Influence of the depth of heat affected zone on the fatigue strength and fracture surface in induction heated JIS SUJ2 bearing steel

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Abstract. Induction heating is used as one of surface hardening methods. Induction heating can control the depth of the heat affected zone. In this work, we prepared two kinds of induction heated bar specimens: one had a shallower heat affected zone; and the other had a thick heat affected zone. After the rotating bending fatigue tests, we observed the fracture surfaces and measured the value of retained austenite. We found that the depth of heat affect zone and the amount of retained austenite relate the fatigue strength.

1. Introduction

JIS SUJ2 bearing steel was used for mechanical parts which required high fatigue strength. For this reason, the effective strengthening method “quenching” is popular. In particular, induction heating is used as one of surface hardening methods. Induction heating can control the depth of the heat affected zone[1,2]. Kawasaki et al. investigated the mechanical properties of induction heated spring steel. They reported that induction heating improved the fatigue strength compared to that of furnace heated spring steel[3]. Komotori et al. prepared four kinds of hardened specimens and performed the rotating bending fatigue tests (RBT) in order to investigate the relation between the depth of heat affected zone and the fatigue strength. They reported that the fatigue limit related the depth of heat affected zone[4].

Yuki et al. investigated the influence of induction heating condition on the amount of retained austenite (RA). They reported that quenching temperature increased the amount of RA during induction heating process[5]. In generally, it is known that RA decreases the material hardness, but RA enhances the material toughness and resists the crack propagation[6,8,9]. Dommarco et al. reported the relation between the amount of RA and the contact fatigue life[10]. RA is effective in improving the fatigue strength.

In our previous work, we investigated the fracture surface of induction-heated JIS SUJ2 steel specimens. After the RBT, we observed the large inner cracks. We defined this crack as ”TRO crack”, and reported that TRO crack size increases with increasing the number of cycles to failure[7].

In this work, we prepared two kinds of induction heated bar specimens: one had a shallower heat affected zone; and the other had a thick heat affected zone. After the RBT, we observed the fracture surface and measured the RA. We investigate the influence of heat affected zone on the fatigue strength based on the stress-induced martensitic transformation.
2. Test method

2.1. Specimen (JIS SUJ2 steel) and heat treatment
We prepared JIS SUJ2 steel bar specimens. Table 1 shows the chemical compositions of the specimens. The specimens were spheroidized annealed [8] and were quenched by induction heating. The samples were heated up by the induction coil (For φ 10 mm) during the 300 rpm rotation. Immediately, the samples were cooled by water at room temperature. After that, Specimens were tempered at 180 °C for 60 minutes. We produced the 40 samples and divided these samples according to their depth of the hardened layer. The deeper samples are referred to as IH-deep and the shallower samples are referred to as IH-shallow.

Figure 1 shows the dimension of the RBT specimen. Stress concentration factor of breaking point was about 1.0[8].

| Table 1 Chemical composition of the JIS SUJ2 steel bar specimens (weight %) |
|---------------------------------|----|----|----|----|----|----|----|---|---|
| C     | Si | Mn | P  | S  | Ni | Cr | Mo | Cu |
| 1.00  | 0.17 | 0.39 | 0.019 | 0.006 | 0.06 | 1.38 | 0.02 | 0.12 |

2.2. Rotating bending fatigue test
Figure 2 shows the RBT machine which was developed by Kida’s group[11]. The rotation speed was about 1600 rpm and the frequency of the fatigue tests was about 25 Hz. The stress amplitude was ranging from 386 to 746 MPa and stress ratio was -1. The target number of cycles was 1.0×10⁸

Modified stress was calculated in order to evaluate the effect of the crack origin depth on low stress amplitude with following equation:

\[
\sigma_m = \frac{r-d}{r} \sigma_n
\]

where \(\sigma_m\) is modified stress amplitude [MPa], \(r\) is radius of specimen [mm], \(d\) is depth of crack origin from the surface [mm] and \(\sigma_n\) is nominal stress amplitude [MPa].

![Figure 1 RBT specimen](image1)

![Figure 2 RBT machine](image2)
2.3. Fracture surface observation
After the RBT, fracture surfaces were observed by an optical microscope SHODENSHA TG140CCD. Vickers hardness distributions were measured by a MATSUZAWA VMT-X7s. The load was 10 kgf and the loading time was 15 seconds.

2.4. Retained austenite measurement method
We used a Bulker D8 DISCOVER with GADDS (2D detector) in order to measure the amount of RA. The measurement increments were 0.2 mm. Table 2 shows the test conditions of the RA measurement. We measured RA distributions on three sections: first and second are before and after the RBT and the last is fracture surface. Figure 3 shows the schematic illustration of their observation points. Figure 3(a) shows the observation points before the RBT. Specimens were cut and then polished by 1µm diamond paste. Figure 3(b) shows the observation points after the RBT. Specimen was cut and measured near the fracture surface. Figure 3(c) shows the fracture surface observation points after the RBT. We measured the amount of the RA at TRO crack and outside TRO crack in order to investigate the influence of crack propagation rate on the amount of RA.

Table 2 Observation conditions for RA measurement.

| X-ray source | Cr Kα |
|--------------|-------|
| Power        | 35 kV 40 mA |
| Diameter of collimator | 0.1 mm |
| Detector distance | 150 mm |
| Measurement angle | 60 to 90 (20) |
| Scan time    | 20000 sec / point |

(a) Observation points before the RBT.
(b) Observation points after the RBT.

