Effect of Loading Frequency in Fatigue Properties and Micro-Plasticity Behavior of JIS S15C Low Carbon Steel

Benjamin Guennec[1,*], **Akira Ueno**[2], **Tatsuo Sakai**[2],
Masahiro Takanashi[3], **Yu Itabashi**[3]

[1] Student Member: Graduate School of Science and Engineering, Ritsumeikan University, Kusatsu, Shiga 525-8577, Japan
[2] College of Science and Engineering, Ritsumeikan University, Kusatsu, Shiga 525-8577, Japan
[3] Research Laboratory, Structural Strength Department, IHI Corporation, Yokohama, Kanagawa 235-8501, Japan
* Corresponding author: gr0081rh@ed.ritsumei.ac.jp

Abstract Ultrasonic testing method has allowed some impressive improvements in order to better grasp fatigue properties of various metallic materials the latest 20 years. It is particularly the case in the very high cycle regime since ultrasonic fatigue tests are conducted at very high stressing frequencies. However, the question of a potential difference of fatigue strengths due to huge frequency gap between ultrasonic method (usually carried out at 20 kHz) and servo-hydraulic one (usually in the range of 1~100 Hz) is still unclear and needs to be studied for a various kind of metallic materials. The case of low carbon steels presents a singularity, as fatigue properties are significantly different between these two fatigue tests methods. It seems particularly interesting to study this kind of materials in order to get a better overview of frequency effect in metallic materials fatigue. Aim of the present work, which consists of a general survey of JIS S15C steel (0.15% C) fatigue properties, is firstly to reconfirm such a frequency effect. Secondly, based on several experiments related to micro-plasticity behavior, some discussions will be held in order to explain this frequency effect in the case of low carbon steels.

Keywords Frequency effect, Low carbon Steel, Ultrasonic test, Cyclic hardening, EBSD observations

1. Introduction

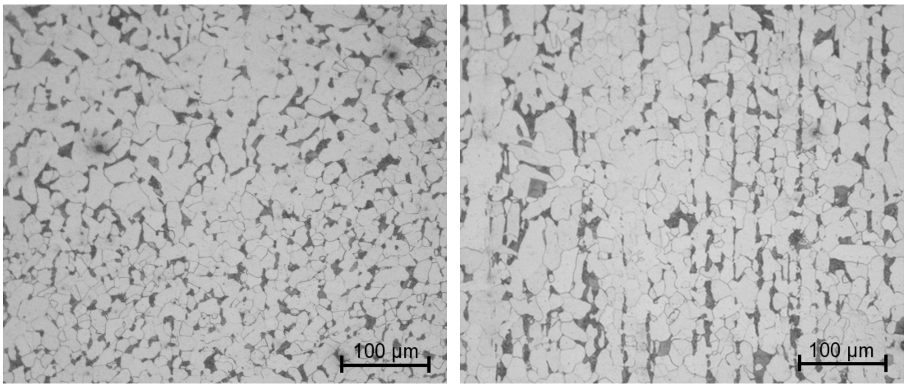
The past 20 years in the field of fatigue test marks increase of ultrasonic testing method for various industrial uses. Since study of the very high cycle regime has become a topical issue, ultrasonic stressing frequency allowed by this fatigue testing method is essential to conduct fatigue test in a definite time. It is indeed almost impossible to reach 10^9~10^{10} cycles with a conventional fatigue testing machine.

However, question of a potential influence of stressing frequency on fatigue test result, usually known as “frequency effect”, have been studied by numerous literatures and is still unclear, except for some particular materials. Low carbon steels reveal usually a clear difference of fatigue strength between usual fatigue testing (servo-hydraulic as instance) and ultrasonic testing method.

As a consequence, it was decided to make a focus on the effect of loading frequency on low carbon steels. The present work discusses some phenomenon possibilities involved in frequency effect of low carbon steels.

2. Experimental Procedure

In the present study, material tested is JIS S15C steel, extracted from as rolled material. Chemical composition and mechanical properties are indicated in Tables 1 and 2, respectively. Figure 1 shows the microstructure of this steel, with typical ferritic and pearlitic composition. One can see that grains are elongated in the rolling direction.



