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On the Fatigue Life of the Single Spot-Welded Joint under the 2-Steps Repeating Loads*

—Comparison of Results for Mild Steel and Those for High Strength Steel—

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Abstract

In this paper, fatigue lives of single spot-welded joints made of mild steel (SPCC) sheets and high strength steel ($HT50$) sheets of 0.8 mm in thickness are obtained by experiments under the constant amplitude repeating loads and the 2-steps repeating loads in tensile-shear, then fatigue lives for both kinds of steel are compared, and moreover the fatigue life obtained by the experiment is compared with the value estimated by using Miner's rule.

Main conclusions obtained are summarized as follows:

(1) *The fatigue life for $HT50$ is generally rather longer than one for SPCC under the 2-steps repeating loads including the peak-overload, which is different from the well-known results under the constant amplitude repeating load.*

(2) *The fatigue life obtained by the experiment under the 2-steps repeating loads including the peak-overload does not as a whole agree with the value estimated by using Miner's rule.*

(3) *From above two conclusions, it is follows that the fatigue life is considerably influenced by the mechanical property in the neighborhood of the spot weld under the 2-steps repeating loads including the peak-overload and cannot be discussed without the consideration of the load history.*

Key Words: *Spot-welded joint, Fatigue life, Fatigue strength, 2-steps loads, Peak-overload, Miner's rule, Load history, High strength steel, Mild steel*

1. Introduction

The fatigue test of the single spot-welded joint is usually throughout the world obtained from the fatigue test under the constant amplitude repeating loads in tensile-shear, based on JIS Z 3138-Method of Fatigue Testing for Spot-Welded Joint-in Japan. According to this test method, the faitgue life of the single spot-welded joint for mild steel is generally superior to one for high strnegth steel, as well-known.

In the spot-welded joint structure in service, the real load on each spot weld is a random one, with the amplitude and the period of the load wave irregularly varying.

The first purpose of this study is to answer the question "Is the fatigue life of single spot-welded joint for mild steel always superior to one for high strength steel, for example under the real loads?". The second purpose of this study is to compare experimental values fo the fatigue life under various load conditions with estimated values using Miner's rule which is one of the fatigue life estimation methods for the cumulative damage, and to investigate why there is a large difference between the experimental value and the estimated value.

In Miner's rule, the fatigue damage at each load level is independent and the effect of the load history is not considered. If we use ΔL-N (ΔL: load range, N:cyclic number) curve obtained under the constant amplitude repeating loads and do the load frequency analysis for the real load, and estimate the fatigue life using Miner's rule, the estimated value will not necessarily agree with the experimental value. Especially in case of the spot-welded joint, the effect of the load history on the initiation time and the propagation behavior of the farigue crack is associated with the elastic-plastic deformation behavior around the spot-weld and this deformation behavior probably depends on mechanical properties of the material of the test specimem. Accordingly, the effect of the load history on the fatigue life of the spot-welded joint may largely differ depending on the sheet materials (mild steel and high strength steel in this paper).

In this study, as the first step to make clear the fatigue life of the spot-welded joint made of thin steel sheets under the real load, we carry out the following experiments and investigations:

(1) Comparison among fatigue lives of single spot-welded joints for mild steel and high strength steel under the constant amplitude repeating loads and the 2-steps repeating loads in tensile-shear, and the comparison between the crack initiation life and the crack propagation life of each spot-welded joint.

(2) Comparison between the experimental value of fatigue lives and the estimated value using Miner's rule.

(3) Invsetigation of the effect of the load history by kinds of the load and of the material of the test specimen on the fatigue life of each spot-welded joint.

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2. The Experimental Method

2.1 *The Test Specimen*

The test specimens used in this experiment are two kinds of single spot-welded joint specimens made of mild steel (SPCC) sheets and high strength steel (HT50) sheets of 0.8 mm in thickness. Table 1 shows chemical compositions of these specimen materials, and Table 2 shows mechanical properties of these specimens sheets.

2.2 *The Shape and Dimensions of the Spot-Welded Joint*

The shape and dimensions of the spot-welded joint are shown in Fig. 1, they are based on JIS Z 3138. The nugget diameter of the spot-weld in this experiment is 5.0 mm$\pm$0.2 mm.

2.3 *The Determination of the Fatigue Life*

When cracks of the same length as diameter of indentation on the spot weld or its vicinity area have developed on either of both surfaces of the joint, such a state is defined as exhausting of the fatigue life.

