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Microstructural Approach of Study on the Fatigue Behavior of Induction-Hardened Steel*

(Report 1)

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In recent years it has been well known that the remarkable improvement of fatigue strength of carbon steel specimen which was induction-hardened, can be due to

- 1) an improvement of mechanical properties of material by rapid heating, and
- 2) prevention of the propagation of the fatigue crack by the residual compressive stress in the surface layer of a specimen.

However, at the initiation stage of a macro- or microscopic fatigue crack, it is not yet defined what kind of role the residual compressive stress in the surface layer of specimen is to play, and what kind of effect the rapid heating has. In this paper, the fatigue behavior of induction-hardened microstructure which is free from the residual compressive stress, is investigated. Also the effect of the microstructural change of material due to induction-hardening on the fatigue strength, is observed.

1. Introduction

In recent years it has been quite well known that the considerable improvement in the fatigue strength of carbon steel which has been induction-hardened can be due to; (1) an improvement of the mechanical properties of the material by rapid heating, and (2) prevention of the propagation of fatigue cracks by the residual compressive stress existing in the surface layer of specimen.⁽¹⁾

However, at the initiation stage of a macro- or microscopic fatigue crack, it is not yet definite what kind of role the residual compressive stress†††† in the surface layer of the specimen is to play, and what kind of effect the rapid heating has. Because of

this, in this paper the fatigue behavior of induction-hardened hollow specimens which were free from residual stress was studied. In particular, the fatigue strength of the microstructure quenched after rapid heating, which was independent of the influence of residual stress, was investigated. The authors endeavoured to investigate the fatigue strength of the induction-hardened microstructure itself, which may be one of the factors governing the fatigue strength of induction-hardened steel.

2. Specimens and experiments

The work was carried out on an annealed 0.17 % C low carbon steel. The composition of the steel and the mechanical properties of the annealed steel are given in Table 1. The specimens were machined to a hollow cylindrical shape, as can be seen in

Table 1
Chemical compositions of the specimens (%)

C	Si	Mn	S	P
0.17	0.20	0.56	0.021	0.016

Mechanical properties of the annealed specimens

	Upper yield point kg/mm ²	Lower yield point kg/mm ²	Ultimate tensile strength kg/mm ²	True rupture stress kg/mm ²	Elongation %	Reduction of area %
S15C	25.5	24.2	43.9	85.5	36.5	62.4

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†††† It may be considered that there are two types of residual stress in the induction-hardened carbon steel. One is the so-called the macroscopic residual stress, and the other the microscopic residual stress in the microstructure. Here, when the residual stress is referred to, it indicates a macroscopic residual stress.

Fig. 1, and rotating bending and reversed torsion fatigue tests were conducted on them after they had been induction-hardened. The condition of induction-hardening will be indicated later.

Generally it is well known that an induction-hardened steel has a residual compressive stress in the surface layer of specimen, and has a microstructure with quite a high strength. Accordingly, 0.7 mm thick thin walled hollow specimens were employed to study the influence of metallurgical changes and residual compressive stress on the fatigue behavior separately. By employing hollow specimens, the influences of macroscopic residual stress and stress gradient are believed to be removed, and the effect of metallurgical changes would be picked up.

Relatively practical work has been done by one of the authors on the influence on the fatigue behavior of induction-hardened steel from a mechanical viewpoint. Some work has also been reported on the improvement of the fatigue strength of microstructure of medium carbon solid specimens.⁽²⁾

From those results, the maximum fatigue strength was obtained, corresponding to the domain of ferrite which becomes narrow as the induction-heating time becomes long. It was reported that the maximum fatigue strength was obtained under the critical condition at which the ferrite vanished, or only a little remained, according to the time of heating duration. From this it was considered that the mechanical behavior of ferrite in the quenched microstructure could be quite an important factor governing the fatigue strength of induction-hardened steel.

Rapid heating is a characteristic of induction-hardening, differentiating it from ordinary electro-furnace quenching. There is considered to exist some relation between the rate of heating and the fatigue behavior. Accordingly the following condition of induction-hardening was selected, as indicated in Fig. 2, namely controlling the peak temperature at 1000°C and the time needed to arrive

at the peak temperature was set at 3 sec, 5 sec, 8 sec, 12 sec, 16 sec, 20 sec, and 25 sec respectively. The condition under which the domain of ferrite vanished was not obtained, but the area of the ferrite domain changed in various ways in the microstructure of specimen. Fatigue tests were carried out on these specimens in rotating bending and in reversed torsion. Some of the specimens were electropolished, and after identifying the microstructure, the metallurgical change due to fatigue testing was investigated at repeated intervals under the microscope. Fatigue testing was carried out using a 10 kg-m Ono type rotating bending fatigue testing machine and a 4 kg-m Schenck type reversed torsion fatigue testing machine operating at 3000 rpm.

