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Study of Japanese sword from a viewpoint of steel strength

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ABSTRACT

Two Japanese swords produced by 70 years ago and 600 years ago were investigated. Four-point bending test has been performed to estimate the strength of sharp edge of Japanese sword for the first time. The strength of sharp edge with fine lath martensite microstructure was evaluated, taking the specimen geometry of bending test into consideration. The strength of modern sword is estimated as high as approximately 4500 MPa (by four point bend test) and is considered to be a great value along with high hardness, which is comparable with the value of high performance tool steels. The fracture surface showed that the crack propagation behavior is smooth around sharp edge and ductile like the zigzag morphology from wavy pattern region into the core region.

1. Introduction

Japanese sword [1–4] has long history of more than 1000 years as recorded in oldest Japanese history book "*Kojiki*". From old days a lot of swordsmiths had made great efforts to make excellent sword and those efforts have been continued up to now. It has been well known to a number of people in the world that such as a splendid Japanese sword has good cutting faculty and indicates beautiful appearance. It is considered that these characteristics are, in fact, attributed to the raw materials and the producing process of Japanese sword. In making Japanese sword, the special steel called "*Tamahagane* [5,6] (in Japanese)" smelted with the unique, traditional steel making process, "*Tatara* [7–10] (in Japanese)" has to be used; otherwise superior Japanese sword cannot be produced.

From the beginning of 1900s, several metallurgists [11–13] studied particular microstructures of sharp edge and wavy patterns (*Hamon* in Japanese) on the sword surface and the cross section by optical microscopy. It was found that martensite was mainly observed in the hard sharp edge and duplex structures consisted of martensite and fine pearlite were occupied around *Hamon*.

However until now there seem to be few studies [14] from a viewpoint of strength and toughness of Japanese sword. In this study four-point bending test using modern sword has been performed to measure the strength of sharp edge of Japanese sword for the first time. Moreover the fracture surface of the specimen after bending test has been observed.

2. Experimental material and methods

Two kinds of Japanese swords were prepared as shown in Fig. 1. One is "modern sword" (made 70 years ago) and the other is "old sword" (made 600 years ago, in the Muromachi period). Modern sword has the dimensions of 0.65 cm (thickness) × 3.0 cm (width) × 66.5 cm (length) and old one has those of 0.55 cm (thickness) × 2.3 cm (width) × 40.6 cm (length). Two pieces were individually cut from the original swords, one having the size 0.5 cm (length) to investigate several metallurgical features of those cross sections, and another size 15 cm (length) to measure the residual stress around the surface and the strength of sharp edge in longitudinal direction.

The carbon distribution of the cross section of both swords was analyzed by Electron Probe Micro-Analyze (EPMA) using JEOL JXA-8900R equipment. The microstructure was revealed with nital etchant and studied by optical microscopy (OM) and scanning electron microscopy (SEM, HitachiS-3500N). Three specific regions in the cross section i.e., (i) sharp edge, (ii) *Hamon* region (side plane) and (iii) core region were observed. Micro Vickers hardness was measured along the cross section through the center line in the both sword. The residual stress along the longitudinal direction on the surface has been measured by XRD. A special type of X-ray diffractometer (Rigaku, MSF-2M) having two-tilt facility was used for this purpose.

As a result of metallurgical investigations and analyses, it is considered that the characteristics of modern sword is similar to that of old one. Therefore it has been decided to perform mechanical tests of the modern sword only. Four-point bending test has been tried by Servo hydraulic fatigue testing machine (Saginomiya, Dynamic Servo EFH 100-38-3) to estimate the strength of sharp edge in longitudinal direction. The cross head speed under loading is 1 mm/min. The fracture surface in the specimen after bending test has been observed by stereo microscope.

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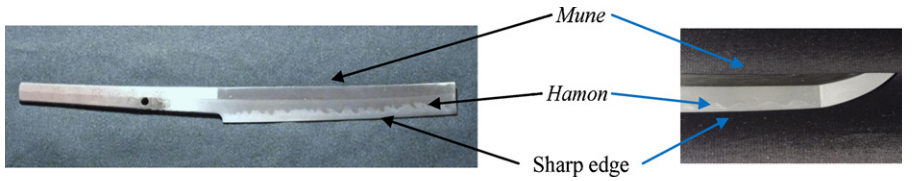

Fig. 1. Appearance of the end part of modern sword (left side) and the top part of old sword (right side).