(a) Along transversal axis (b) Along longitudinal axis

Fig.1. Microstructure of S15C steel

Table 1. S15C chemical compositions (mass %)

C	Si	Mn	Cu	Ni	Cr	Fe
0.15	0.21	0.40	0.02	0.02	0.15	*Re*

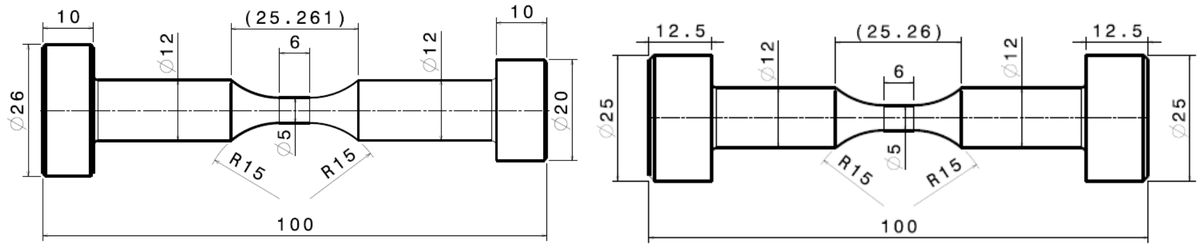
Table 2. Mechanical properties of S15C steel

Mechanical properties	Value
Lower yield stress (MPa)	273
Tensile strength (MPa)	441
Young modulus (GPa)	207
Elongation (%)	40.2
Reduction of area (%)	65.8
Vickers hardness (HV)	161

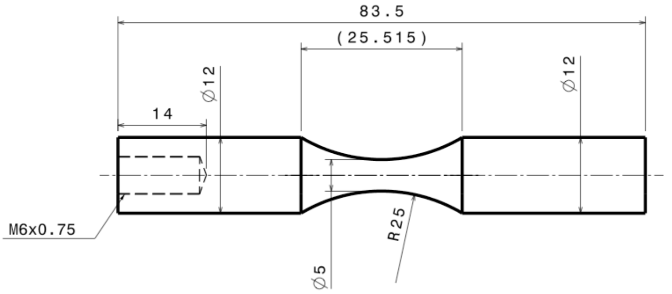
Fatigue tests have been conducted at several frequencies: 20 kHz using an ultrasonic type machine, under displacement control; 140 Hz using an electro-magnetic type machine under stress control; 20 Hz, 2 Hz and 0.2 Hz using servo-hydraulic type machine under stress control. An air-cooling system and intermittent loading conditions were admitted to avoid temperature rising of specimen in the case of ultrasonic fatigue tests. For fatigue tests performed at 140 Hz, an air-cooling system has been also added for the same reason.

All fatigue tests were performed in air, at room temperature, with a stress ratio R = -1. Configurations of fatigue specimens are presented in Fig. 2. Diameter of tested portion was fixed at 5 mm, whatever the testing method used. After machining, center portion of specimens are electro-polished to remove residual stresses. As a consequence, we avoid any size effect and residual stress effect on the *S-N* properties of S15C steel.

One can see that servo-hydraulic and electro-magnetic specimens present a cylindrical shape at center rather than usual hour glass shape. It allows us to carefully attach a 4-strain gauge system in order to follow micro-plasticity behavior during fatigue test. Choice of this type of full-bridge system has been done in order to obtain accurate measures and to avoid heating influence on strain measures.



(a) Specimen for servo-hydraulic type machine (b) Specimen for electro-magnetic type machine



(c) Specimen for ultrasonic type machine

Fig.2. Shape and dimensions of fatigue specimen

3. Experimental Results

3.1. *S-N* data

S-N diagram of JIS S15C steel used here is depicted in Fig. 3. One can see a clear difference of fatigue strength between ultrasonic 20 kHz fatigue test results and other results from servo-hydraulic and electro-magnetic machines. Fatigue limits found under these four fatigue tests conditions are 248 MPa, 200 MPa for 20 kHz and 140 Hz respectively, and a similar fatigue limit of 185 MPa has been found in the case of servo-hydraulic fatigue tests at a testing frequency of 2 and 20 Hz. This kind of large discrepancy between fatigue tests performed in usual testing frequency range and ultrasonic frequency has been also found in several other literatures as Kikukawa *et al.*[1], Yokobori *et al.*[2] or Setowaki *et al.*[3] for different other kinds of low carbon steels.