3. Results and discussion of fatigue tests

3.1 Fatigue strength of induction-hardened hollow specimen

Details of the results of the fatigue test carried out on the induction-hardened hollow specimens are given in Fig. 3 and Fig. 4. From these figures, there can not be found any extraordinary improvement of fatigue strength as in the case of solid specimen, the rise of the fatigue limit being only 50%.

Also it can be seen that the fatigue limit is constant in spite of the fact that the time of the heating duration is varied. The rise of fatigue limit is as follows, that is, from $\tau_{w0}=12 \text{ kg/mm}^2$, $\sigma_{w0}=19 \text{ kg/mm}^2$ which are the fatigue limits for reversed torsion and rotating bending of annealed specimens to $\tau_{w0}=18 \text{ kg/mm}^2$, $\sigma_{w0}=30 \text{ kg/mm}^2$ which are the values for induction-hardened specimens. Then the fatigue strength of induction-hardened microstructure itself which is free from residual compressive stress, shows not so high fatigue limit as can be seen in the case of induction-hardened

Fig. 1 Shape and dimensions of the specimen

Fig. 2 Illustrative figure of the condition of rapid heating

solid specimen, namely, $\sigma_{w0}=60 \text{ kg/mm}^2$. Rapid heating is the characteristic of induction-hardening and is different from ordinary electrofurnace quenching.

The fatigue strength was expected to show some dependence on the various heating durations, however no appreciable difference can be found in this study. Associated with this point, it is reported that for a 0.41% C carbon steel solid specimen there is a maximum fatigue strength corresponding to the particular heating duration.⁽²⁾ However, in the case of an induction-hardened solid specimen, the residual stress in the surface layer of the specimen is considered to have some influence on the fatigue behavior, and the result obtained from the case of solid specimen may not show simply the inherent fatigue strength of induction-hardened microstructure itself. Referring to the fatigue strength of thin walled hollow specimens, it is found that the residual compressive stress seems to be an important factor governing the fatigue strength as can be found in solid specimens and the fatigue strength of hollow specimens may be considered to be independent of the change of the heating duration. However, it has not become clear how the residual compressive stress has an effect on the fatigue behavior.

Fig. 3 S-N curve (Schenck type reversed torsion)

Fig. 4 S-N curve (Ono-type rotating bending)

Also the difference of the quenching condition between solid and hollow specimens should be considered with respect to the fact that the quenched microstructure itself shows a relatively low fatigue strength. Induction-hardening treatment is conducted with a high frequency induction-current, and only the surface of the specimen is heated to a high temperature, say 1000°C , in quite a short period, that is in a second.

When the solid specimen is induction-hardened, the thermal expansion of surface layer is constrained by the inside volume of specimen. Thus the metallurgical change may be influenced by the various kinds of thermal effects and it can be subjected to rather high pressure during the cooling time, so an extremely high strength steel can be obtained by the process of treatment like the so-called Ausforming.⁽²⁾ However in the case of hollow specimens, there is a lack in the metallurgical transformation under the condition like the case of the solid specimen. Accordingly the quenched microstructure after rapid heating does not seem to show as high a fatigue strength as the solid specimen. It therefore appears necessary to study the difference of the fatigue behavior between hollow specimens induction-hardened which are free from residual compressive stress and specimens made into hollow specimen after induction-hardening, in order to clarify the metallurgical factor governing the fatigue strength of induction-hardened steel. Recently it has become well known that there is a close relation between fatigue strength and residual compressive stress. Accordingly the Sachs' method of measuring residual stress was employed on the hollow specimens of this study, in order to determine how much residual stress exists in the surface layer.

At the time of measuring the residual stress, nitric acid was employed for expanding the hole in order to avoid the plastic deformation associated with enlarging the hole by drilling. The results obtained are given in Fig. 5, Fig. 6, and Fig. 7. In these figures, σ_r , σ_t , and σ_z correspond to the residual stress in the radial direction, tangential direction and axial direction respectively. It is shown that the residual compressive stress of $\sigma_z = -5 \sim -10 \text{ kg/mm}^2$ was found in the surface layer of hollow specimen. This is sufficiently small to allow it to be assumed that the influence of residual compressive stress on the fatigue strength was ignored.

