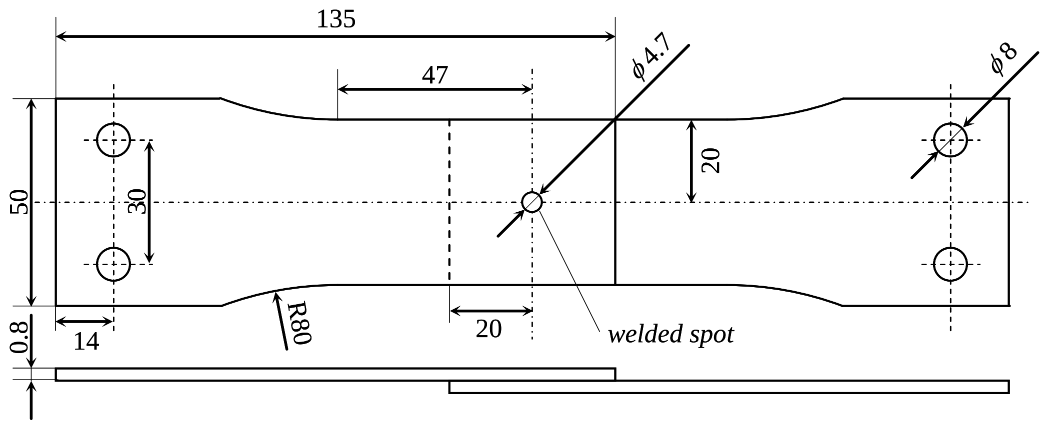


Fig.1 Shape of specimen and dimensions.

Experimental Results

Static Tensile Test Results and Fatigue Test Results under Constant Loading Conditions

Figure 2 shows the typical static tensile test result of the spot welded joints. A loading rate was 0.1kN/sec. In Fig.2, the vertical and lateral axes indicate the tensile shear load and the displacement respectively. Conducting static tensile tests using a few specimens, they hardly had the noticeable difference. Then, the averaged maximum tensile load was 8.4kN. Although it is difficult to evaluate quantitatively the tensile strength of specimen used in this study because of the complex stress state near the welded spot, the maximum tensile load corresponds to 480 MPa of the nominal shear stress which is defined as the load divided by the nugget area.

Fatigue test results under constant loading conditions are shown in Fig.3. In Fig.3, the vertical and lateral axes indicate the load amplitude and the number of cycles to failure respectively. As the fatigue test result shown in Fig.3, the fatigue limit of the spot welded joints was 0.7 kN which corresponded to 20 MPa of the nominal shear stress. Then, it was found that the fatigue limit was remarkably low compared with the tensile strength of the base metal (σ_B=612 MPa) and that of the joint's own self.

In addition, there was the obvious loading dependency on the fatigue fracture morphology as the macroscopic observation result after the fatigue test. Figure 4 shows macroscopic fracture morphologies. In the region of the high load amplitude and short fatigue life, the static fracture was observed toward loading direction when the fatigue crack, which had penetrated the thin sheet, propagated around the welded spot as shown in Fig.4(a). In this study, this fracture morphology is referred as *the Button fracture*. On the other hand, in the region of the low load amplitude and long fatigue life, the fatigue crack propagated around the welded spot after it penetrated the thin sheet like the *Button fracture*. After that, specimen was fractured statically when the fatigue crack had propagated toward width direction as shown in Fig.4(b). Then, this fracture morphology is referred as *the Base-metal fracture*. Now, paying attention to Fig.3, fatigue test results hardly has scatter nevertheless the macroscopic fracture type is differed involved with the load amplitude. At this point, it has been found that the fatigue propagation life in the base metal is comparatively short over the whole fatigue life[10]. Therefore, fatigue test results are thought to be arranged in unity because the fatigue propagation life in the base metal hardly contributes to the whole fatigue life.