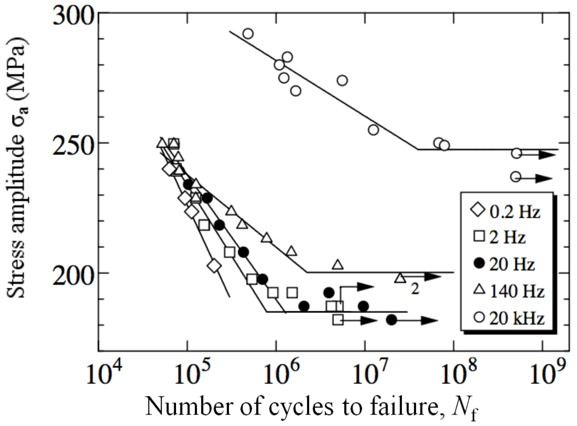
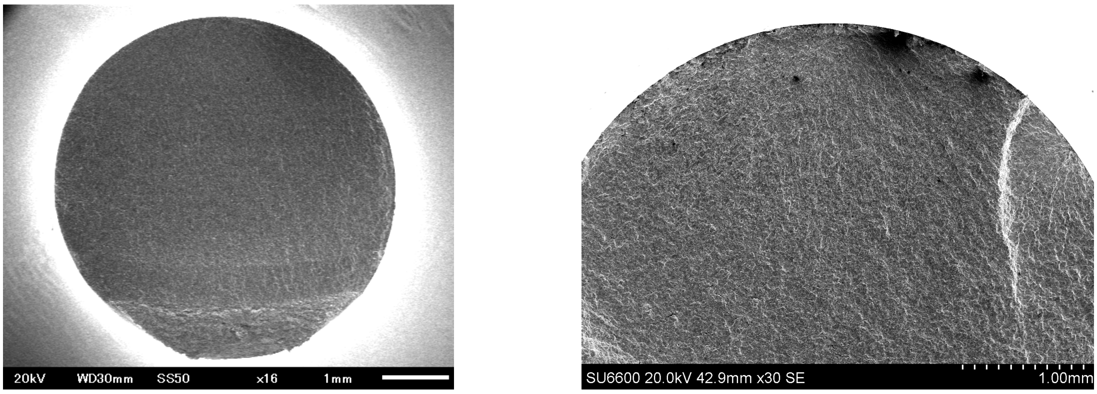


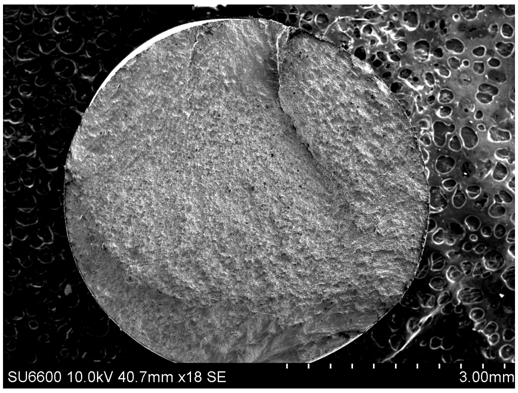
Fig.3. General *S-N* property of S15C steel

In addition, one can see that there are some fatigue strength differences between tests performed in the range from 0.2 Hz to 140 Hz. The fatigue properties are equivalent for high stress tests in this frequency range. However, as the stress level decreases, some fatigue life differences can be seen. In a general way, the higher is frequency, the higher becomes the fatigue strength. Particularly, even though tests performed at 2 and 20 Hz reveals the same fatigue limit, a relatively higher fatigue limit is found for 140 Hz tests. Nevertheless, those fatigue strength differences are far smaller than compared with ultrasonic fatigue test results.

3.2. Fracture surface observation



(a) f=20 kHz, σ_a=255 MPa, N_f=1.25×10^7 (b) f=2 Hz, σ_a=228.8 MPa, N_f=1.25×10^5



(c) f=140 Hz, σ_a=244.4 MPa, N_f=7.29×10^4

Fig. 4 Typical examples of fracture surface

Fracture surface observation reveals that, for all the fatigue tests conducted up to failure, fracture has been initiated from the specimen surface, even under ultrasonic fatigue loading. This fact is usual for this kind of low strength steels, where number of inclusions, and so main factor of fish-eye fracture occurrence, is low. Figure 4 shows some typical examples encountered in the present study. Two kinds of fracture conditions have occurred. On the one hand, Fig. 4(a) presents a fracture behavior initiated by only one crack. On the other hand, Figs. 4(b) and (c) depict a clear multiple cracks conditions before specimen's failure. In order to gather such these data, Fig. 5 is an S-N diagram, which makes clearly distinction between simple and multiple cracks behavior found.