2.4 *Repeating Load Patterns*

All the repeating load patterns used in this experiment are R$>$0, 40Hz in frequency, which are illustrated in Fig. 2. Type I is the constant amplitude repeating load that is usually used in the fatigue test, and Types II, III, IV are the 2-steps repeating loads, where the minimum load is constant in Type II, the mean load is constant in Type III, and the maximum load is constant in Type IV. In this figure, the range of the constant amplitude repeating loads is indicated as ΔL and a larger load range and a smaller load range in 2-steps load patterns are indicated as ΔL_1 and ΔL_2, respectively. Repeating numbers of ΔL_1 and ΔL_2 in a unit sequence are indicated as n_1 and n_2, respectively, which are chosen in multipliers of 10, such as 10^0, 10^1, 10^2, 10^3, 10^4, 10^5. In this paper, results in case of $n_1=1$ that corresponds to the case of the peak-overload are mainly described.

Table 1 Chemical compositions of sheet materials used

Material	Chemical compositon (wt.%)					
	C	Mn	P	S	Si	Al
SPCC	.025	.23	.013	.016	—	—
HT50	.107	1.34	.002	.009	.25	.043

Table 2 Mechanical properties of sheet materials used

Material	Sheet thick. t (mm)	Mechanical property		
		YP (MPa)	TS (MPa)	El (%)
SPCC	0.8	193	329	50
HT50	0.8	425	546	25

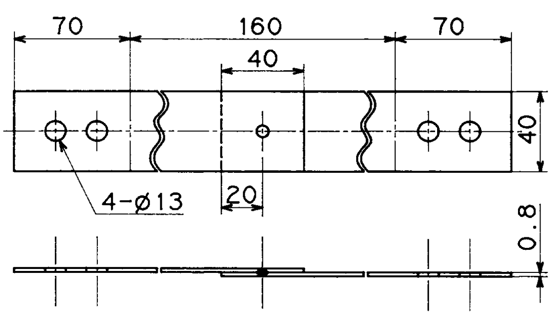

Fig. 1 Shape and dimensions of spot-welded joint used

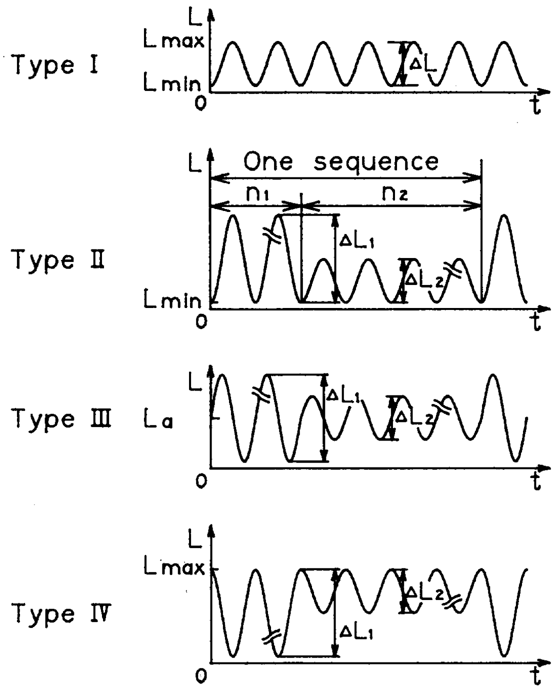

Fig. 2 Types of repeating load pattern used

2.5 *The Detection Method of the Crack Initiation and the Crack Propagation*

The detection of the crack initiation and the crack propagation is based on the semi-quantitative behavior of the strain range $\Delta\varepsilon$ ($\Delta\varepsilon+\bar{\varepsilon}$, $\bar{\varepsilon}$: offset strain) obtained by a strain gauge which is bonded in the direction of the load axis on the indentation on the joint sheet, and this method was developed by the authors.[1,2]

