An Experimental Study on Blade Curving due to Quenching in the Japanese Sword

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Abstract

Blade curving due to quenching in the Japanese sword has been recognized by swordsmiths through the ages. In the late 1920s, Hattori noted that the sword curving is induced from not only martensitic transformation expansion in the near-edge region but also non-uniform elastic and plastic strains distributed in the section, based on his experimental results using cylindrical specimens. Our research for an updated explanation on the subject prepared Japanese sword (JS) type specimens made of the same steel and process as the Japanese sword, and model JS (MJS) type specimens with the almost same shape as the JS type specimens, which were machined from commercial carbon steel and austenite stainless steel bars. All specimens quenched by a swordsmith using the traditional way showed a usual curved shape with different curvatures. Curving, temperature, hardness, metallic structure and residual stress measurements for the specimens were performed to prepare their future simulation works.

Introduction

It has long been known that quenching induces distortion in processed steel parts. Explanation on the quench distortion mechanism has been attempted by experiments using simple shape specimens and applications of the theory to the results [1]. Since simple distortion modes such as bending are easier to explain its origin, long objects have been often used as test pieces. In Japan, similarity between bending in long specimens and curving in the Japanese sword after quenching has been discussed with familiarity in societies. However, some engineers may believe the blade curving in the Japanese swords occurs only due to a martensitic expansion effect in the near-edge region. Also we may hear a tentative theory that the Japanese swords made of austenitic stainless steel does not curve because martensitic transformation due to quenching is not induced there.

In the late 1920s, Hattori performed single-sided cooling tests of cylinders made of three different steels for explaining the origin of curving in Japanese swords [2]. Using the experimental results and theoretical consideration based on his knowledge from the strength of materials, he described that the curving is induced from not only expansion due to martensitic transformation in the near-edge region but also non-uniform elastic and plastic strains distributed in the section due to uneven cooling [3].

On the other hand, the heat treatment simulation, which has been developed integrating theoretical researches on the subjects, was applied to clarify the phenomenon in the Japanese sword during quenching [4]. The simulated results, especially strains in the sword, were not used effectively to explain the origin of the curving. Meanwhile, a similar condition including Hattori's experiments was tested and simulated successfully for validation purpose [5, 6].

Since only certified swordsmith produces Japanese swords, the previous studies were not based on a rigorous record of the curving processes. Therefore, bar specimens without a tip, which have the same material and cross-section as the Japanese sword, were produced and quenched traditionally by a swordsmith for simulation works. Additionally model Japanese sword type specimens made of commercial carbon steel and austenite stainless steel bars were machined and quenched for comparison purpose.

Previous Studies

Experiment

The explanation that the blade curving in the Japanese swords occurs only by a martensitic expansion effect might be spread from a scholar who applied the knowledge on the martensite density to the phenomenon at that time. However, Hattori [2] revised the explanation by considering the elastic and plastic strains based on his experimental works.

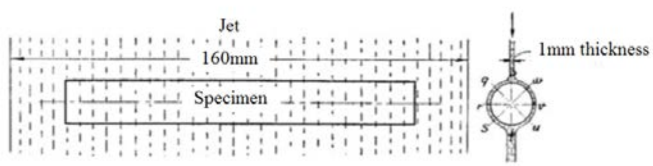

Figure 1: Method to quench specimens from a single side.

Hattori devised a testing method to cool on the single side of steel cylindrical specimens for examining bending phenomena during their quenching as shown in Fig. 1. After heating the specimens in a furnace, their upper surface was cooled continuously with the 1 mm thick water jet at 18 °C, 0.5 m/sec in flow rate. Cylindrical specimens, 15 mm in diameter and 120 mm in length, were made of the carbon tool steel (1.46% C, 0.099% Si, 0.208% Mn, 0.024% P, 0.023% S, 0.361% Cr and 0.081% Ni), the Armco iron (0.015% C, 0.010% Si, 0.032% Mn, 0.003% P, 0.030% S and 0.013% Cu) and the low-tungsten steel (1.03% C, 0.215% Si, 0.997% Mn, 0.033% P, 0.042% S, 0.102% Cr, 1.02% W and 0.110% Ni).