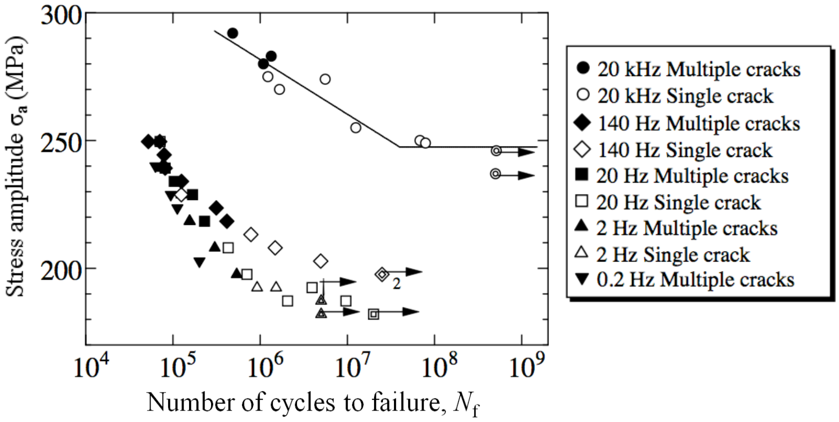


Fig.5. General fracture crack behavior

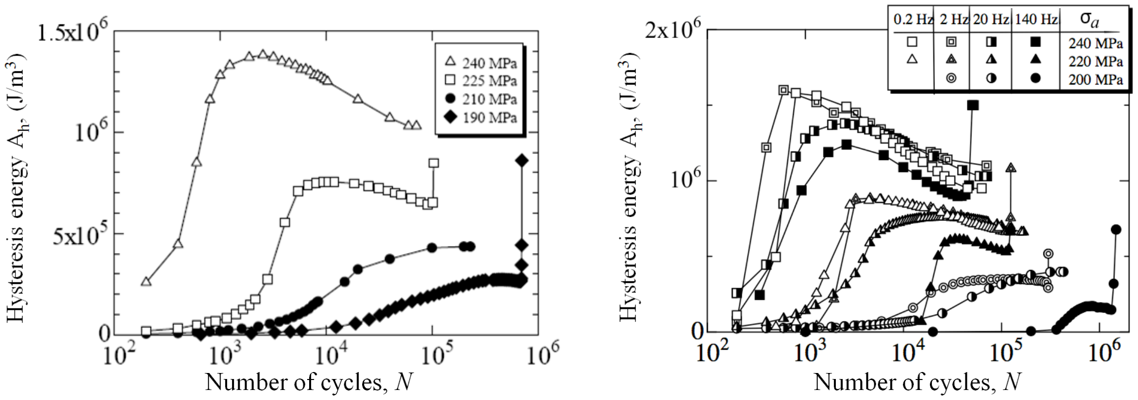
It is not surprising at all to see that multiple crack behavior is able to occur only for relatively high stress level tests, whereas simple crack condition is more likely to happen for low stress levels. One important finding related to this fracture behavior is that the transition between multiple to single crack appears around fatigue strength of 10^6 cycles, regardless testing frequency. In other words, this fracture behavior is not directly related to the stress level, but is mainly governed by the fatigue strength at a specific fatigue test condition. As fatigue strength of S15C steel is dependent of the testing frequency, the stress level where takes place this fracture behavior transition tends also to increase when testing frequency is increasing.

3.3. Stress-strain hysteresis

Stress-strain behavior in the present study has been studied for 0.2, 2, 20 and 140 Hz loading frequencies; as such a study is not possible in the case of ultrasonic method. Stress signal was directly recorded from testing machine load cell, whereas strain was measured from strain gauge system introduced before. As failure of fatigue specimen occurs almost all the time at the extremity of central cylindrical shape due to a slight stress concentration factor K_t=1.04, crack propagation does not influence measures on strain gauge at the center.