Fig. 3 shows an example of the strain range behavior under the constant amplitude repeating loads. In this figure, when the measured strain range has the same phase as the load phase, the strain range is indicated as $+\Delta\varepsilon$; and when it has a reverse phase, the strain range is indicated as $-\Delta\varepsilon$. The strain range measured under the constant amplitude repeating loads keeps almost the same value as the initial strain range ($\Delta\varepsilon_1$) up to a specific number of cycles, and after passing this number of cycles shows a rapid variation and lastly reaches a number of cycles that corresponds to the fatigue life N_f. The start point of this rapid variation corresponds very exactly to the crack initiation time. The correspondence of the strain range behavior to the crack initiation and the fatigue life etc. has been proved by the authros. In Types II, III, IV, the behavior of the strain range is basically the same as that in Type I. In Fig. 4, an example of the strain range behavior in Type II is shown. In this case two curves of the strain range

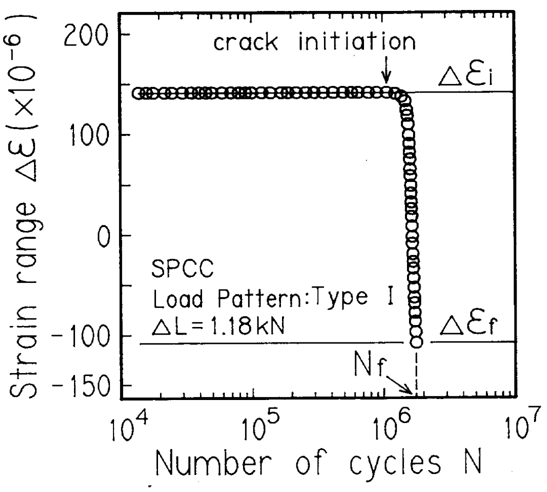

Fig. 3 An example of relation between strain range and number of cycles (Type I)

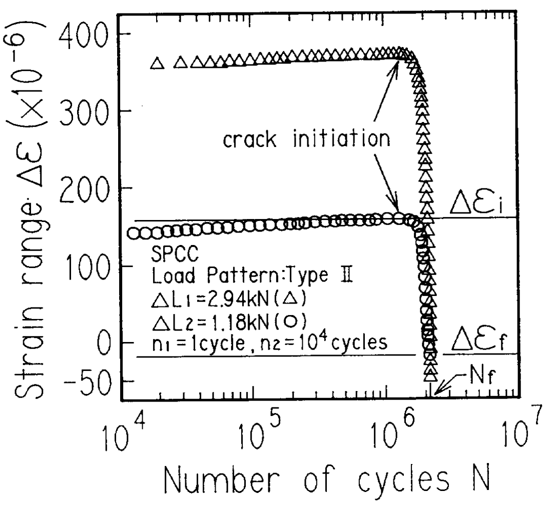

Fig. 4 An example of relation between strain range and number of cycles (Type II)

that correspond to ΔL_1 and ΔL_2 are detected and each curve has the same tendency as that in Fig. 3, as seen easily.

3. Experimental Results and Discussion

3.1 *The Fatigue Life under the Constant Amplitude Repeating Loads*

In Fig. 5, ΔL-N curves of spot-welded joints for SPCC and HT50 in the case of Type I are shown. It is found from this figure that the fatigue life for SPCC is longer than that for HT50 over the load range for $N>10^4$, and at $N>10^6$ the fatigue life for SPCC is very superior to that for HT50.

Next, we carried out the fatigue test using test specimens in SPCC and HT50 under the constant amplitude repeating loads for various ΔL_1's and ΔL_2's with different R's values. Average values of the fatigue life obtained in this experiment are shown in Table 3, which are utilized in the fatigue life estimation by Miner's rule described later. As seen from this Table, most of fatigue lives for SPCC are longer than those for HT50.

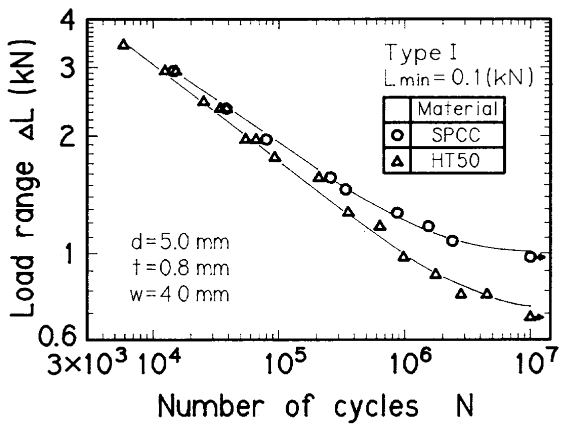

Fig. 5 ΔL-N diagram (Type I)