The bending of cylinders observed as viewed from above was concave initially and then convex as cooling progressed. Final bending shapes in the cylinders after quenching and additional reheating-cooling processes in a furnace were depicted as shown in Fig. 2. Bending displacements at the center of the Armco iron and low-tungsten steel cylinders after quenching were about 0.65 mm (2.8 m in curvature radius) each. Both the displacements were changed little by cooling after the 30 minutes reheating at the specified temperatures in a furnace. Meanwhile, the carbon tool steel cylinder showed different displacements, about 0.95 and 0.5 mm (1.9 and 3.6 m in curvature radius), after quenching and cooling after reheating, respectively.

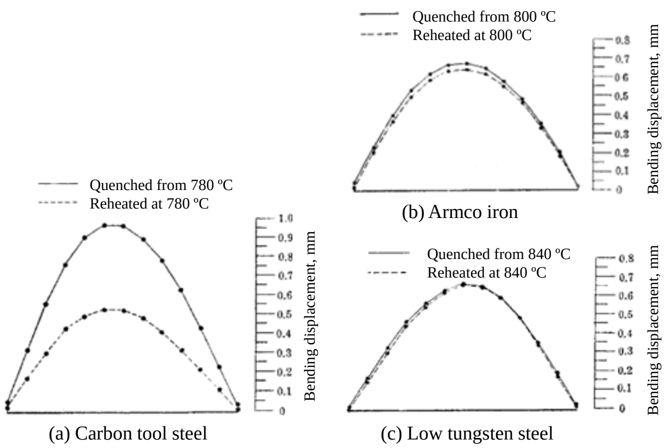

Figure: 2 Bending in steel cylinders after quenching and reheating-cooling in furnace.

Hardness measurements in the sections showed that the carbon tool steel cylinder was hardened at the upper part and unhardened at the lower part, while the low-tungsten steel cylinder was fully hardened. Hattori suggested that the reduced bending in the carbon tool steel cylinder due to reheating-cooling process corresponds to dissolution of uneven martensite and residual stress distributions, and then the retained bending is almost due to plastic strain. Finally, he concluded the origin of the Japanese sword curving is similar to the bending in the carbon tool steel cylinder, which includes not only martensite but also elastic and plastic strains effects.

Simulation

The Heat treatment simulation, which was realized based on results of theoretical studies in the 1970s, can predict a variety of quantities, temperature, volume fraction of metallic phase, stress, strains, and so on during the processes [1]. A practical simulation tool was applied to clarify the phenomenon in the Japanese sword during quenching in the middle of 1990s [4]. Since the simulated strains in the sword were not used effectively to explain the origin of the curving, the Hattori's proposal was not evaluated.

A similar quenching condition included in the Hattori's experiments was tested and simulated successfully by the collaboration [5, 6] in the late 1990s. An uneven cooling of a specimen quenched in a water container was realized to machine the keyway into the 0.44% C steel cylinder as shown in Fig. 3. Specimens were soaked for 20 minutes at 860 °C in a furnace and quenched in three different types of quenchants, water, polymer liquid and oil. The water quenched specimen corresponds to the Hattori's low tungsten steel specimen because the cylinder is fully hardened.

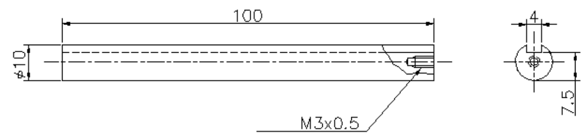

Figure 3: Shape and dimension of cylinder with keyway.