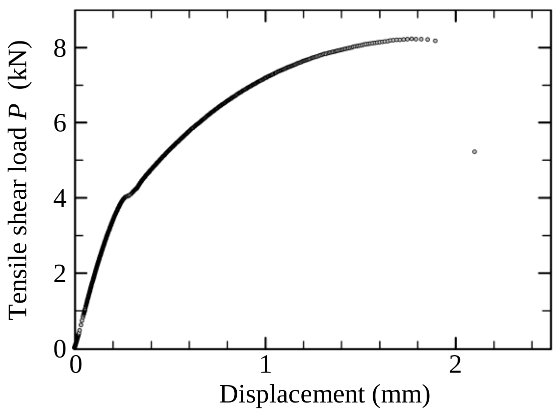


Fig.2 Result of static tensile test

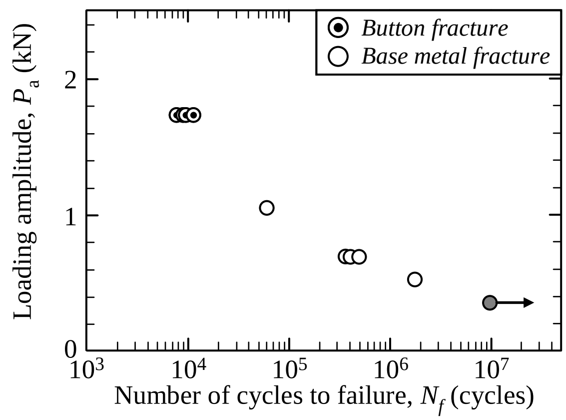
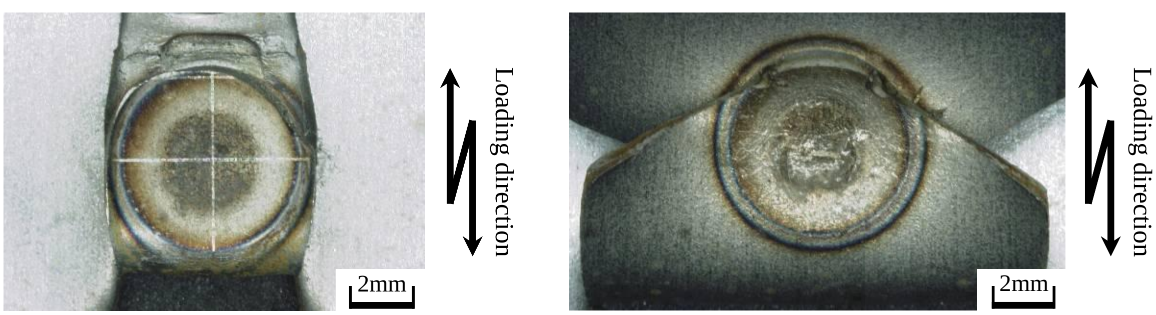


Fig.3 Result of fatigue tests.



(a) *Button fracture*

(b) *Base metal fracture*

Fig.4 Macroscopic fracture morphologies

Effect of the Mean Load on the Fatigue Life

Normally, automobiles are thought to be taken the loading which varies randomly in service. Therefore, it is thought that the car body is taken the loading with various kinds of the mean load and load amplitude. Then, the effect of the mean load on the fatigue life was investigated conducting fatigue tests under constant loading conditions with various kinds of load ratio defined as the ratio of maximum and minimum load. Figure 5 shows fatigue test results conducted under constant loading conditions with four kinds of load ratio. As shown in Fig.5, it is clear that the fatigue life is decreased as the mean load increases. Therefore, it was found that the mean load affected the fatigue life of the thin structure which was jointed using the spot welding technology.

In this study, the rearrangement of the fatigue results which accounted for the mean load was considered following idea of the fatigue limit diagram in order to evaluate the fatigue life in unity. Although many fatigue limit diagrams have been proposed, the modified *Goodman*'s diagram shown in equation(1) was applied to evaluate the effect of the mean load in this study.

$$P_{eq}=\frac{P_a}{1-\left(P_{mean}/P_B\right)} \qquad (1)$$

P_a :Loading amplitude [kN]
P_{mean} :Mean loading [kN]
P_B :Maximum tensile loading [kN]

Figure 5 shows also rearranged fatigue test results using the equivalent load amplitude P_{eq} obtained from the calculated original fatigue tests based on the modified *Goodman*'s diagram. As shown in the figure, original fatigue test results seem to be arranged correctively. So, it is enable to evaluate the effect of the mean load on the fatigue life of the spot welded joints using the modified *Goodman*'s law.