Table 3 Fatigue lives of spot-welded joints for SPCC and HT50 under constant amplitude repeating loads

ΔL (kN)	$R=\frac{L_{min}}{L_{max}}$	SPCC (cycle)	HT50 (cycle)
2.94	0.03	1.4×10^4	1.4×10^4
1.96	0.05	8.0×10^4	6.0×10^4
1.18	0.08	1.7×10^6	6.0×10^5
	0.45	3.8×10^5	2.7×10^5
	0.61	2.9×10^5	2.0×10^6
0.69	0.64	$>10^7$	3.9×10^6

3.2 *The Fatigue Life under the 2-Steps Repeating Loads*

In Fig. 6, as an example the fatigue life for SPCC in the case of Type II is compared with that for HT 50, where ΔL_1: 1.96kN and ΔL_2: 1.18kN, n_1: 1 cycle, n_2: variable. It is seen that the relationship beteeen fatigue lives for SPCC and HT50 in this fatigue is reverse to that obtained for Type I, and especially in the case of $n_2=10^5$ cycles, the fatigue life of HT50 is about twenty times as long as that of SPCC.

The crack initiation life obtained by separating the

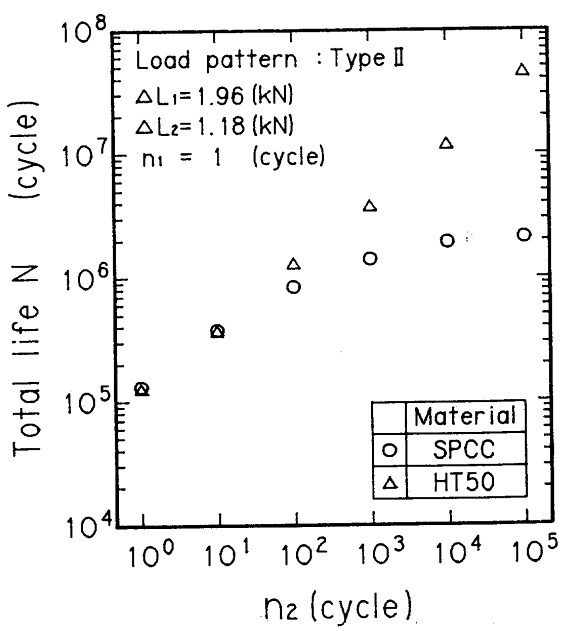

Fig. 6 Comparison of SPCC with HT50 in total life (Type II)

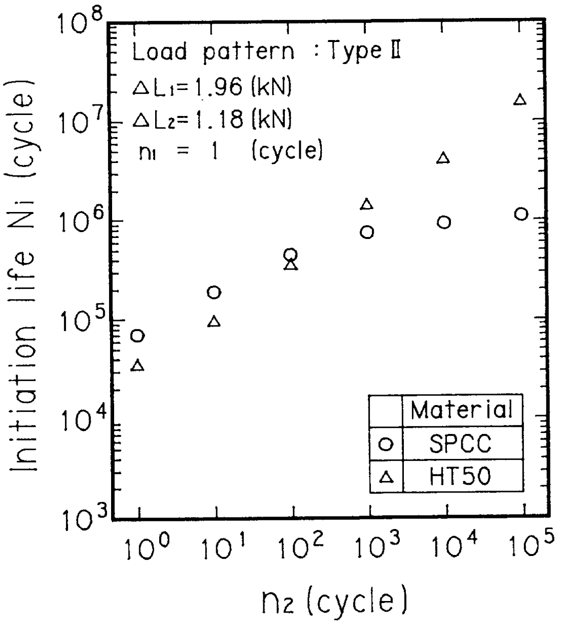

Fig. 7 Comparison of SPCC with HT50 in initiation life of fatigue crack (Type II)

total fatigue life in this case into the crack initiation life and the crack propagation life is shown in Fig. 7. In this figure, the crack initiation life of HT50 for $n_2<10^2$ is shorter than that for SPCC. and this is similar to the case under the constant amplitude repeating loads. However, the crack initiation life of HT50 for $n_2>10^3$ is longer than that of SPCC, and this is reverse to the case under the constant amplitude repeating loads. Especially, in the case of $n_2=10^5$ cycles, the crack initiation life of HT50 is one hundred times as long as that for the same value of ΔL_2 under the constant amplitude repeating loads, that is to say, the crack initiation life of HT50 is about ten times as long as the total fatigue life of SPCC for the same ΔL_2. These results clearly indicate that the effect of the load history on the crack initiation life is very large and we can not discuss the total fatigue life without taking account of this effect.

