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Existence of Non-propagating Micro-cracks under the Fatigue Limit

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Summary

The authors have experimentally confirmed that the non-propagating micro-cracks are observed in the low carbon plain specimens subjected to the stress of fatigue limit by 1×10^7 cycles and not observed in those of pure copper and aluminum alloys etc.. In addition, there exists clear fatigue limit in typical austenitic stainless steel SUS304 but not exist the non-propagating micro-cracks subjected to the stress of fatigue limit by 1×10^7 cycles. On the other hand, there exist not only clear fatigue limit but also non-propagating micro-cracks in the high manganese austenitic steel (HMA 0.20%C steel). Then, the authors have focused to the existence of non-propagating micro-cracks under the fatigue limit and investigated the effect of carbon content on the above existence using SUS304 and high manganese austenitic steels (HMA steels) with changing its carbon content only and clarified that the limit of the existence of non-propagating micro-cracks under the stress of fatigue limit by 1×10^7 cycles is concluded to be between 0.10% ~0.20% of carbon content.

Introduction

Though it is well known fact, there exists clear fatigue limit in the case of structural steels and does not in the case of copper and aluminum alloys etc.. In addition, the authors have experimentally confirmed using 0.13%C steel and pure copper specimens, that is, in 0.13%C steel specimens, the non-propagating micro-cracks exist in the ferrite not only at the surface but also in the inside and the tip part of those cracks become 24~34% harder than in the virgin state. In copper specimens, the tip part of the fatigue micro-crack in copper, appearing after 10^7 cycles of the stress which corresponds to the fatigue strength for 2×10^7 cycles, do not become so hard than the ones in 0.13%C steel and the authors have insisted that the above results show the existence of fatigue limit in steel is due to the strengthening effect at the tip parts of the non-propagating micro-crack [1][2].

On the other hand, there does not exist non-propagating micro-crack in typical austenitic stainless steel (SUS304) specimens suffered by 1×10^7 cycles of its fatigue limit [3]. The authors have confirmed that there exist non-propagating micro-cracks in austenitic high manganese steel (HMA 0.20%C steel) specimens suffered by 1×10^7 cycles of its fatigue limit [4][5]. It is said that high manganese non-magnetic austenitic steel (HMA steel) has been expected to be a promising component materials of the linear induction motor tracks, nuclear fusion electric

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power systems etc. because of its extra-stable non-magnetic properties, high tensile strength and ductility even in low temperature. Then, the fatigue properties of HMA steel have been investigated in this paper, especially in view point of fatigue crack initiation by successive-taken replica method under the cyclic stress with comparing that of the representative austenitic stainless steel (SUS304), which is also well-known as a non-magnetic one. In addition, the effect of carbon content on the existence of non-propagating micro-cracks in the austenitic steels has been evaluated using four kinds of HMA steels with changing and decreasing the carbon content only between 0.025%∼0.100%

Testing Methods

The experimental procedures are divided into the following two processes. That is, step one: the materials used in this test are HMA(0.20%C) steel and typical stainless steel (SUS304), which are both non-magnetic austenitic steels of hot-rolled thick plate. Step two: the authors have evaluated the effect of carbon content on the fatigue properties of four kinds of HMA steels with changing an decreasing the carbon content only in this study. Tables 1 lists chemical composition and mechanical properties of the materials used in this test for "Step one" and "Step two", respectively.

Table 1: Chemical composition and mechanical properties mass%

Materials	C	Si	Mn	Ni	Cr	Nb	$\sigma_{0.2}$ MPa	σ_B MPa	EL %
SUS304*1	0.048	0.50	0.81	8.47	18.49	-	253.8	623.5	66.0
HMA*1	0.178	0.23	23.8	0.23	2.05	0.04	251.9	751.7	56.0
HMA-1*2	0.027	0.20	23.7	0.27	2.08	0.04	196.5	783.0	41.6
HMA-2*2	0.047	0.20	23.4	0.32	2.19	0.04	164.6	766.9	45.7
HMA-3*2	0.048	0.44	23.6	0.30	4.82	0.04	181.8	746.3	46.5
HMA-4*2	0.107	0.44	23.3	0.30	4.82	0.04	219.5	770.3	47.5