3.2 Vickers hardness and ferrite in the quenched microstructure

It can be assumed that there is a linear relation between surface hardness and fatigue limit for some variations of hardness.⁽²⁾ Because of this, various

methods of increasing the surface hardness have been tried recently in order to obtain a high fatigue strength. From this point of view, it may also seem for induction-hardened steel that the fatigue strength, say, σ_{w0} * and τ_{w0} , increases with a rise of hardness. Consequently the surface hardness of hollow specimens induction-hardened was investigated. The results are given in Fig. 8 and Fig. 9 which show the relation between surface hardness and fatigue limit. In these figures, the surface hardness given is the mean value of the hardness

obtained from 60 random locations of the surface. The microvickers hardness tester with 500 g load was employed. It can be seen from these figures that the mean value of hardness is increased. In spite of the fact, however, that the mean value of hardness rises, the fatigue limit can be seen to be a constant value. This could be quite an interesting fact, and therefore the microstructure of the specimen surface was studied in order to investigate into it. The results are shown in Figs. 10~16 corresponding to the various durations of heating.

Fig. 5 Residual stress distribution (Heating duration 3 sec)

Fig. 6 Residual stress distribution (Heating duration 8 sec)

Fig. 7 Residual stress distribution (Heating duration 25 sec)

Fig. 8 Relation between the fatigue limit of reversed torsion, mean value of surface hardness and hardness of the retained ferrite

Fig. 9 Relation between the fatigue limit of rotating bending, mean value of surface hardness and the hardness of the retained ferrite

* It is well known that the approximate fatigue strength of low carbon steel flat specimens is $\sigma_{w0}=60 \text{ kg/mm}^2$ and $\sigma_{w0}=80 \text{ kg/mm}^2$ corresponds to medium carbon steel flat specimens. The exact value of fatigue strength changes depending on the various conditions of induction-hardening⁽²⁾⁽³⁾.

From the microvickers hardnesses taken at random positions, given in Fig. 17, it can be said that the microstructures at the surface of the specimens are quenched mixed structures. The microphotographs on the microstructures shown in Figs. 10~16 are investigated in order to clarify the reason why the rise of fatigue limit, corresponding to the rise of mean value of Vickers hardness, did not occur. It is quite clear from the surface microstructures that the ferrite is retained in the microstructure irrespective of the length of heating duration.

Emphasis was then put on investigating this ferrite, and the Vickers hardness was measured at only the ferrite in order to show how this ferrite influences the fatigue behavior of the bulk specimen. Results are also given in Fig. 8 and Fig. 9. From these figures it becomes clear that the ferrite

has a constant Vickers hardness, say $H_V(100\text{ g})=190$, irrespective of the heating duration.

In this case, the domain of ferrite in the quenched microstructure decreases gradually with an

Heating duration 3 sec
Magnification 50

Fig. 10 Microstructures of induction-hardened steel

Heating duration 5 sec
Magnification 50

Fig. 11 Microstructures of induction-hardened steel

Heating duration 8 sec
Magnification 50

Fig. 12 Microstructures of induction-hardened steel

Heating duration 12 sec
Magnification 50

Fig. 13 Microstructures of induction-hardened steel

Heating duration 16 sec
Magnification 50

Fig. 14 Microstructures of induction-hardened steel

Heating duration 20 sec
Magnification 50

Fig. 15 Microstructures of induction-hardened steel

Heating duration 25 sec
Magnification 50

Fig. 16 Microstructures of induction-hardened steel

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Magnification 50

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Heating duration 20 sec
Magnification 50

Fig. 15 Microstructures of induction-hardened steel

Heating duration 25 sec
Magnification 50

Fig. 16 Microstructures of induction-hardened steel

increase in heating duration but no appreciable influence can be seen. Accordingly, from the viewpoint of hardness, it can be concluded that the fatigue strength has no relation to mean hardness as long as the fracture of ferrite is considered to lead to a fracture of the bulk specimen. This is so because the Vickers hardness of ferrite in the microstructure remains constant and the corresponding fatigue strength also shows a constant value. Here, it is interesting to know how the ferrite in the quenched microstructure, which can be considered to be quite an important factor governing the fatigue strength, differs from the annealed ferrite.

At least, from the viewpoint of hardness there is some difference in the value of hardness between ferrites, that is, the hardness of ferrite in the quenched microstructure is $H_V=190$, and that of annealed ferrite $H_V=120$. Thus, there is a difference in the value of hardness between the two, and it can be appropriate to consider the ferrite in the quenched microstructure to be so-called special "retained ferrite". Nevertheless, it can be expected that there is some difference in fatigue behavior between "retained ferrite" and "annealed ferrite". That is, it may be considered that there would be some difference in the state of solid solution of carbon and nitrogen resulting from induction-hardening between retained ferrite and annealed ferrite. Besides it may be considered that special ferrite might exist which was restricted by the surrounding quenched microstructure.

However, it is not clear whether this retained ferrite was the product of the cooling process after

complete austenizing, that is, proeutectoid ferrite or non-melting ferrite resulting from the incomplete austenizing due to the rapid heating.

