Evaluation of rolling contact fatigue of induction heated 13Cr-2Ni-2Mo Stainless steel bar with Si₃N₄-ball

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Abstract. 13Cr % martensitic stainless steels were used in various industry, because they have excellent corrosion resistance and high hardness among other stainless steels. They are also expected as a bearing material, however, the research on rolling contact fatigue (RCF) is not enough. In this study, 13Cr-2Ni-2Mo stainless steels were quenched by induction heating and their RCF lives were evaluated. A Si₃N₄-ball was used in order to apply higher stress (P_{max} =5.6 GPa) than our previous tests (P_{max} =5.3 GPa), in a single-ball RCF testing machine. It was found that the basic life (L_{10}) was 2.20×10⁶ cycles and Median life (L_{50}) was 6.04×10⁶ cycles. In addition, Weibull modulus became higher than the previous tests.

Nomenclature

| Symbol | Description |
|--------|-------------|
| L_{10} | The basic life |
| L_{50} | The Median life |
| P_{max} | Hertzian maximum stress |

1. Introduction

Stainless steels are used for various machine components, especially under the corrosive environment because they have excellent corrosion resistance. For these reasons, they are expected as one of bearing materials. However, it is necessary to process the heat treatment in order to improve durability for machine components. As the heat treatment method of ‘Induction Heating (IH)’ can harden only the surface for short time, it takes a low energy and cost. In the present study, the specimens of 13Cr-2Ni-2Mo stainless steel were quenched by the induction heating. This material obtains higher strength among other stainless steels by applying heat treatment [1-2]. Previous research reported induction heating improved the wear resistance [3]. According to Yuki and Sato [4], it was clear that induction heating has a positive effect on rolling contact fatigue (RCF). In our previous study [5], RCF life of the 13Cr-2Ni-2Mo stainless steel which were quenched by induction heating using a single-ball RCF system was investigated. However, most of the samples didn’t generate flaking failure because RCF tests were performed by using a SUJ2-ball.

The purpose of this study is to evaluate the RCF life of 13Cr-2Ni-2Mo stainless steel bars which were quenched by induction heating based on only flaking fatigue data. In order to apply higher stress than the previous tests, RCF tests were performed by using the Si₃N₄-ball, which had higher hardness and Young’s modulus than the SUJ2-ball.
2. Test method

2.1 Bar specimens and heat treatment
The bar specimens of 13Cr-2Ni-2Mo stainless steel bars were quenched by induction heating. Table 1 shows the chemical composition in weight percent of 13Cr-2Ni-2Mo stainless steel. Induction heating was carried out under the following conditions: Voltage of 10 kV, current intensity of 9 A and feed speed of 300 m/s. After the induction heating, bar specimens were tempered at 180 °C for 120 minutes.

Length of the bar specimen is 290 mm and a diameter is 20 mm. Mechanical properties of the specimen are Young’s modulus of 199 GPa and Poisson’s ratio of 0.30. Before measuring Vickers hardness, cross section of specimen bar was polished. The Vickers hardness was measured by a standard Vickers hardness tester (VMT-X7s, Matsuzawa Co., Ltd, Japan) under a load of 10 kgf and a loading time of 15 sec.

|     | C  | Si | Mn | P  | S  | Ni | Cr  | Mo | N  | Fe |
|-----|----|----|----|----|----|----|-----|----|----|----|
| wt.%| 0.18| 0.29| 0.18| 0.022| 0.001| 1.03| 13.12| 1.85| 0.07| R.  |

2.2 Rolling contact fatigue test
Figure 1 shows a single-ball RCF testing machine which was developed by Kida’s group in their previous work [6]. It can reproduce RCF of bearings by rotating a shaft while pushing up the ball with four bearings to apply a load. The diameter of a Si3N4-ball was 9.525 mm (3/8 inch). Mechanical properties of Si3N4 are Young’s Modulus of 294 GPa and Poisson’s ratio of 0.27.