Fig. 8 shows the fatigue life of SPCC for two ΔL_1's in Type II. From this figure, it is seen that the fatigue life for the larger ΔL_1 becomes longer than that for the smaller ΔL_1 for $n_2>10^4$. Results shown in Figs. 6, 7 and 8 are different from the common knowledge obtained under the constant amplitude repeating loads.

3.3 *The Comparison of Experimental Results of the Fatigue Life with Its Estimated Results*

Figs. 9∼13 show the comparison of experimental results of the fatigue life with the estimated results by using Miner's rule, where the solid line and the dashed line correspond to estimated results for SPCC and HT50, respectively. As Miner's rule is basically a linear cumulative law of damage, it is possible to presume an effect of load history on the fatigue life, from the comparison of experimental values with estimated values by using Miner's rule. In Fig. 9, where the load pattern is Type II, ΔL_1: 2.94 kN, ΔL_2: 1.18 kN, the experimental value of the fatigue life of HT50 is longer than that of SPCC with an increasing n_2, the same as Fig. 6. In the case of SPCC, for $n_2>10^3$ cycles experimental values are a little smaller than estimated values, and for $n_2>10^4$ cycles experimental values are a little larger than estimated values, that is to say, it is concluded that both values agree to some extent with each other. Meanwhile in the case of HT50, experimental values are larger than estimated values with an increasing n_2; especially when n_2 is 10^5 cycles, the experimental value is about one hundred times as large as the estimated value. It is considered from the above results that the fatigue damage due to ΔL_2 after the application of ΔL_1 in Type II is much smal-

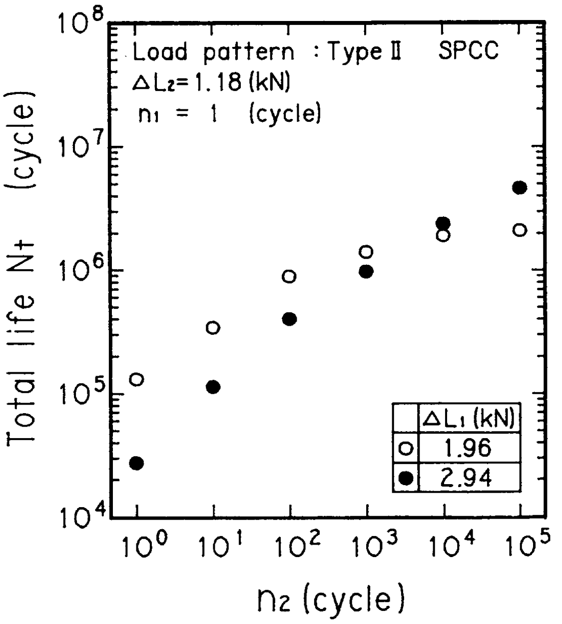

Fig. 8 Relationsip between total life and n_2 under different peak-overloads for SPCC and HT50

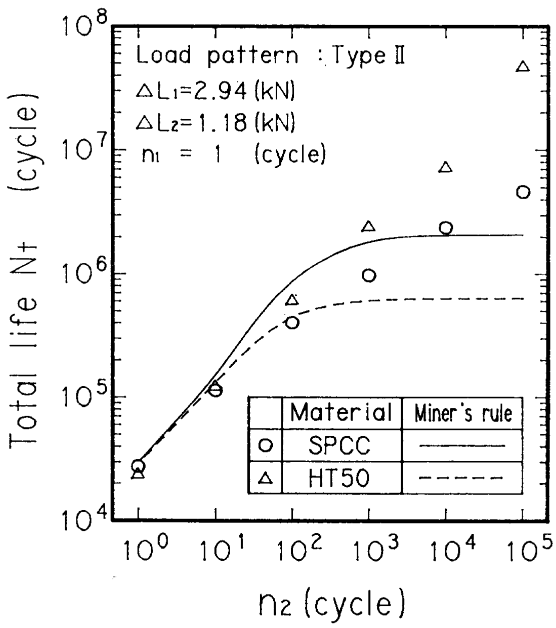

Fig. 9 Comparison of experimental results with estimated results in total life for SPCC and HT50 specimens (Type II)

