Evaluation of Local Mechanical Properties of High Strength Steels by Indentation Method

High strength steels are used for important components such as rolling bearings, for which surface treatments such as induction and carburized hardenings are applied. Strength designs for these components require material properties at the local areas, since the material properties are different at the treated locations. The objective of the present study is to evaluate the local mechanical properties of high strength steels by the dual indenter method. Non-dimensional \( f \) function is developed for 118 degree trigonal pyramid indenter using finite element method. Dual-indenter method is conducted by indenters with the apex angles of 115 and 118 degrees for JIS-SUJ2 and JIS-SUJ3. The results reveal that good agreements are achieved between stress-strain curves of tensile testing and those of the dual-indenter method. The local mechanical properties are evaluated by the dual-indenter method for induction-hardened and carburized components. There are some differences in stress strain curves at the locations of the components by the influence of the heat treatments.

1. Introduction

For important components such as rolling bearings, hardening is applied for either all the components or only local areas where high strength is needed by surface treatments such as induction and carburized hardenings. Since the local areas where surface treatment is applied have different material properties, local evaluation for those local areas is required when mechanical properties are evaluated. A dual indenter method \(^1\) has been proposed for evaluating local mechanical properties as an indentation method. One of the authors (Ogawa) has been applying the dual indenter method to diverse materials for the mechanical evaluation \(^2\). However, it was revealed that the prediction on high-strength-bearing steel did not always match the tensile testing results. Therefore, in this study, a method of estimating mechanical properties of high-strength materials was studied using the indentation method and finite element method (FEM).

2 Material under test and test piece

The chemical components of materials under test, high-carbon chrome-bearing steel JIS-SUJ2 and JIS-SUJ3, are shown in Table 1. The standard overall hardening was applied to the materials under test, and then, they were tempered at 180–350°C and used as test pieces. Induction-hardened and carburized materials were also used as test pieces. The surface of test pieces was treated with emery paper polishing, buffing, and lapping with diamond paste.

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Cu</th>
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<tr>
<td>SUJ2</td>
<td>1.02</td>
<td>0.27</td>
<td>0.43</td>
<td>0.014</td>
<td>0.007</td>
<td>0.05</td>
<td>1.48</td>
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<tr>
<td>SUJ3</td>
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<td>0.47</td>
<td>1.06</td>
<td>0.014</td>
<td>0.006</td>
<td>0.07</td>
<td>1.06</td>
<td>0.14</td>
</tr>
</tbody>
</table>

*Professor, Department of Mechanical Engineering, College of Science and Engineering, Aoyama Gakuin University
**Advanced Technology R&D Center
3. Testing machine and conditions

Six indentation tests were conducted for each condition, using Dynamic Ultra Micro Hardness Tester DUH-W201 of Shimadzu Corporation. Tests were all conducted at room temperature (approximately 20˚C) with the loading/unloading speed of 10.1 mN/s and the maximum test force of 1961 mN. In addition, trigonal pyramid indenters with apex angles φ of 100˚, 115˚, and 118˚ were used for the testing.

4. Indentation test

4.1 Dual indenter method

In this study, a trigonal pyramid indenter with apex angle of 118˚, which has relatively small plastic deformation, is used in addition to φ = 100˚ and 115˚, as the dual-indenter method is applied. The following analysis was conducted using a conical indenter with apex angle θ, where the ratio of projected area and h of the indenter is the same. In general, indentation force F and indentation depth h are in the relationship of 

\[ F = C h^2 \]  

and can be expressed as follows after a dimension analysis:

\[ F = F(E^*, n, \sigma_r, \theta, h) \]  

Where \( E^* \) is the complex Young’s modulus, \( n \) is the work-hardening exponent including influence of elastic deformation of indenter. \( \sigma_r \) is called the typical stress that characterizes the plastic deformation region. When the II theory is applied to the equation (1), the following is obtained:

\[ \frac{F}{C \sigma_r h^2} = \frac{C}{\sigma_r} = \Pi \left( \frac{E^*}{\sigma_r}, n, \theta \right) \]  

The typical stress-strain relationship for each indenter can be obtained by finding this II function for each of the indenters of apex angles \( \phi \) and testing two types of indenters, and using the II function and the experiment result, that is, the slope \( C \), which is \( F \) against \( h^2 \) in the load process. \( n \) is determined from the relationship of these two points. Also, from the generally known stress-strain relationship, the yield stress \( \sigma_y \) and the strength coefficient \( K \) can be obtained from the following equation: where \( \varepsilon_r \) is the typical strain.

\[ \sigma_r = K \varepsilon_r^n \quad \sigma_r = \sigma_y \left( 1 + \frac{E}{\sigma_y} \varepsilon_r \right)^n \]  

4.2 Finite Element Method (FEM) analysis

A general-purpose non-linear structural analysis program, MSC.MARC Mentat 2005, was used for analyzing newly generated II functions in this mechanical property evaluation using dual-indenter method. In the previous indentation tests with trigonal pyramid indenters, it has been verified that the three-dimensional analysis result of trigonal pyramid indenters is equivalent to the analysis result from the axisymmetric model of conical indenters with the same depth-projected ratio. Axisymmetric model with 2549 elements and 2658 nodes simulating conical indenter of apex angle \( \theta = 77.37˚ \) was used for the indenter of \( \phi = 118˚ \) in the FEM analysis. Fig. 1 shows the analysis model. For generating new II functions, total of 72 combinations were analyzed with a range of material parameters, namely, Young’s modulus \( E = 50 \) to 300 GPa, yield stress \( \sigma_y = 0.1 \) to 5.0 GPa, and work-hardening exponent \( n = 0.1 \) to 0.5. The Poisson’s ratio was set to \( \gamma = 0.3 \) for all combinations.