P=0.0160.026, S=0.0010.007, N=0.0290.047, Al=0.0030.010
*1 : Step 1, *2 : Step 2

Figure 1 shows the shape and size of the fatigue specimen, which was cut out by coinciding the rolling direction with the specimen's axis and by making partial shallow notch with its surface side. This shallow notch was made for limiting fatigue damage portion and does not affect for its fatigue strength at all [6]. All of the specimens have been annealed in vacuum for one hour at 600 ˚C after polishing with fine emery paper to the longitudinal direction and after that electro-polished to the depth of about 50μm. A four point rotating bending (Ono-type) fatigue testing machine of 98kN-m capacity was used under the cyclic speed of 3400rpm. The stress was expressed by the nominal one at the minimum diameter of the specimens by neglecting about the partial notch.

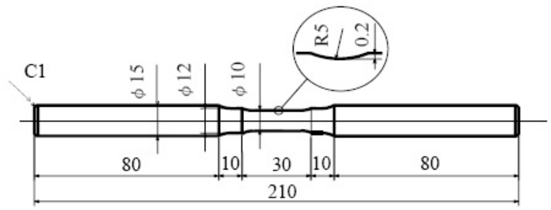

Figure 1: Shape and dimensions of specimen

In the case of fatigue test about SUS304, testing part of each specimen was cooled by pouring fresh water for preventing exothermic fracture. It is confirmed that there is no difference between the results under low frequency in air and that under high frequency with cooled by distilled water [7]. The micro-crack initiation was observed by successive–taken replica method at the specimen's surface to the circumferential direction and defined as one grain length or so.

Results and discussions

Figure 2 shows the S-N curves of HMA(0.20%C) steel and SUS304, which are both austenitic steels. As shown in this figure, there exists the same fatigue limit of σ_{wo}=265 MPa about both materials, while the gradient of SUS304 has a little smaller than that of HMA steel. When considering the relation between mechanical properties and their fatigue limits, it is generally expressed that the fatigue limit of steel specimenσ_{wo} is closely dependent on its tensile strength σ_B. That is, as HMA steel shows higher tensile strength and a little smaller proof stress than SUS304, that is, the former has smaller proof stress ratio than the latter, the fatigue limit of both materials happened to agree with each other and shows higher value than proof stress to be about 5%.

On the other hand, Figure 3 shows the surface state under the fatigue limit of σ_{wo}=265 MPa by 1×10^7 cycles about both materials. As shown in this figure, the non-propagating micro-cracks are observed in the specimen's surface of HMA steel and its length is about 45μm in this case, while the non-propagating micro-cracks are not observed in the case of SUS304, though there appeared only slip bands due to the former cyclic stress. It is considered that the above phenomena would be caused by the difference of carbon content, corrosion resistance, proof stress ratio, etc.. In addition, the micro Vickers hardness number, where slip bands are generated, becomes increase by about 30% than that of the grains of before test or the grains where slip bands are not generated under the above cyclic stress amplitude by 1.21×10^7 cycles.

Figure 4 shows the S-N curves of four kinds of HMA steels as listed in Table 1, whose carbon content is decreased than 0.20% C. When defined the fatigue limit as the fatigue strength of 1×107 cycles, the fatigue limits of HMA1, HMA2, HMA3

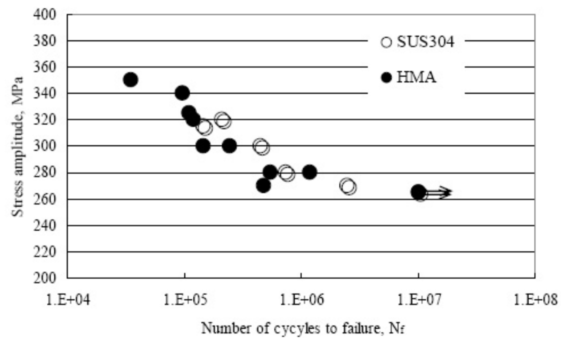

Figure 2: S-N curves (Step one)