When one considers factors governing the fatigue strength, the critical length of heating duration which is the border line determining whether the ferrite vanishes or not, as well as the residual compressive stress can both be considered important factors. In the connection with these points, it has been reported by one of the authors that the relation between the length of heating duration and the temperature required for the vanishing of ferrite was studied for various kinds of microstructure. According to the above results, it can be said that the length of heating duration deciding whether the ferrite vanishes or not, is associated with the phenomenon of the diffusion of carbon atom in the pearlite structure when the temperature remains constant⁽⁴⁾. Other works also exist which studied the relation between the fatigue strength and the length of heating duration required for the vanishing of ferrite. In this case the fatigue strength was interpreted by the concept of effective length of heating duration corresponding to the diffusion phenomenon of carbon and vanishing time of ferrite.⁽²⁾ In this way, it seems likely that the retained ferrite may have quite an important effect on the fatigue strength. In order to study the fatigue behavior of this retained ferrite, the Vickers hardness of retained ferrite was measured after 10^7 stress cyclings. It becomes clear from the result that there is no strain aging as was expected before the fatigue tests were done. It has been said that an improvement of aging ability through quenching from the temperature below the A_1 transformation point (low temperature quenching) leads to an improvement of mechanical behavior, but in this study, such an improvement can not be seen in this retained ferrite.⁽⁵⁾ Especially, with respect to the hardness which was investigated after 10^7 fatigue stressings, there is some difference in the mechanical property between retained ferrite and low temperature quenched ferrite which was reported to contain a lot of carbon and nitrogen.

3.3 Fatigue behavior of retained ferrite

It has been made clear that the origination of slip bands associated with fatigue stressing has a close relation with the origination of microcracks.⁽⁶⁾

In this paper, the specimens which were induction-hardened for 8 sec and 16 sec were tested in reversed torsion and rotating bending at the stress levels of $\sigma=21$ kg/mm² and $\sigma=35$ kg/mm² which correspond to 120% of fatigue limit, that is $\tau_{w0}=18$ kg/mm² and $\sigma_{w0}=29$ kg/mm², in order to clarify the fatigue behavior of the retained ferrite which may

Fig. 17 Relation between heating duration and hardness distribution

be considered to have a close relation with the fracture of bulk specimen. The surface of the specimen was observed under the microscope ($\times 400$ magnification) after the constant stress cycling. It was found from the metallurgical observation that slip bands appear in the retained ferrite after 1% of fatigue life has been spent. (Fatigue life is about $2\sim 3 \times 10^5$.) And it was also found that during the first 5~10% of fatigue life, the slip bands spread in the retained ferrite preferentially. After 80% of fatigue life has been spent, a dense slip band was observed which could not be eliminated by light electro-polishing. It could be that these slip markings by this time are not simple slip bands but microcracks.⁽⁷⁾ Fig. 18 and Fig. 19 illustrate the appearances of slip bands and microcracks. These observations were made after $N=10^5$ cycles. From these observations, it would appear that the fatigue crack originates from the retained ferrite and this is the origin of fatigue fracture.

Accordingly, it may be said that the fatigue fracture starts at the retained ferrite of the induction-hardened microstructure which is free from the

residual stress.

4. Conclusions

In order to investigate the factors which might be influencing the fatigue behavior of induction-hardened steel, fatigue tests were carried out in reversed torsion and rotating bending. The specimens employed were S15C (0.17%C) low carbon steel and they were machined hollow, in order to avoid the influence of residual compressive stress. The specimens were induction-hardened for various lengths of heating duration. Results obtained are as follows:

i) It was found that the fatigue limit of the specimens which were induction-hardened, is approximately a constant value irrespective of the length of the heating duration. The fatigue limits of annealed specimens are $\tau_{w0}=12 \text{ kg/mm}^2$, $\sigma_{w0}=19 \text{ kg/mm}^2$ and the fatigue limits of induction-hardened specimens are $\tau_{w0}=18 \text{ kg/mm}^2$, $\sigma_{w0}=30 \text{ kg/mm}^2$. It may be said from this study that the quenched microstructure after rapid heating itself does not show the high fatigue strength which is seen in the case of solid specimen, and a relatively low fatigue limit, say $\sigma_{w0}=30 \text{ kg/mm}^2$ is obtained.

ii) It seems clear that the fatigue strength was governed by the existence of the retained ferrite. The improvement of fatigue limit has a constant value irrespective of the heating duration.

iii) It was confirmed that the slip markings and microcracks originate at the retained ferrite. The first appearance of slip markings was observed after 1% of fatigue life was spent.

iv) It is pointed out that further work is necessary to study the fatigue behavior of retained and annealed ferrite.

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$\tau=21 \text{ kg/mm}^2$
50~60% of fatigue life has been spent
Magnification 140

Fig. 18 Slip band originating in the retained ferrite

$\sigma=36 \text{ kg/mm}^2$, $N=10^5$
Magnification 140

Fig. 19 Microcracks originating in the retained ferrite