General evolution of stress-strain hysteresis loop of S15C studied here is presented in Fig. 6. In this diagram, hysteresis loop's area A_h from some fatigue tests is plotted against the number of cycles. One can clearly see on Fig. 6(a) that an increasing general trend occurs. In other words, as those tests are stress controlled, S15C is generally softening when fatigue goes. This result can be explained by the fact that this material is as rolled, and so has a hardened initial condition.

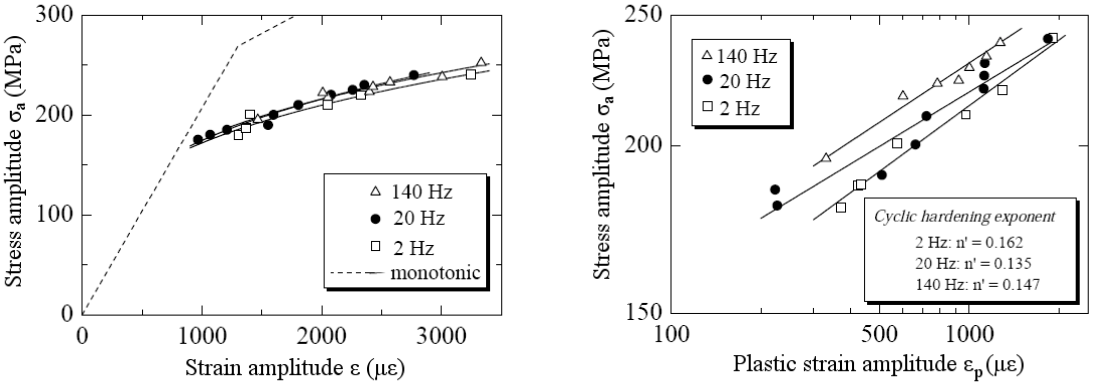
In addition, it is obvious that increasing trend becomes dramatic as the stress level increases. This result is natural, since cyclic softening phenomenon becomes usually more remarkable when material is subjected to higher stress amplitude. One can note that softening get to saturation at a certain number of cycles and then a slight cyclic hardening behavior is observed, as hysteresis loop's area tends to decrease. This phenomenon is particularly obvious for high stress tests.



(a) Hysteresis area under 20 Hz tests (b) Hysteresis area for several tests conditions

Fig.6. Evolution of stress-strain hysteresis loop's area

Figure 6(b) allows a comparison of hysteresis loop's area value between 0.2 Hz, 2 Hz, 20 Hz and 140 Hz fatigue tests at three different stress amplitudes. One can see clearly that hysteresis loop's area is dependent of the fatigue test as the smaller is the frequency, the higher becomes hysteresis energy. In addition, primary cyclic softening behavior is also more severe when frequency decreases.



(a) Comparison Monotonic and CSSC (b) Determination of cyclic hardening exponent

Fig.7. Comparison of CSSC under 2 and 20 Hz

Let us pay now a particular attention on the cyclic stress-strain curve (CSSC). Figure 7(a) allows a comparison of monotonic and cyclic stress-strain curves from fatigue tests at 2, 20 and 140 Hz. One can find that cyclic stress-strain data are lower than monotonic ones. This behavior is in accordance with general cyclic softening already mentioned[4].

In addition, if we consider only plastic strain of hysteresis loops as in Fig. 7(b), the cyclic hardening exponent is equal to 0.162, 0.135 and 0.147 for 2, 20 and 140 Hz fatigue tests respectively. One can note that theses values are close to the usual estimation 0.15 for most of metallic materials[5], regardless its initial conditions. Even though CSSC from 20 and 140 Hz fatigue tests are really close one to each other, one can see that for a similar stress amplitude, total strain amplitude and particularly plastic strain amplitude decreases when the testing frequency is increasing. This fact is of course correlated with the decrease of hysteresis energy already highlighted.

4. Discussion

A clear effect of the testing frequency on the fatigue properties of JIS S15C steel has been reconfirmed in the previous section. Now let us make a discussion on some phenomena, which can be involved in fatigue behavior for the present material.

4.1. Yield stress influence

Effect of strain rate on the yield stress value for this kind of low carbon steels has been reported in some publications[3,6]. This phenomenon is most of the time considered as one of the main phenomena that can explain frequency effect observed.