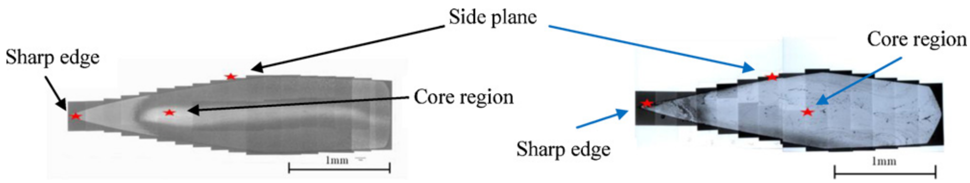

Fig. 2. Macro structure of cross sections in modern sword (left side) and old sword (right side).

Table 1
Carbon distribution of the cross section measured by EPMA.

	Carbon mass% (cf. Si, Mn < 0.10, Fe: bal.)		
	Sharp edge	Side plane	Core region
Modern sword	0.71	0.69	0.01
Old sword	0.67	0.48	0.02

3. Results and discussion

3.1. Microstructure observations with SEM

The macro structure of the cross section in modern sword and old sword is shown in Fig. 2 and the carbon distribution of the cross section of both swords analyzed by EPMA is indicated in Table 1. It is known that the carbon content of sharp edge especially influences the performance of Japanese sword and its amount is analyzed as 0.5–0.7 mass% in the greater part of Japanese swords [11,13]. These swords are found to be composed of two kinds of middle carbon steel, outside and low carbon steel, inside. In other words, Japanese sword is one of composite materials. There are hardly harmful impurities such as Si and Mn which decrease the sword quality.

Fig. 3 shows the microstructures of the three specific regions in the cross section observed by SEM. Around the sharp edge, the microstructure is fully occupied with fine martensite. The morphology of martensite is lath [15–17]. This martensite is occurred by water quenching after hot forging of 10 several times in the process of sword making. The wavy pattern area in side plane contains hard martensite and semi-hard fine pearlite. The core region shows dominantly soft ferrite.

3.2. Distribution of micro Vickers hardness in the cross section

In the cross section of both swords, micro Vickers hardness was measured along center line from the sharp edge. The hardness of sharp edge shows 830-880HV in Fig. 4 and this high hardness corresponds to the hardness of martensite which contains approximately 0.70 mass% carbon [18]. As there are rarely effective alloying elements in the material of Japanese sword, it is estimated to be one of the most difficult materials for quenching. Therefore it is said several particular techniques by each swordsmith are performed to improve its hardenability of sharp edge before quenching sword.

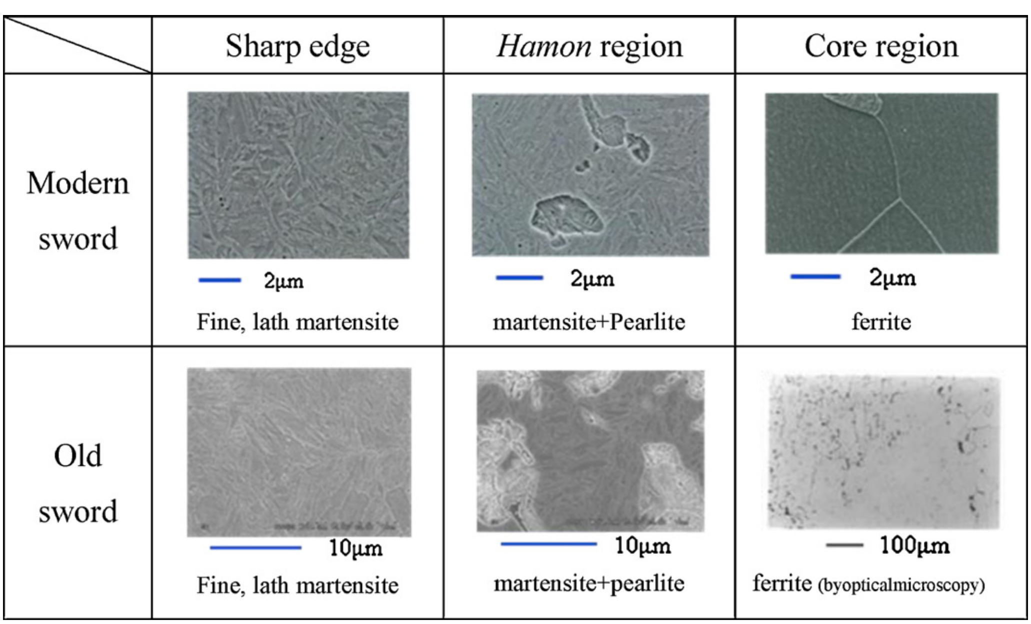

Fig. 3. Microstructure of cross section of modern sword and old sword by scanning electron microscopy.