The specimen was bended during water quenching as shown in video grab images in Fig. 4 (a), in which the keyway was located in the left-hand side of the specimen. The corresponded images from simulated results agree well with experiment as shown in Fig. 4 (b). At stage A, 0.25 s, the specimen bends concavely as viewed from the keyway side, since the side is cooled and contracted more quickly due to better heat transfer. This bending reaches to the maximum at stage B, 0.75 s, and is reversed after that. Passing through the neutral stage C, 1.0 s, the maximum convex curvature arises at stage D, 1.7 s. In addition, the bent shape at stage E of the final cooling condition becomes almost the same as that at 3.9 s, although it is not depicted in Fig. 4 (a). Shape measurements on specimens revealed that the bent curves were coincident with arc. The curvature radius of the quenched specimen was defined as 1.1 m.

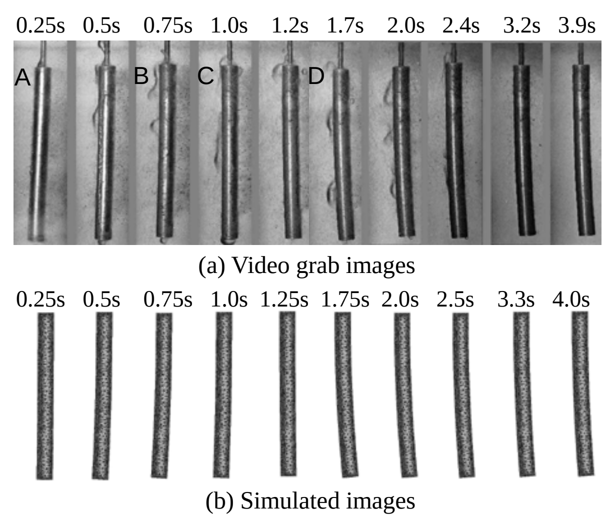

Figure 4: Distortion in cylinder with keyway during water quenching.

Distributions of axial strains were examined to explain the origin of distortion in the specimen. Figure 5 depicts the simulated distribution changes of (a) total strain, (b) expansion strain, (c) plastic strain, and (d) the sum of expansion and plastic strains. Expansion strain represents the sum of thermal and phase transformation strains. The numbers 1–10 in the abscissa describe the output points in the cross section of the cylinder.

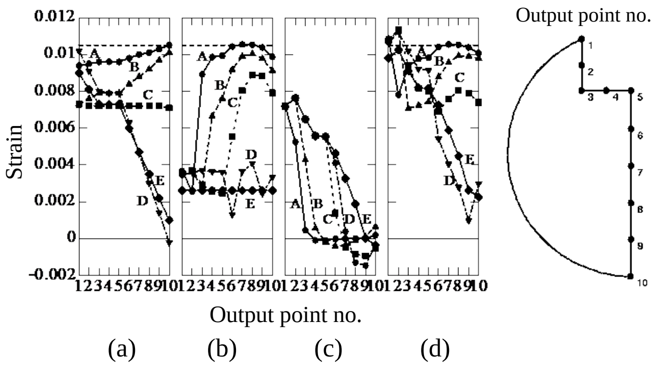

Figure 5: Axial strain distributions along output points in specimen section during water quenching. (a) total; (b) expansion; (c) plastic; (d) sum of expansion and plastic strains.

The dashed horizontal line in Fig. 5 (a), (b), and (d) shows a distribution of expansion strain just before quenching. At this time, other types of strain, such as elastic and plastic strains, are not evident. At stage A, thermal strain in the keyway side decreases rapidly with the sudden cooling, and then the expansion strain at points 1 and 2 becomes 0.0037 and 0.0026, respectively, as shown in Fig. 5 (b). The value at point 1 is greater than point 2 because martensite has transformed there. At points 3 to 10, the expansion strain does not decrease as much because of less cooling rate.

Since the hypothesis that cross sections remain plane is imposed on long objects, total strain does not follow directly a local decrease of expansion strain therein as compared between Fig. 5 (a) and (b). This decrease is compensated by the increase in the positive plastic strain of 0.0072 as shown in Fig. 5 (c). Expansion strain falls toward the opposite side of the keyway, with the progress of stages. Finally, the strain distribution reaches to the horizontal line of 0.0026, since martensite has been induced entirely in the cylinder, which was confirmed by hardness measurements in the cross section.