Figure 8 shows results of tensile tests conducted at different speeds in order to assess the strain rate effect on the present S15C steel. These tensile tests have been conducted according to JIS Z2201 standard, with a 14 mm diameter tested section. Results are compared with data from Tsuchida[7].

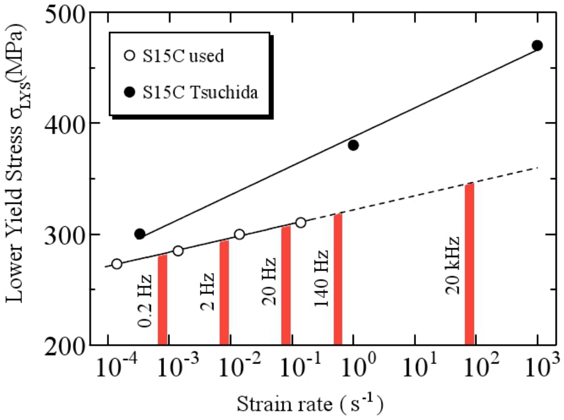


Fig.8. Strain rate effect on yield stress

One can easily find that S15C lower yield stress tends to increase when strain rate is increasing. This trend may be certainly linked with resistance of deformation, which decreases under high-speed tests.

Accordingly to literature from Tsuchida, a logarithmic law has been chosen. Difference of slope between the present work and Tsuchida's results may comes from that tensile test specimens in the case of very high stain rate are significantly smaller than those in usual strain rate range.

The present S15C used shows a regression with a correlation coefficient of 0.998, in the strain rate range from 10^{-4} to 10^{0} s^{-1}. This regression was extrapolated up to a strain rate of 10^{2} s^{-1} in order to assess yield stress value under equivalent ultrasonic fatigue strain rate. For instance, by this means, we obtain a difference of lower yield stress value between 20 Hz and 20 kHz fatigue test conditions of nearly 40 MPa.

This difference has been compared with the fatigue properties of S15C steel already introduced in Fig. 3. The following diagram, in Fig. 9, takes into consideration variation of yield stress by using normalized stress amplitude σ_a by the lower yield stress σ_{LYS} previously assessed.

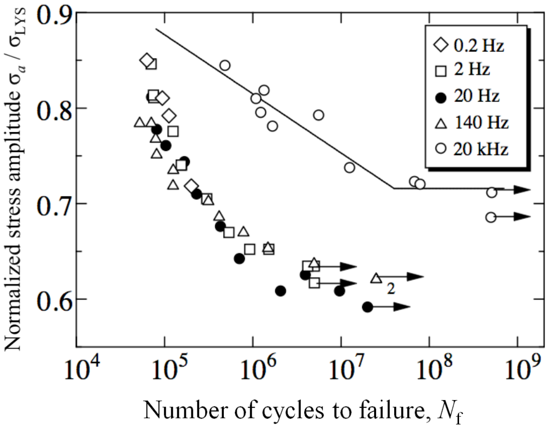


Fig.9. Evaluation of yield stress variation on *S-N* properties

Such a diagram gives us two very interesting points, which have to be discussed. First, if we consider only results from tests performed at 0.2, 2, 20 and 140 Hz, one can see that fatigue strength of S15C steel gathers in a thin area. Besides, fatigue limits from 2 and 140 Hz fatigue tests become really close each other. As a consequence, such a diagram is significant in order to evaluate the yield stress influence on the *S-N* property of S15C steel.

The second main point is of course the case of fatigue results from ultrasonic tests. Due to relatively high difference of yield stress introduced before between ultrasonic tests conditions and usual test frequency conditions, the huge gap of fatigue strength seen in Fig. 3 is significantly lower by taking into consideration the effect of strain rate. Nevertheless, it is not enough to claim that *S-N* properties are similar with other results from usual range frequency. So, the strain rate effect on yield stress is not sufficient to give an entire explanation of fatigue strength gap found in Fig. 3.