The relationship of \( E^*/\sigma_r \) and \( C/\sigma_r \) obtained from this analysis is shown in Fig. 2. The analysis result is indicated by one curve for each value of work-hardening exponent \( n \) in the analysis conditions. For
the determination of $\varepsilon_r$, the fitting to the curve is tested in $\varepsilon_r = 0.001$ increments to obtain $\varepsilon_r = 0.020$ for the indenter of $\phi = 118^\circ$. As a result, the relationship of $E*/\sigma_r$ and $C/\sigma_r$ is expressed by one curve independent from the work-hardening exponent $n$ and the non-dimensional function $\Pi_{118}$ is obtained by the following equation:

$$II_{118} = \frac{C_{118}}{\sigma_{118}} = 43.25 \ln \left( \frac{E^*/\sigma_{118}}{C_{118}/\sigma_{118}} \right) - 55.90 \quad \ldots (4)$$

5. Test result and observation

5.1 Evaluation of mechanical properties of bearing steel

Mechanical properties were evaluated by the dual-indenter method using the newly generated $II$ function for the $118^\circ$ indenter. Fig. 3 shows the evaluation results of SUJ2 and SUJ3, tempered at $180^\circ$C, using indenters of $\phi = 115^\circ$ and $118^\circ$, and $\phi = 100^\circ$ and $115^\circ$. It can be seen that the evaluation tests using the $115^\circ$ and $118^\circ$ indenters provide similar results as the tensile test results. On the other hand, the dual-indenter method using the $100^\circ$ and $115^\circ$
indenters gave significantly different results from the tensile tests. Fig. 4 and Fig. 5 show the yield stress $\sigma_y$ and work-hardening exponent $n$ obtained from the dual-indenter method. Since the indenters of 115˚ and 118˚ provided similar values as the tensile test results, evaluating correct tempering temperature dependency of the mechanical properties, the validity of the dual-indenter method using those 115˚ and 118˚ indenters is verified.

In order to review the cause of the significant difference between the test results using the indenters of 100˚ and 115˚ and the tensile tests, impressions were observed. Fig. 6 shows the photo of impressions of each $\phi$ and AFM observation result. It can be observed that the smaller the apex angle $\phi$, the larger the pile-up around the impressions. As the pile-up is not well simulated with the FEM analysis that generates IT functions, it is assumed that the significant pile-up prevented valid results to be generated in the dual-indenter method using indenter of 100˚.

5.2 Evaluation of mechanical properties of surface treated components

The local mechanical properties were evaluated for test pieces cut out from the induction-hardened carbon steel S53C and carburized chrome steel SCr420 components. In order to evaluate local mechanical properties on these test pieces, hardness distribution was verified to identify the range of effect of the respective heat treatments. The distribution of Vickers hardness HV is shown in Fig. 7 and Fig. 8. The measurement was carried out with Vickers micro-

Fig. 6 Shapes of impressions and height profiles measured by AFM formed by 100˚(a), 115˚(b) and 118˚(c) indenters
hardness tester MVK-G3, made by Akashi. The test force is 2940 mN (300 gf) and measurement was taken toward the direction of the arrow in the picture at the same intervals. HV of induction-hardened component in Fig. 7 shows distribution of 304 to 746. In contrast, HV of carburized hardened component in Fig. 8 shows distribution of 383 to 744. As such, the difference of HV by heat treatment methods can be confirmed.

Defining the region of 700 or higher of HV as “high hardness” and 450 and lower as “low hardness”, the local mechanical properties were evaluated using the dual-indenter method. The 115˚ and 118˚ indenters were used for indentation test. The results are shown in Fig. 9 and 10. In the high-hardness region, the test result shows large yield stress and it is possible to confirm the relationship between the hardness and the yield stress. When the induction-hardened components and carburized-hardened components are compared in the high-hardness region, the hardness of the induction-hardened components is higher and the yield stress is also larger. In the low-hardness region, however, different from the high-hardness region, the carburized-hardened
components are superior in both hardness and yield stress.

Induction hardening has a hardening effect only on the surface but the internal organization remains the same. On the other hand, carburized hardening hardens the surface and also the internal organization to some extent. The test result clearly shows these characteristics of the respective heat processes, indicating the clear difference of the impact of the heat processes in \( \sigma - \epsilon \) curve of the local areas.

5. Summary

The dual-indenter method using trigonal pyramid indenters of apex angles of 115˚ and 118˚ applied to the test pieces of high-strength steel with different heat processes revealed equivalent stress-strain properties as the test results of tensile tests.

With the evaluation of mechanical properties of surface-hardened components, the difference of induction-hardened and carburized-hardened heat processes was verified from the stress-strain properties of the local areas.

Also, pile-up was confirmed around the impressions of the 100˚ indenter. When pile-up is formed, the relationship between the indentation force and depth is affected and the dual-indenter method cannot be applied.

When stress-strain properties obtained from the dual-indenter method are used for the analysis of the actual machines, it is possible to conduct more detailed elastic/plastic analysis than conventional methods.

Reference