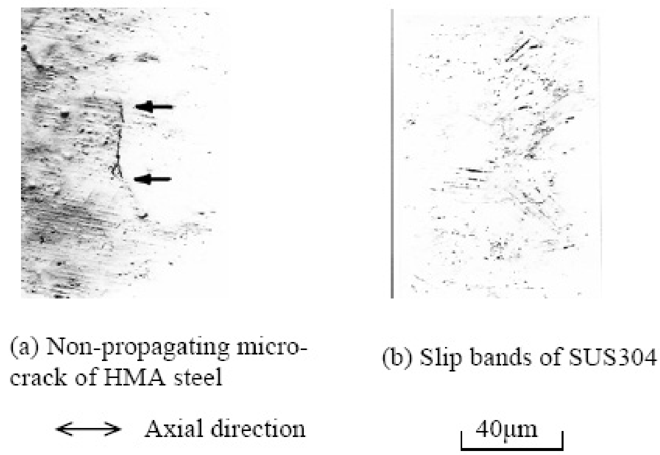

Figure 3: Specimen's surface state subjected to the stress amplitude of fatigue limit by 1×10^7 cycles

and HMA4 are 245, 248, 235 and 262 MPa, respectively. As shown in this figure, the four kinds of HMA1 to HMA4 steels do not show distinct knee point with comparing to that of HMA(0.20% C) steel. Figure 5 shows an illustration of S-N curves according with the result of Fig. 4. Each S-N curve in Fig. 4 deviates from a linear line at A point and its gradient becomes smaller according to approaching the stress level (B point) of fatigue limit. Table 2 lists the value of stress level at A and B point, respectively.

Each specimen was observed the representative specimen's surface states subjected to the stress amplitude of each fatigue limit by 1×10^7 cycles about HMA1 to HMA4. Although not shown in this paper, there did not exist non-propagating micro-cracks except slip bands due to the former cyclic stress. That is, the fatigue limits of HMA1 to HMA4 specimens are based on the limit of micro-crack initiation.

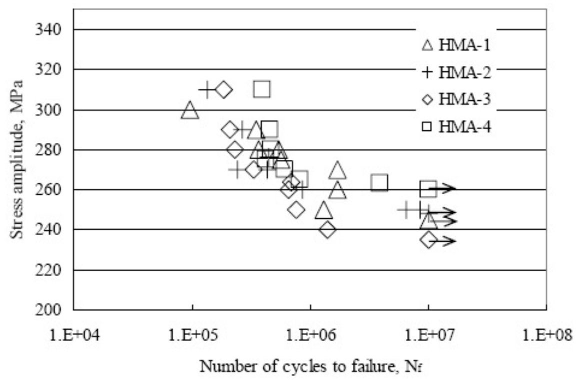

Figure 4: S-N curves (Step two)

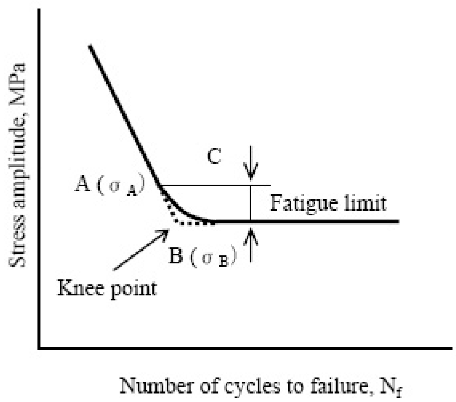

Figure 5: Typical S-N curve (Step two)

Table 2: Stress value at point A and B (Step two) [MPa]

Materials	σ_A	σ_B	$\sigma_A - \sigma_B$
HMA	265	265	0
HMA-1	278	245	33
HMA-2	272	248	24
HMA-3	264	235	29
HMA-4	273	262	11

As shown in Fig.4, HMA steel specimen (0.20%C) exists the non-propagating micro-cracks. On the other hand, the non-propagating micro-cracks are not observed in the HMA1, HMA2, HMA3 and HMA4 specimens (ref. Fig. 6), though the slip bands are generated in these specimens due to subjecting to the former cyclic stress. It is considered that whether the non-propagating micro-cracks exist or not, would be caused by the difference of carbon content.