Table 2 shows experimental conditions of RCF testing which were calculated using the mechanical properties. Based on the Hertzian contact theory, Hertzian maximum stress (P_max) were calculated [7]. Single-ball RCF tests were performed under the following conditions until flaking failures: rotating speed of 3000 rpm and Hertzian maximum stress of 5.6 GPa. Flaking failures and their maximum depths from the surface were observed by a Laser Confocal Microscope (LCM). It is noted that the present load was 833 [N], which was lighter that in our previous work (877 [N]) [5].

Figure 1 Single-ball RCF testing machine.
Table 2: Experimental conditions of rolling contact fatigue test.

| Load [N] | Hertzian maximum stress $P_{\text{max}}$ [GPa] | Semi-major radius of contact area [mm] | Semi-minor radius of contact area [mm] |
|----------|-----------------------------------------------|----------------------------------------|----------------------------------------|
| 833      | 5.6                                           | 0.303                                  | 0.233                                  |

3. Experimental result and discussion

3.1 Vickers hardness distribution

Figure 2 shows Vickers hardness distribution on the section of the 13Cr-2Ni-2Mo stainless steel bar. The Vickers hardness of surface was 576 HV, and the depth of heat affect zone is 0.8 mm from the surface.

Figure 3 shows an example of flaking failures. This was observed at $6.34 \times 10^6$ cycles. Based on the LCM observation results, it was found that the size of flaking failures in all samples is similar and the maximum depths from the surface is about 200 μm. Flaking failure occurred from heat affect zone in all samples.

3.2 Weibull distributions

Reliability and fatigue life of bearings has been investigated based on Palmgren and Lundberg’s investigation [8-9]. Based on this investigation, Ioannides & Harris [10] took into consideration the idea of ‘fatigue’ for life evaluation. Here, the life is evaluated based on the statistical data of RCF tests. In this study, the number of samples that generated flaking failures was 10. These datum were used to obtain Weibull distributions of RCF life. Based on Median rank method, the empirical datum are ranked in the Weibull analysis.

Figure 4 shows two Weibull distributions. One was calculated from the present results of RCF testing and the other from the previous data (Kida et al. [5]) for the same material. Significant difference of these data was $P_{\text{max}}$. In the previous study, RCF tests were performed under the following conditions: the ball was SUJ2 whose Young’s modulus was 207 GPa and Poisson’s ratio was 0.30; $P_{\text{max}}$ was 5.3 GPa. Other conditions were the same as in the present tests. In addition, because the previous data includes the suspended data of the specimens which didn’t generate flaking failures, these were modified using L.G. Johnson’s statistical method [11].
Flaking failures lives in all samples range from $1.0 \times 10^6$ to $2.0 \times 10^7$ cycles. The basic life ($L_{10}$) is $2.20 \times 10^6$ cycles and Median life ($L_{50}$) is $6.04 \times 10^6$ cycles. The present RCF life is lower than the previous data. This is because the present $P_{\text{max}}$ is higher than the previous $P_{\text{max}}$. This result however indicates that the range of RCF life becomes smaller when $P_{\text{max}}$ is higher. Furthermore, it is found that the Weibull modulus of RCF life of the present tests is 1.88, which is higher than the previous data. It is noted that the RCF life obtained under this experimental conditions is reliable because this Weibull modulus is sufficiently higher than the standard value (10/9) proposed by Palmgren and Lundberg [12].

![Figure 4 Weibull distribution of RCF life.](image)

*1 RCF tests were conducted under the conditions shown in Table 2. Weibull modulus was 1.88 and the basic life was $2.20 \times 10^6$ cycles.

*2 RCF tests were conducted under the following conditions ($P_{\text{max}}$ of 5.3 GPa, rotating speed of 3000 rpm and #46-lubricant conditions). Weibull modulus was 1.38 and the basic life was $9.01 \times 10^6$ cycles.

4. Conclusions
13Cr-2Ni-2Mo stainless steel bars were quenched by induction heating. Rolling contact fatigue tests of the bars were conducted using a Si₃N₄ single-ball RCF testing machine.
(1) Flaking failures generated in heat affected zone.
(2) The basic life ($L_{10}$) was $2.20 \times 10^6$ cycles and Median life ($L_{50}$) was $6.04 \times 10^6$ cycles.
(3) The present Weibull modulus of RCF life was 1.88, which was higher than the standard value (10/9).
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