4.2. Cyclic hardening / softening behavior

In Figs. 6 and 7, a difference of stress-strain hysteresis phenomenon can be highlighted between 0.2, 2, 20 and 140 Hz fatigue tests. In other words, cyclic softening and hardening behavior seems to be slightly influenced by fatigue test frequency in this range. Of course, it is impossible to undertake similar stress-strain hysteresis study in the case of ultrasonic testing method, as real stress applied on specimen in unknown under ultrasonic technique. So, we cannot assess in the same way a potential discrepancy between ultrasonic and fatigue tests conducted in usual frequency range.

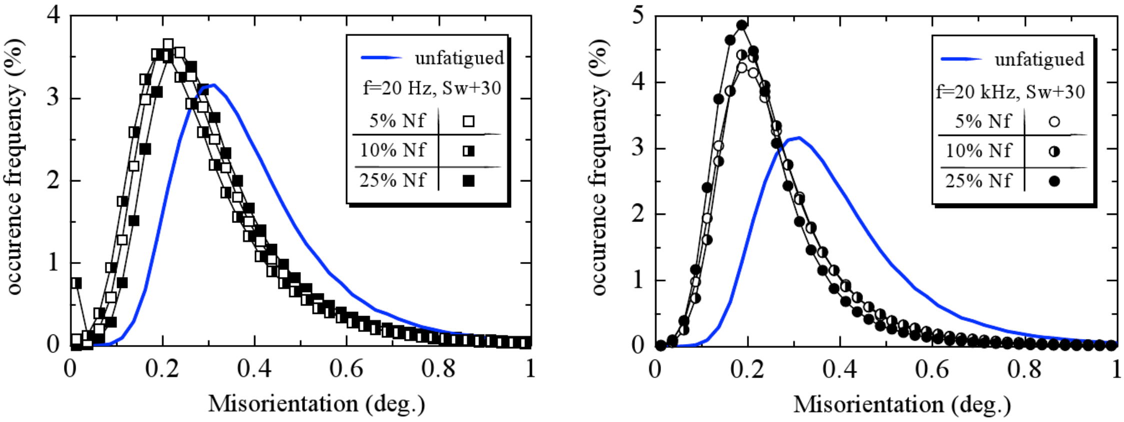
In order to highlight anyway a possible frequency effect on the cyclic hardening and softening, misorientation observation by EBSD method has been performed. This comparison involves 20 kHz and 20 Hz fatigue tests.

The samples used in this study have been prepared following hereafter instructions. For each frequency, two particular stress levels have been chosen, which are the fatigue limit plus 10 and 30 MPa. These stress levels are called S_w+10 and S_w+30 in the rest of the present paper.

For each stress level, corresponding fatigue strength is given by *S-N* model shown in Fig. 3. Three different specimens were stopped at 5%, 10% and 25% of the calculated fatigue strength. So, 12 different specimens have been fatigued in this process considering both 20 kHz and 20 Hz fatigue tests. After fatigue test has been stopped, center section of the specimen has been extracted, and then polished. Sample final condition has been prepared by OP-AA polishing method in order to prepare samples for EBSD observations.

Aim of these observations is to determine how lattice misorientation in ferrite phase evolves when fatigue goes. As well-known, cyclic hardening / softening behavior has an impact on dislocation structure[8-9]. This type of experiments can be considered as a first step to evaluate dislocation changes, before conducting direct observation of dislocations.

For each sample, two distinctive map scans of a 200x180 μm^2 area have been conducted. Misorientation curves presented in Figs. 10 and 11 are the average of these two scans. Figure 10(a) reveals that misorientation distribution does not significantly change between stages 5 and 25% of N_f for 20 Hz tests. This is less the case of ultrasonic tests, according to Fig. 10(b), even though dramatic change cannot be seen between these three fatigue stages. However, main result that has to be pointed out here is the drift of distribution into lower misorientation values for fatigued specimens, compared to the condition before fatigue test.