(c) Fracture surface observation points after the RBT.

Figure 3 Schematic illustration of RA measurement method.
3. Results and discussion

3.1. Rotating bending fatigue test and Vickers hardness distribution

Figure 4 shows Vickers hardness distributions of IH-deep and IH-shallow samples. Vickers hardness distribution of IH-shallow samples (○) is referred from our previous data[7]. Figure 5 shows the microstructures of the samples which were etched by nital. At heat affected zone, ferrite transformed into martensite. We defined the area where Vickers hardness is higher than 600 HV as “martensitic transformed area”. Similarly, we also defined the area from 200 HV to 600 HV as “transition area” and the area below 200 HV as “ferrite area”.

Vickers hardness of IH-deep and IH-shallow samples at 0.2 mm from the surface were 772 HV and 750 HV. The depth of martensitic transformed area of IH-deep were 1.1 mm and that of IH-shallow was 0.8 mm. Martensitic transformed area of IH-deep samples were larger than that of IH-shallow samples.

Figure 6 shows S-N diagram of nominal stress amplitude. S-N diagram of nominal stress amplitude of IH-Shallow samples (○) is referred from our previous data[7]. TRO crack can be seen in all specimens. The fatigue limit of IH-deep and IH-shallow samples were 427 MPa and 386 MPa. The fatigue limit of IH-deep sample was higher than that of IH-shallow samples under nominal stress amplitude. Figure 7 shows S-N diagram of modified stress amplitude. At the 10^8 cycles, we stop the test because it is fatigue limit. Therefore, we cannot calculate the modified stress. The fatigue strength of IH-deep samples was equal to that of IH-shallow samples under the modified stress amplitude.
3.2. Fracture surface observation

Figure 8 shows TRO crack area of IH-deep sample ($\sigma_n=445$ MPa, $N_f=2.76 \times 10^6$). This TRO crack originated at the depth of 1.61 mm from the surface. Figure 9 shows TRO crack area of IH-shallow sample ($\sigma_n=427$ MPa, $N_f=2.0 \times 10^6$). This TRO crack originated at the depth of 1.28 mm from the surface. Figure 10 shows one of the SEM images at the crack origin. The non-metallic inclusions can not be seen and the crack initiated from the boundary of the hardness layer. In this tests, all of the specimens were broken from the TRO cracks.

Figure 11 shows the relation between the TRO crack size and number of cycles to failure. TRO crack size of IH-shallow (○) is referred from our previous data[7]. TRO crack size of IH-deep samples was equal to that of IH-shallow at the same number of cycles to failure. Figure 12 shows the relation between aspect ratio and number of cycles to failure. Aspect ratio of IH-deep samples was equal to that of IH-shallow at the same number of cycles to failure. TRO crack size and aspect ratio increased with number of cycles to failure. This indicates that TRO crack size and aspect ratio did not relate the depth of martensitic transformed area.
3.3. Results of retained austenite measurement

Figure 13 shows the RA distributions before the RBT. The value of RA of IH-deep and IH-shallow samples at 0.1 mm from the surface were 16.5 % and 7.2 %. At 0.7 mm from the surface, the value of RA of IH-shallow sample decreased to 0 %. At 1.3 mm from the surface, the value of RA of IH-deep sample decreased to 0%. The value of RA at martensitic transformed area of IH-deep sample was higher than that of IH-shallow sample. We suggest that the value of RA at martensitic transformed area related the depth of martensitic transformed area.

Figure 14 shows the RA distributions of IH-deep sample after the RBT. The value of RA after the RBT at 0.1 mm from the surface was 16.5 %, which is similar to the RA before the RBT. This means that the retained austenite did not decrease with only the bending moment. In both the TRO crack and the outside TRO crack, the decreasing values of RA were 1.4 % and 4.6 %. The values of both area were lower than that before the tests. This supports that the retained austenite did not decrease with only the bending moment without crack propagation. Figure 15 shows the RA distributions of IH-shallow sample after the RBT. The brief tendency of Fig. 14 is similar to that of Fig. 15. The value of RA after the RBT is the same as before the RBT and the value of RA at the fracture surface is lower than that before the
test. These results concluded that the stress induced transformation occurred in both inside/outside TRO crack areas.

![Graph showing retained austenite percentage vs depth from the surface for before and after test conditions.](image1)

**Figure 13 RA distributions before the RBT.**

![Graph showing retained austenite percentage vs depth from the surface for before and after test conditions.](image2)

**Figure 14 RA distributions of IH-deep sample after the RBT.**

![Graph showing retained austenite percentage vs depth from the surface for before and after test conditions.](image3)

**Figure 15 RA distributions of IH-shallow sample after the RBT.**

4. **Conclusions**

We prepared two kinds of induction heated bar specimens, one was shallower heat affected zone (IH-shallow sample) and the other was thick heat affected zone (IH-deep sample). After the RBT, we observed fracture surfaces and measured the amount of retained austenite. The conclusions are as follows.
1. The fatigue limit of IH-deep sample was higher than that of IH-shallow samples under nominal stress amplitude.
2. The fatigue strength of IH-deep samples was similar to that of IH-shallow samples under the modified stress amplitude which included the effect of crack size and aspect ratio.
3. The value of RA at heat affected zone of IH-deep sample was higher than that of IH-shallow sample.
4. In both inside/outside TRO crack areas, stress induced transformation occurred.

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