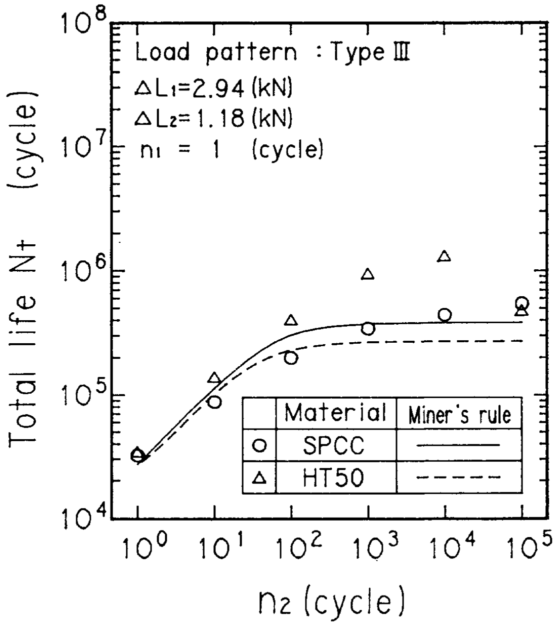

Fig. 10 Comparison of experimental results with estimated results in total life for SPCC and HT50 specimens (Type III)

ler than the fatigue damage due to ΔL_2 in Type I.

In Fig. 10, the load pattern is Type III and each load range is the same as Fig. 9. In these load conditions, the fatigue life of HT50 is longer than that of SPCC. The relationship between experimental values and estimated values for SPCC is similar to that obtained for Type II (Fig. 9). However, the experimental value for HT50 at $n_2=10^5$ cycles is smaller than that at $n_2=10^4$ cycles. Under this condition, both the crack initiation life and the crack porpagation life are almost the same as those for the same load range in Type I with this ΔL_2.

In Fig. 11, the load pattern is Type IV and each load range is the same as Fig. 9. Under this condition, experimental values agree with the estimated ones for both SPCC and HT50, and ratio of the crack initiation life to the crack propagation life or the propagation behavior of the fatigue crack almost agrees with the results obtained in Type I. It is considered from this fact that the fatigue damage for each load range is independent, when two maximum loads of 2-steps repeating loads are the same.

In Fig. 12, the load pattern is Type III and ΔL_1: 2.94 kN, ΔL_2: 0.69 kN. The fatigue life of SPCC in the case of the constant amplitude repeating loads: $\Delta L=0.69$ kN is more than 10^7 cycles, and that of HT50 is 3.9×10^6 cycles as shown in Table 3. It is understood from the above fact that the load range $\Delta L=0.69$ kN is below the fatigue limit for SPCC, while this load range is over the fatigue limit for HT 50. However, even under such a load range the fatigue life of HT50 is much longer than that of SPCC for $n_2>10^3$. Moreover, experimental values for HT 50 are larger than estimated ones as in Fig. 9, while experimental values for SPCC are much smaller than estimated values, for example the experimental value at $n_2=10^5$ cycles is about one 200th of the estimated value, unlike all results of cases described hitherto. It is supposed from the above fact that the compressive residual strain formed in the neighborhood of the spot-weld by the application of ΔL_1 decreases after many times of application of ΔL_2, thus the load range of ΔL_1 after applications of ΔL_2 increases substantially and the fatigue damage after application of ΔL_1 increases.

In Fig. 13, the load pattern is Type II, ΔL_1: 2.94 kN, ΔL_2: 1.18kN and n_2 is fixed at 10^4 cycles, while n_1 is varied over a range $10^0\sim10^3$ cycles. In this condition, the fatigue life of HT50 is also longer than that of SPCC. And experimental values for SPCC