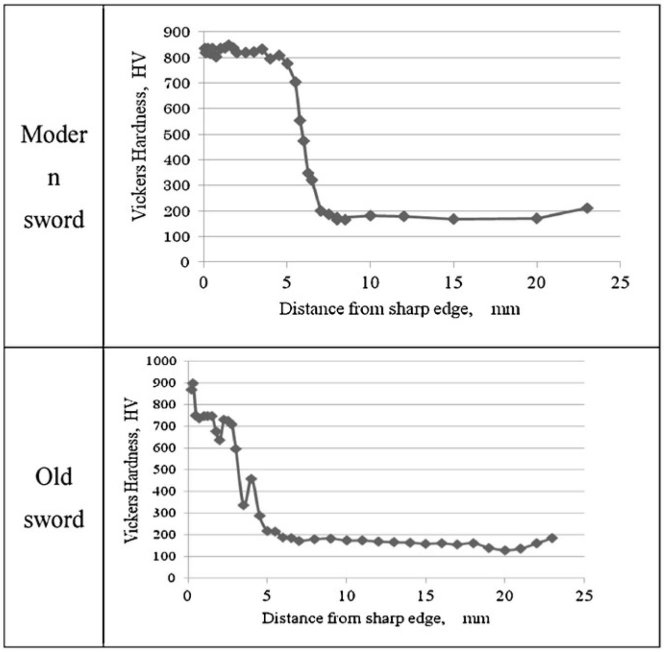

Fig. 4. Distribution of micro Vickers hardness in the cross section.

It is found the hardened area is limited to sharp edge and a few distance from the sharp edge decreases hardness drastically. In the core region occupied almost all ferrites its hardness is very soft.

3.3. Residual stress at the surface of Japanese sword

The residual stress was measured at the surface of the sharp edge, side plane and thick edge (the opposite side of sharp edge which is called *Mune* in Japanese) using XRD technique respectively. The magnitude of residual stress on the surface in longitudinal direction is found to not tensile but compressive. In the process of quenching sword, this stress is considered to be occurred by the difference of expansion between outside martensite and inside ferrite. Maximum compressive residual stress in modern sword, 520 MPa is observed at the sharp edge, as shown in Fig. 5. This compressive stress is said to play a role to contribute to strengthen sword material [14] and protect cracks.

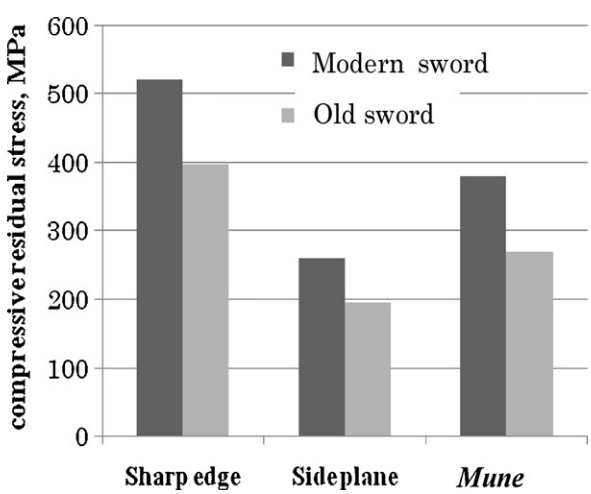

Fig. 5. Residual stress along the longitudinal direction on the surface measured by XRD.

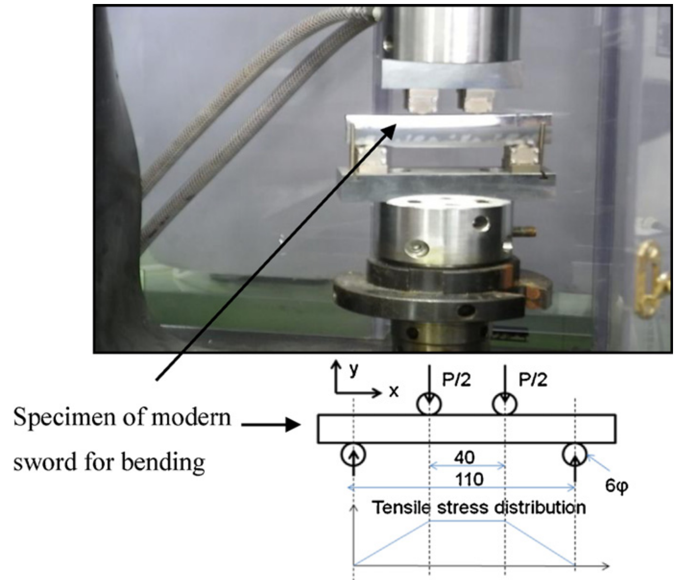

Fig. 6. Specimen set on the special jig of bending machine.