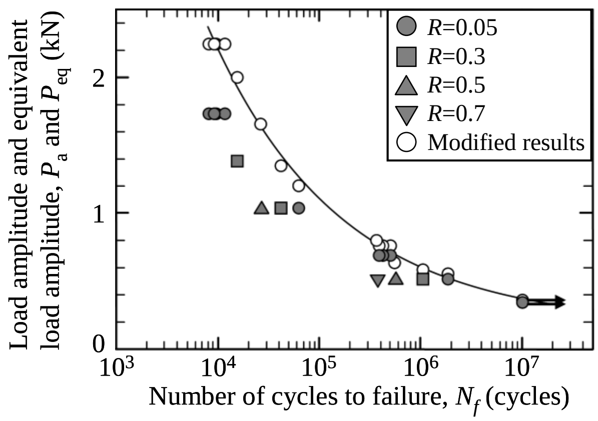


Fig. 5 Fatigue test results under the constant loading conditions with various stress ratio and arranged *P-N* curve by the modified Goodman's law

Experimental Method on Random Loading Fatigue Tests

In the execution of fatigue tests under random loading condition, random analog output signals were applied to tests using the digital simulation by the computer. In detail, random output signals were simulated using the stationary *Gaussian* random process whose mean value equaled to 0 as shown in equation(2). In this study, a thousand extreme values were applied to the random loading wave in one loop. At this point, each extreme value was complemented with the half-cosine wave whose test frequency was 10 Hz. Thus, the testing machine was operated using the output signals through the analogue input-output transformation device.

$$x(t)=\sum_{k=1}^{N}2\sqrt{S(\omega_k)\Delta\omega}\cos\left(\omega_k t+\phi_k\right) \qquad (2)$$

$S(\omega)$:Function of the power spectrum distribution
N :Divided number of the power spectrum
$\Delta\omega$:Divided number of the angular frequency
t :Time
ϕ_k :Uniform random number in $[0, 2\pi]$

In this study, two kinds of random loading wave were prepared for considering about the effect of the rate of the load amplitude below the fatigue limit on the fatigue damage of the spot welded joints. One is the narrow-band random loading pattern which is consisted with the load amplitude above the fatigue limit. Another is the broad-band random loading pattern which includes also the load amplitude below the fatigue limit. The narrow-band one was prepared to remove the load amplitude below the fatigue limit on the broad-band random loading pattern. On the other hand, the broad-band random loading pattern was simulated using the unified power spectrum distribution as shown in Fig.6. In addition, each random loading pattern has the optional mean value to avoid acting the compressive loading to the spot welded joints during the fatigue test. That is to say, all random fatigue tests were conducted under the positive load ratio. Fig.7 and 8 show a part of the typical broad-band and narrow-band random loading waves respectively.

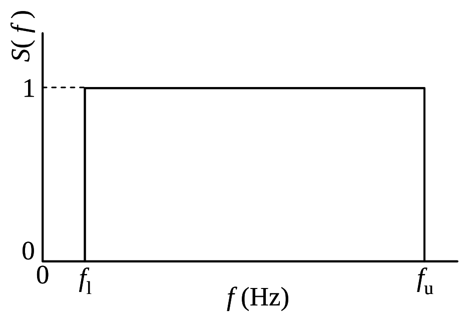


Fig.6 Power spectrum distribution

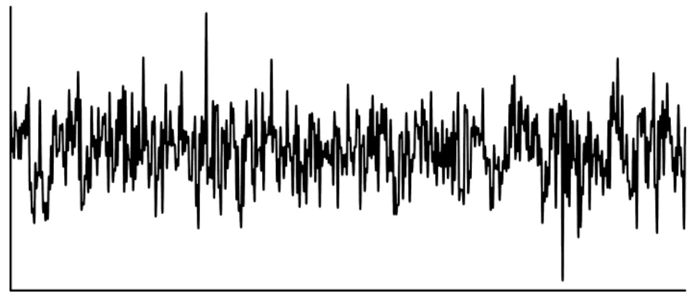


Fig.7 Instance of the pseudo widespread random loading pattern

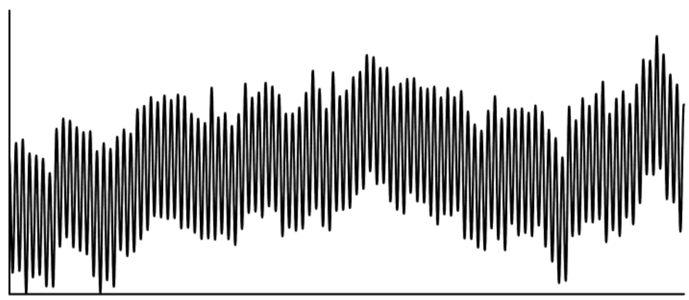


Fig.8 Instance of the pseudo narrow band random loading pattern

It has been clarified that the spot welded joints has comparatively high percentage of the fatigue crack initiation life over the whole fatigue life from the previous study [10]. Therefore, the fatigue life was evaluated using the linear cumulative damage rule based on the external loading which acted to the joints. The cumulative fatigue damage value D was calculated using the following equation.

$$D = \sum_{k=1}^{N} \frac{n_i}{N_i} \qquad (3)$$

In equation(3), N_i means the estimated fracture life which was obtained from the modified S-N curve as shown in Fig.5. In addition, n_i means the actual number of cycles on some load amplitude. Furthermore, the actual load amplitude which acted to the joints was extracted applying the rain flow method for input signals obtained from the load cell of the testing machine.