Figure 6 shows the relation between carbon content and BC value (ref Fig. 4 about this value). As shown in this figure, the carbon content becomes increased, BC value becomes smaller, that is, the stress level of A point approaches the fatigue limit. Therefore, S-N curve shows distinct knee point. In addition, the non-propagating micro-cracks are existed in the specimen's surface subjected to the stress of fatigue limit by 1×10^7 cycles. In other words, the carbon content affect to the existence of non-propagating micro-cracks in the specimen's surface of HMA steel specimen.

Table 3 lists the factors related to the existence of non-propagating micro-cracks. There are four main factors, that is, (1)Structural barrier, (2)Work hardening, (3)Strain aging and (4)Micro-scopic residual stress. In the case of ferritic steel, these factors affect for preventing the fatigue micro-crack propagation under the stress level of the fatigue limit. On the other hand, in the case of SUS304 and HMA steels, some factors remarkably affect but the other factors do not affect so much for preventing when fatigue micro crack initiated under the around stress level of the fatigue limit. Especially in the case of HMA steels, it remarkably depends on the carbon content whether a fatigue micro-crack propagates or not. Therefore, the non-propagating micro-cracks exist in the case of low carbon steel and do not exist in the case of SUS304. In addition, the existence of the non-propagating micro-cracks depends on its carbon content in the case of HMA steels and its critical value is considered to be between 0.10∼0.20%, that is, about 0.15%C.

Table 3: Factors related to the existence of non-propagating micro-cracks

Factor	Ferritic steel	Austenitic steel	
		SUS304	HMA steel
Structural barrier	○	△	△
Work-hardening	○	◎	◎
Strain aging	○	△	○ (0.2%C) ⇒ △(0.03%C)
Micro-scopic residual stress	○	△	△
Non-propagating micro-cracks	Exist	Not exist	Exist (0.20%C) Not exist (<0.10%C)

◎: Very large ○ : Large △: Small

Conclusions

The main results obtained in this test are as follows;

1. The fatigue strength of HMA steel (0.20%C) and SUS304 shows comparatively the same result, that is, the same fatigue limit and distinct knee point.
2. Though the non-propagating micro-cracks are not observed in SUS304 specimen subjected to the stress of fatigue limit by 1×10^7 cycles, the non-propagating micro-cracks are generated in the HMA steel specimen (0.20%C) subjected to the same condition. In addition, the same phenomena as SUS304 is observed in the carbon decreased HMA specimens (HMA1 to HMA4)
3. From the above result, though the fatigue limits of SUS304 including HMA1 to HMA4 are based on the limit of micro-crack initiation, that of HMA steel

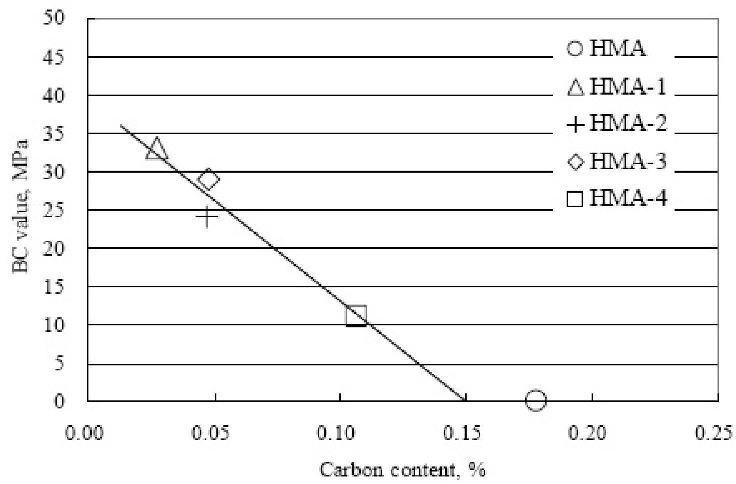

Figure 6: Relation between carbon content and BC value (ref. Fig.4)

specimen (0.20%C) is based on the limit of micro-crack propagation. The limit of the existence of non-propagating micro-cracks under the stress of fatigue limit by 1×10^{7} cycles is concluded to be between 0.10∼0.20% of carbon content. In addition, the characteristics for the above crack initiation are predominantly affected by its carbon content.

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