3.4. Bending test and stress analysis

Four-point bending test was performed by Servo hydraulic fatigue testing machine. Features of this four-point bending test in Fig. 6 are as follows.

(1) Fixed and load points are not constraint in the *x* direction by 6 φ rolling parts.
(2) Tensile stress distribution between load points is constant in order to extend evaluation volume and prevent deviation.

The sword specimen set on the special jig for bending machine is indicated in Fig. 6 and the curve of bending load vs. loading time (inherently equal to displacement) is shown in Fig. 7. That sword specimen was broken down at load of 2.618 tf, 54 s later after test starting. Using strength of materials [19] in consideration of the specimen profile of bending test in Fig. 6 because exact solution can be obtained under elastic region as estimated by Fig. 7 when the effect of residual stress are ignored in low dimensional stress field. Detail of calculations is shown in the following procedures.

First, the origin is set on *Mune* in order to calculate centroid as shown in the left side of Fig. 8. Centroid means the center of balance.

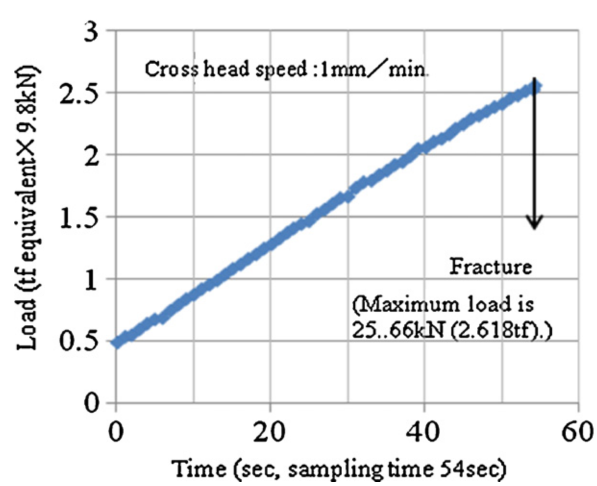

Fig. 7. Bending test chart of modern sword.

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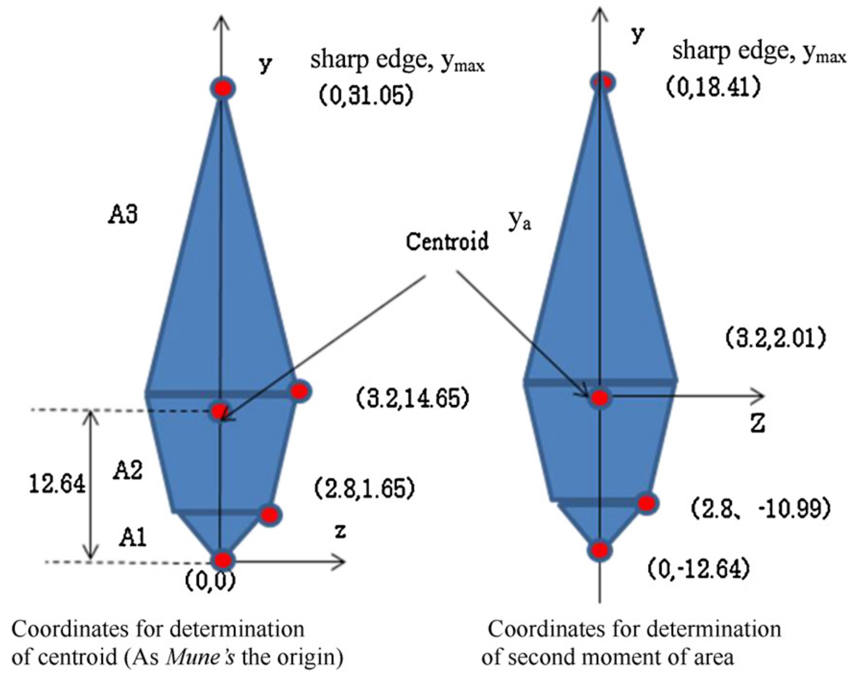

Fig. 8. Coordinates of centroid of cross section in modern sword.