Now, the actual fatigue damage occurred at the local region of the welded spot though the cumulative fatigue damage was calculated using the input signals from the load cell. So, it is necessary to confirm the correspondence between the behavior of input signals from the load cell and the local response near the welded spot for evaluating the cumulative fatigue damage properly.

Figure 9 shows the relationship between the wave of voltage signals obtained from the load cell and the local strain behavior near the welded spot. The local strain near the welded spot was measured using four strain gages as shown in Fig.10. Moreover, results of the local strain were arranged with the absolute value in Fig.9 after their results were averaged. In Fig.9, their results were normalized using the maximum value of input voltage signals and the local strain value in a loop of the random testing wave to compare their behavior.

From Fig.9, their behavior has good accordance qualitatively. So, the cumulative fatigue damage near the welded spot can be evaluated properly using input signals from the load cell. This fact was confirmed about several random loading tests.

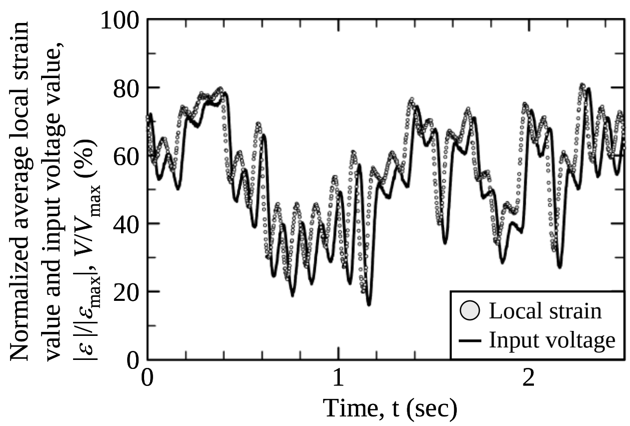


Fig.9 Behavior of averaged local strain value and input voltage

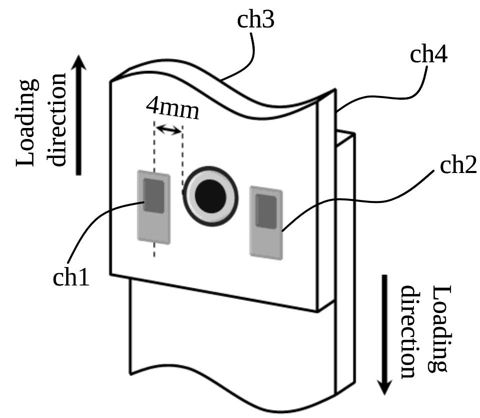


Fig.10 Position of the strain gauge near the spot weld

Experimental Results of Random Fatigue Tests

Figure 11 shows the test results under random loading conditions. In this figure, the vertical and lateral axes represent the cumulative damage value based on the linear cumulative damage rule and the rate of the load amplitude below the fatigue limit in a loop of the random loading wave respectively. As shown in the result, cumulative damage results distribute above 0.5 considering the mean load effect. Generally, the fatigue damage evaluation is though to be proper when the cumulative damage value converges from 0.5 to 2.0 in automobile industry. The proposed evaluation method in this study was satisfied with the typical standard mentioned above.

Figure 11 also shows the cumulative damage value considered without the mean load using the solid circular symbol. In that results, cumulative damage values were calculated using fatigue test results under the constant loading condition with the load ratio of 0.05.

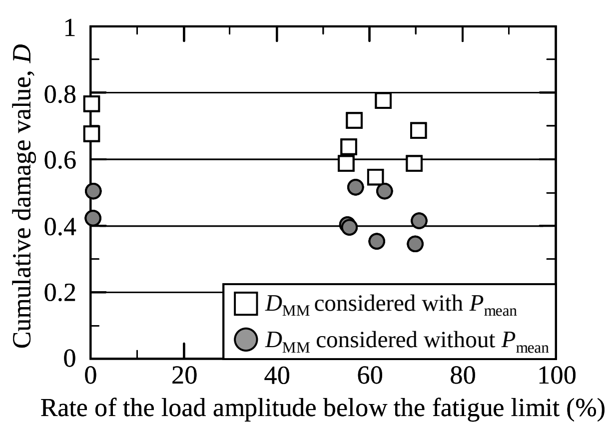


Fig.11 Relationship between cumulative damage value and rate of the load amplitude below the fatigue limit

Their results mostly distribute below the cumulative damage value of 0.5. In some case, it indicated remarkable low value such as 0.36.This experimental fact implies that the extreme un-conservative expectation is obtained from this evaluation method which considers no mean load effect. In other words, the mean load affects the fatigue life of the spot welded joints remarkably under random loading conditions.