On the other hand, a region of positive plastic strain expands to the opposite side of the keyway by cooling, and then a downward-sloping line is produced at stage E as shown in Fig. 5 (c). This final distribution of plastic strain contributes to produce the state of total strain as compared between Fig. 5 (a) and (c). The generation mechanism of bending has been solved by the explanation for the total strain distribution changes, since a smoothed slope of the total strain distribution almost corresponds to curvature of bending.

Experiment

Outline

For ending the speculation on the curving in the Japanese sword in societies, the experimental works were performed by helping from a certified swordsmith at his workshop. Curving phenomenon and temperature changes in the two types of specimens were recorded there. Also hardness, metallic structure and residual stress measurements for the specimens were performed at a laboratory for future simulation works.

Specimen

Two kinds of specimens were prepared to clarify effects of different steels as follows:

(1) Japanese sword (JS) type specimen made by the swordsmith using the same steel and manufacturing processes as the Japanese sword.

(2) Model Japanese sword (MJS) type specimen produced at Osaka Institute of Technology, which were made of carbon steel and austenite stainless steel with Japanese Standard code numbers: S55C and SUS304, respectively, and machined for the almost same shape as the JS specimen.

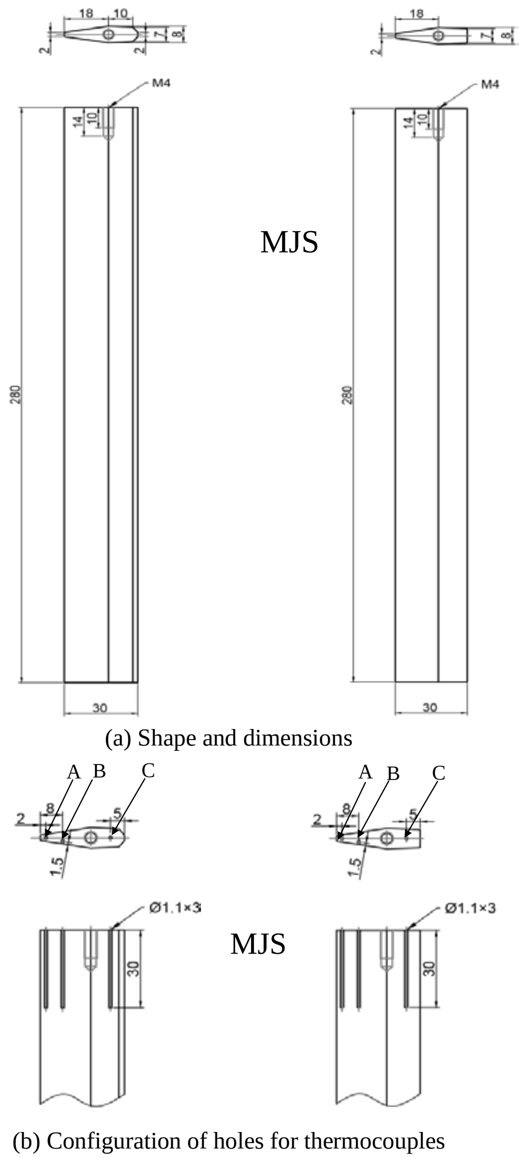

Figure 6: Shape and dimensions of specimens with configuration of holes for thermocouples.

The shape and dimensions of specimens are shown in Fig. 6 with the configuration of holes for thermocouples. The shape of cross-section was selected by the swordsmith from examples of the traditional Japanese swords. The threaded screw hole at the end was provided to connect to a handle for supporting the specimen for quenching process.

All specimens were coated with clay before quenching as shown in Fig. 7. The coating process in the figure is described as follows: (a) placing an appropriate amount of clay as a line at the near-edge border, (b) spreading the clay on the near-edge region by sliding a key shaped tool in the axial direction, (c) applying the same processes as the previous one to an opposite side of the edge with a tool and dry for about 10 minutes, and coating another side of blade in the same way, (d) scraping off the coated clay of the 5 mm range from the edge by a tool, after drying both sides of clay, (e) coating clay thinly with a brush on the near-edge region, and (f) obtaining the coated specimen for quenching.