It is nearly equal to neutral axis when force is loaded. First moment of area is calculated by below equation on this coordination system sequentially.

$$Z = \int y\,dA \tag{1}$$

Here, Z, y and A show first moment of area, length of y direction and area of cross section, respectively.

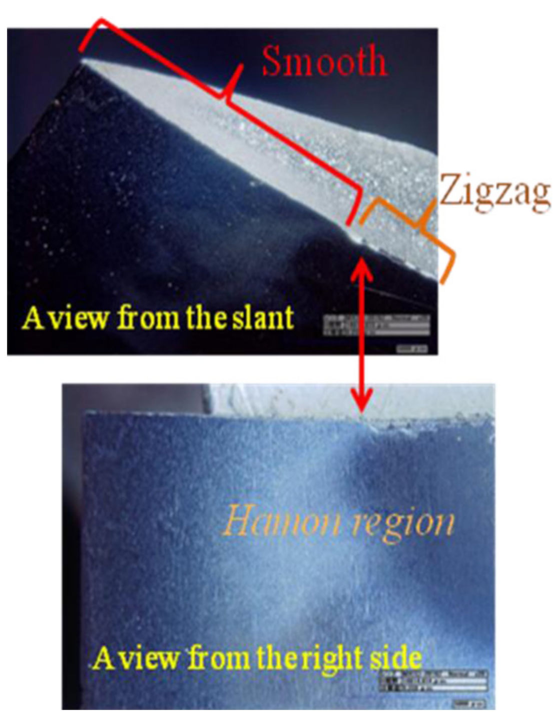

Fig. 9. Appearances of specimen after bending test and fracture surface (upper side: appearance from slant, lower side: one from side plane).

The centroid point, y_a is determined by below equation.

$$y_a = \frac{Z}{A} = 12.6 \tag{2}$$

Next, the origin is moved into the point of (0, 12.6) in previous coordination system as shown in the right side of Fig. 8. Second moment of area is calculated on this system by using below equation.

$$I = \int y_2\,dA \tag{3}$$

Here, I shows second moment of area. Finally, strength of edge is calculated by below equation.

$$\sigma_{\max} = \frac{My_{ec}}{I} = \frac{(L_1 - L_2)P_{\max}}{4} \times \frac{y_{ec}}{I} \tag{4}$$

Here, $\sigma_{\max}$, M, and y_{ec} indicate strength of edge, moment and length between top of the edge and centroid. Moreover, L_1, L_2 and $P_{\max}$ show length between fixed points, length between load points in Fig. 6 and maximum fracture point in Fig. 7, respectively. The strength of edge for modern sword is calculated as 4645 MPa by the Eq. (4). This strength is estimated to be a great value along with high hardness, which is comparable with the value of high performance tool steels [20]. It is considered that this measurement of edge strength of Japanese sword was performed at the first time in the world.

Fig. 9 shows the result of the observation of the fracture surface. The crack propagation behavior is smooth around sharp edge at the first stage and next, it is ductile like zigzag morphology from Hamon boundary into the core region. Near the centroid point, the macroscopic direction of propagation changes form vertical one of maximum principal stress to slightly tilted one as shown in Fig. 10. It is considered that velocity of crack propagation is too fast to reserve time to redistribute stress field by crack propagation in itself.

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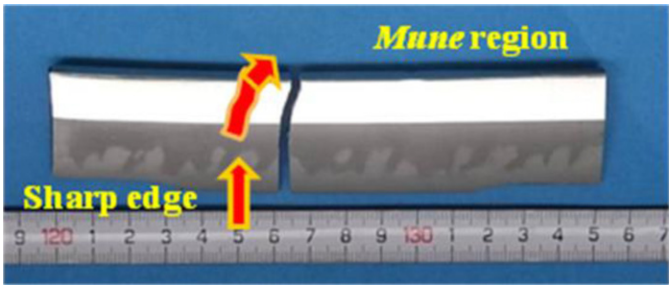

Fig. 10. Direction of crack propagation.

4. Conclusion

Four-point bending test has been performed to estimate the strength of Japanese sword for the first time in addition to a series of metallurgical investigations. The observed main features are as follows:

The microstructure of sharp edge in Japanese sword is fine lath martensite, resulting high hardness.
The sharp edge has extremely large compressive stress like carbonized steels. This stress should contribute to steel strength of sharp edge greatly.
The strength of 4645 MPa for sharp edge in modern sword was measured, and the fracture surface after bending test showed that the crack propagation behavior and the change in the macroscopic direction of propagation were observed.

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