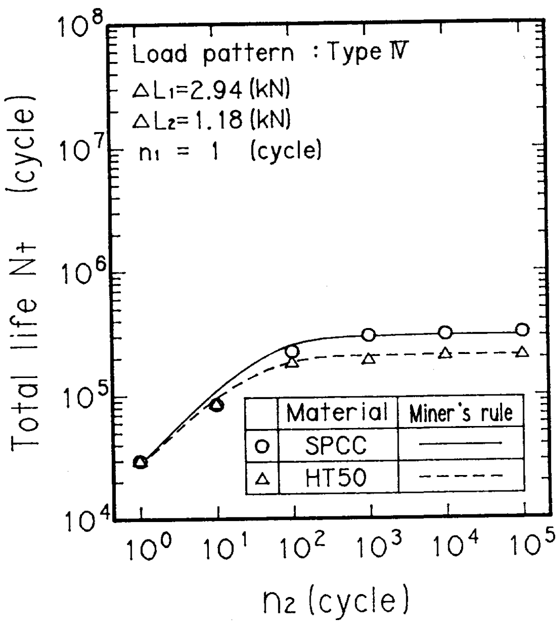

Fig. 11 Comparison of experimental results with estimated results in total life for SPCC and HT50 specimens (Type IV)

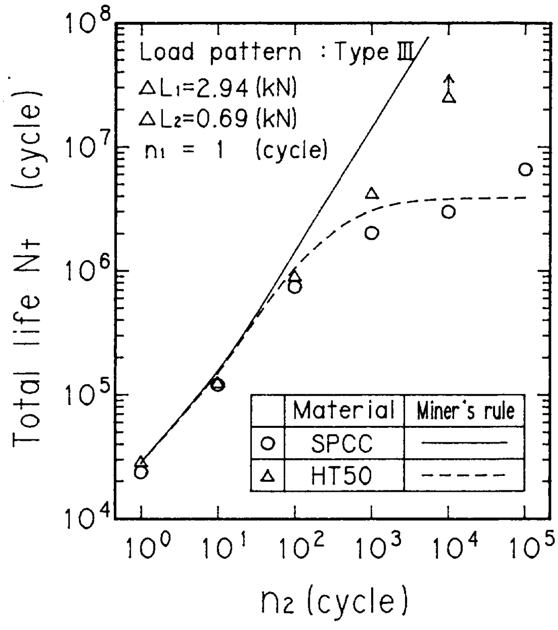

Fig. 12 Comparison of experimental results with estimated results in total life for SPCC and HT50 specimens (Type III)

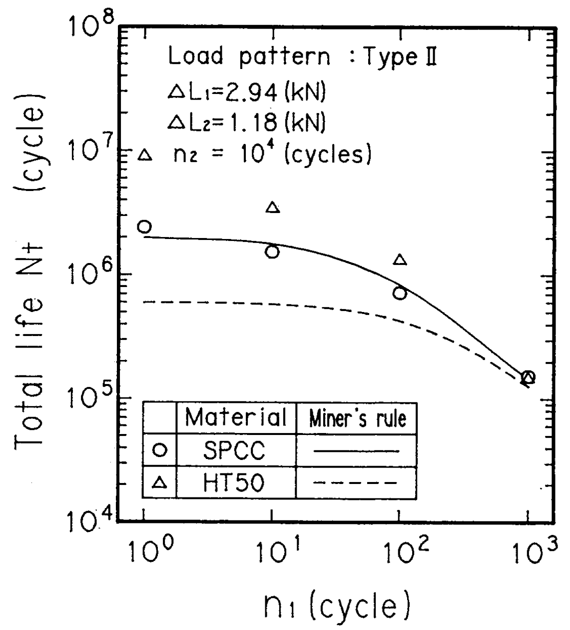

Fig. 13 Comparison of experimental results with estimated results in total life for SPCC and HT50 specimens (Type II)

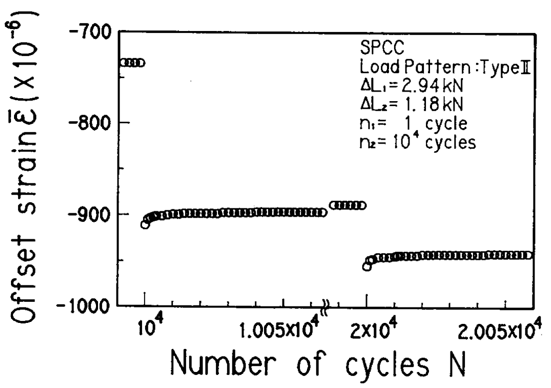

Fig. 14 An example of relation between offset strain and number of cycles (Type II)

agree as a whole with estimated values, while experimental values for HT50 are much larger than estimated values for $n_1 < 10^2$.