As the results mentioned above, the proposed evaluation method in this study is very useful in practice because it is easy to evaluate so that the damage value is calculated using only the external loading. In addition, it is another advantage to obtain results with the comparable high precision. At this point, the cumulative damage value was not affected by the rate of the load amplitude below the fatigue limit in a loop of random loading wave as shown in Fig.11. This result means that it is enable to apply the proposed method widely about various kinds of the random loading wave in practical objects.

The Effect of the Mean Load Involved with the Local Strain Behavior

So far, it has been shown that the proposed method is applicable on the cumulative damage evaluation. However, results of the cumulative fatigue damage distribute below the value of 1 though their results indicates near the value of 1. This result means that the proposed method gives the un-conservative prediction on the fatigue life estimation.

Figure 12 shows the local strain behavior in absolute vale in some fatigue test result under repeated two-step loading condition. Then, the fatigue test was carried out under the loading with 1.73 kN as the high level load amplitude P_H and that with 1.04 kN as the low level load amplitude P_L. The position of the measured local strain is same as shown in Fig.10. Moreover, the test result was arranged using the averaged value from four strain gages in the absolute value. As shown in Fig.12, the averaged local strain value was increased with approximately 150 με involved with the high level load amplitude. After that, there was stationary on the behavior of the local strain in the low level load amplitude P_L. Therefore, it is thought that the deformation formed by the high level load amplitude P_H affects the deformation behavior on the low level one P_L after P_H So, it is assumed that the increase of the local strain, which is the deformation increased by the maximum load in P_H, adds to P_L as the local mean load. The proposed method as mentioned before does not account for that deformation near the welded spot because it estimates the fatigue damage of the spot welded joints using only the apparent external loading which acts to the specimen. These facts caused that un-conservative prediction was still obtained on the cumulative fatigue damage of the spot welded joints nevertheless accounting for the effect of the mean load as mentioned at the beginning in this section. So, more precise evaluation is expected on the life estimation by accounting for their effect.

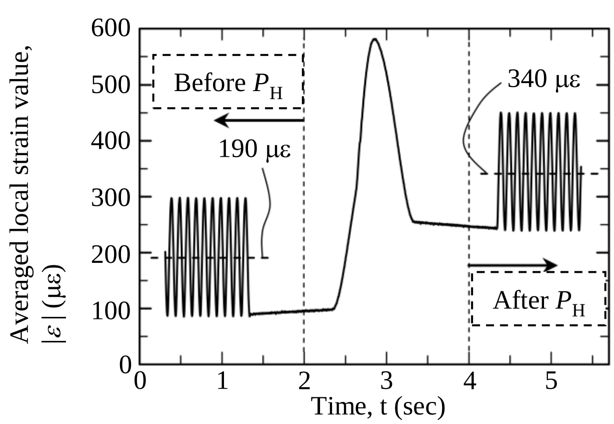


Fig.12 Relationship between $|\varepsilon|$ and t under repeated two-step loading condition

Summaries

In this study, fatigue tests were conducted under random loading conditions which were supposed as the practical loading in service using the cold rolled high strength steel; JIS SPFC590Y applied to general automobiles. Then, the estimation method was proposed on the fatigue damage of the spot welded joints from obtained experimental results. Summaries obtained in this study are shown in following;

(1) The obvious mean load effect was confirmed as results of fatigue tests under constant loading condition with various kinds of the load ratio. Then, the effect is enable to be arranged by the modified *Goodman*'s law.
(2) The proposed method which accounts for the mean load effect is very easy to evaluate the cumulative fatigue damage on the spot welded joints so that it needs only the external loading as the evaluation parameter. Moreover, it enables to apply for various kinds of random loading wave. Furthermore, it gives results of the cumulative fatigue damage with the high precision comparatively. Then, the evaluation method proposed in this study is very useful in practice.
(3) In the proposed evaluation method, more precise estimation is expected to account for the additional mean load effect involved with the deformation near the welded spot.

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