(a) Case of 20 Hz loading frequency (b) Case of 20 kHz loading frequency

Fig.10. Change of misorientation distribution for S_w+30 stress level

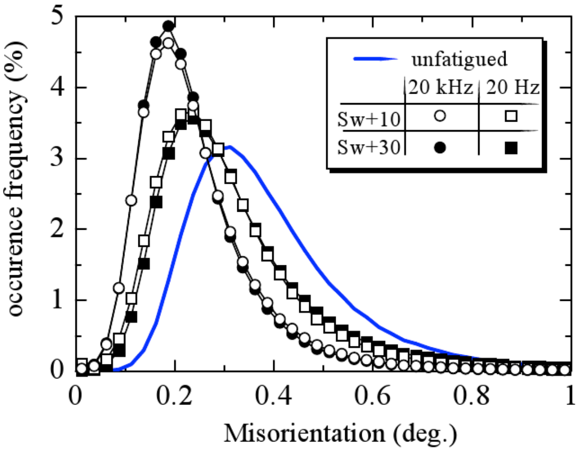


Fig.11. Comparison of misorientation distributions for 20 Hz and 20 kHz conditions at N=25% N_f

Such a result is confirmed in Fig. 11, where results at N=25% N_f for both stress levels studied are presented. It is found at a same frequency, distribution from S_w+10 and S_w+30 are similar. However, mode of distributions from 20 kHz tests is obviously lower than 20 Hz. This significant change of mode is certainly linked with dislocation structure changes. More precisely, such a result is an indication that dislocation structure changes due to fatigue loading at 20 Hz and 20 kHz is not equivalent. A possible explanation of this fact is the time allowed to dislocations to move is necessarily different for a same material fatigued under 20 Hz and 20 kHz conditions.

As a consequence, we can assess that fatigue frequency has an effect on cyclic behavior of S15C steel. Nevertheless, other results are needed to conclude in this way. It is particularly expected to undertake direct dislocations observation in order to be able to detect such a discrepancy in dislocations substructures.

5. Conclusions

(1) Frequency effect on fatigue properties of S15C low carbon steel has been reconfirmed. Fatigue strength tends to increase when testing frequency is increasing.

(2) Strain rate has a clear effect on yield stress value of S15C steel. This phenomenon is involved in the trend described before and explains the slight change of fatigue strength between 0.2 and 140 Hz. However, it is not sufficient to explain the *S-N* properties gap found from ultrasonic method.

(3) Comparison of stress-strain hysteresis loops and EBSD observations indicate a frequency dependence in cyclic behavior. This fact urges us to consider the cyclic hardening / softening properties as one other main phenomenon involved in frequency effect of S15C steel.

(4) Some other works have to be conducted to finalize the study of frequency effect on S15C steel. Particularly, further experiments on cyclic hardening / softening behavior will be undertaken, like dislocation observations.

References

[1] M. Kikukawa, K. Ohji, K. Ogura, Push-Pull Fatigue Strength of Mild Steel at Very High Frequencies of Stress Up to 100 kc/s. J. Basic Eng. T. ASME D, 87 (1965) 857–864.

[2] T. Yokobori and T. Kawashima, Acoustical Fatigue with Special Emphasis on Ferrite Grain Size Dependence of Fatigue Strength. J. of the Japanese Society for Strength and Fracture of Materials, 4 (1969) 19–16. (In Japanese)

[3] S. Setowaki, Y. Ichikawa, I. Nonaka, Effect of Frequency on High Cycle Fatigue Strength of Railway Axle Steel. Proceedings VHCF-5 (2011) 153–158.

[4] C.E. Feltner, C. Laird, Cyclic Stress-Strain Response of F.C.C. Metals and Alloys-I. Acta Metall., 15 (1967) 1621–1632.

[5] L. Landgraft, J. Morrow, T. Endo, Determination of the Cyclic Stress-Strain Curve. Journal of Materials, 4 (1969) 176–188.

[6] N. Tsutsumi, A. Shiromoto, V. Doquet, Y. Murakami, Effect of Test frequency on Fatigue Strength of Low Carbon Steel, J. Jpn Soc. Mechanical Eng. A, 72, 715 (2006) 317–325. (In Japanese)

[7] N. Tsuchida, H. Masuda, Y. Harada, K. Fukaura, Y. Tomota, K. Nagai, Effect of Ferrite Grain Size on Tensile Deformation of a Ferrite-cementite Low Carbon Steel. Material Science and Engineering A, 488 (2008) 446–452.

[8] J.R. Hancock and J.C. Grosskreutz, Mechanisms of Fatigue Hardening in Copper Single Crystals, Acta Metall., 17 (1969) 77–97.

[9] H. L. Huang, A Study of Dislocation Evolution in Polycrystalline Copper during Low Cycle Fatigue at Low Strain Amplitude, Materials Science and Engineering A, 342 (2003) 38–43.