3.4 *The Effect of the Load History*

The effect of the load history on the fatigue life of spot-welded joint for SPCC quantitatively is very different from that for HT50, as seen from the result in the forgoing section. Here is stated our reasoning about the effect of the load history. Firstly, it is considered that this effect is caused by different mechanical properties such as yield stress and elongation in the neighborhood of the spot-weld between SPCC and HT50. And it is supposed that the size of the plastic region and the magnitude of the compressive residual stress formed in the neighborhood of the spot-wled by the application of ΔL_1 are largely different between SPCC and HT50.

On the other hand, when the maximum load of ΔL_2 is smaller than that of ΔL_1, the local bending behavior and the opening displacement in the neighborhood of the spot-weld edge or the crack top are restricted by the compressive residual stress formed by the application of ΔL_1. Hence, the fatigue damage due to ΔL_2 after the application of ΔL_1 decreases unlike that due to the same ΔL_2 under the constant amplitude repeating loads. Consequently, the fatigue life in this case becomes larger compared with the case under the constant amplitude repeating loads. (For example, refer to the case for HT50 in Fig. 9.) From now this effect is called "an effect to lengthen the fatigue life".

While, the compressive residual stress formed by ΔL_1 is released partially by multiple applications of ΔL_2. Ocurrence of this phenomenon is proved from the variation of the offset strain in Fig. 14, which shows a sudden variation toward minus side of the offset strain after the applications of ΔL_1 at $N = 1 \times 10^4$ and 2×10^4 and the variation toward plus side of offset strain immediately after each application of ΔL_1 by the applications of ΔL_2.

It is considered that the offset strain obtained from the strain gauge bonded on the indentation on the test specimen under the constant amplitude repeating loads of ΔL_1 larger than the fatigue limit generally increases linearly toward minus side with an increasing repeating number N. Hence, the variation toward plus side of the offset strain means a partial release of compressive residual stress after the applications of ΔL_2. As a result, the load range of ΔL_1 after applications of ΔL_2 increases substantially and the fatigue damage by the application of ΔL_1 increases. (For example, refer to the case of SPCC in Fig. 12.) From now this effect is called "an effect to shorten the fatigue life".

In the case of ΔL_2 larger than the fatigue limit in Types II and III, the fatigue life obtained by the experiment for SPCC apparently agrees with that estimated by Miner's rule because an effect to lengthen the fatigue life ≒ an effect to shorten the fatigue life, while the fatigue life obtained by the experiment for HT50 becomes much larger than that estimated by using Miner's rule because an effect to lengthen the fatigue life is much larger than an effect to shorten the fatigue life. The reason why an effeet to lengthen the fatigue life for HT50 is larger than that for SPCC is because the yield point of HT50 is larger than that of SPCC, while the reason why an effect to shorten the fatigue life for SPCC is larger than that for HT50 is because the yield point of SPCC is smaller than that of HT50.

Moreover, in the case of ΔL_2 smaller than the fatigue limit in Type II and Type III, the fatigue life for SPCC obtained by the experiment becomes smaller with an increasing n_2 than the fatigue life estimated by using Miner's rule, because there is only an effect to shorten the fatigue life in this case.

In addition, the effect of the load history on the fatigue life in the multispot-welded structure may be smaller than that in the single spot-welded joint.

4. Conclusions

In this paper, fatigue lives of single spot-welded joints made of mild steel (SPCC) sheets and high strength steel(HT50) sheets of 0.8 mm in thickness are obtained by epxeriments under the constant amplitude repeating loads and the 2-steps repeating loads in tensile-shear, then fatigue lives for both kinds of steel are compared, and moreover the fagitue life obtained by the experiment is compared with the value estimated by using Miner's rule, that is one of the cumulative damage rules.

Main conclusions obtained are summarized as follows:

(1) The fatigue life of HT50 is generally rather longer than one of SPCC under the 2-steps repeating loads including the peak-overload, which is different from the well-known result under the constant amplitude repeating loads. (Refer to Figs. 6, 7, 9, 10, 12 and 13.) This conclusion will give rise to discussion on the testing method of the spot-welded joint made of various materials sheets.

(2) The fatigue life obtained by the experiment under the 2-steps repeating loads including the peak-overload does not as a whole agree with the value estimated by using Miner's rule. (Refer to Figs. 9, 10, 12 and 13)

(3) From above two conclusions, it follows that the fatigue life is considerably influenced by the mechanical property in the neighborhood of the spot-weld under the 2-steps repeating loads including the peak-overload and it can not be discussed without the consideration of the load history.

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