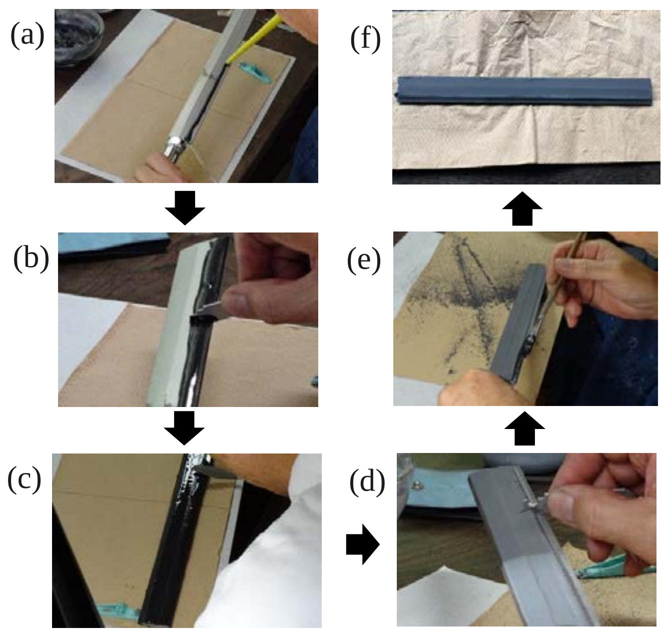

Figure 7: Clay coating process of the Japanese sword specimen.

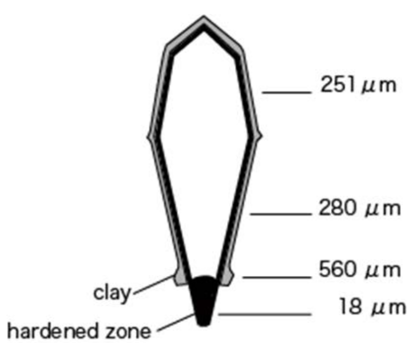

Figure 8: Clay coated cross-section.

Thickness of clay in cross-section of the specimens was measured with an ElektroPhysik's product as shown typically in Fig. 8. The existence of the 560 μm thickness mound at the border region was not depicted in the conceptual figure of the clay coating [7].

Procedure

The quenching in the experimental works was done under traditional conditions by the swordsmith. Curving phenomena in the specimen during quenching in a transparent acrylic vessel were photographed with a video camera as shown in Fig. 9. Heating was performed under no light condition in a workshop for confirming heated charcoal colors, on the other hand quenching was under controlled light to photograph curving of the specimen and cooling phenomena around them. Figure 10 shows the appearance of quenching a specimen in the prepared vessel by the swordsmith.

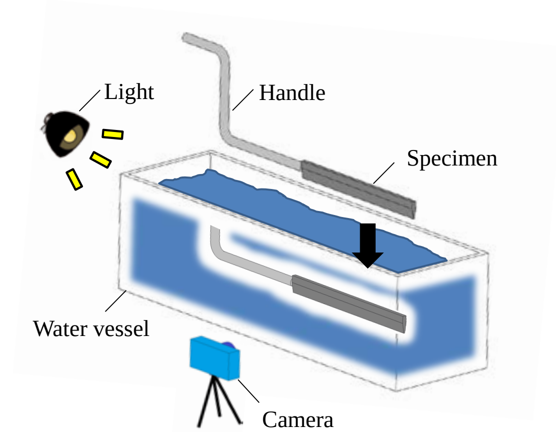

Figure 9: Experimental environment.

Figure 10: Performance of quenching by swordsmith.

Experimental results

Curving

Images of the JS specimen curving during quenching were grabbed from video at the four stages as depicted in Fig. 11. The 0.5, 1 and 2 s stages induce a small reverse curving. On the other hand, the MJS-S55C and MJS-SUS304 specimens did not show the reverse curving clearly during quenching. Dropping off of the coated clay from the specimen can be seen in Fig. 11.

Appearances of the quenched JS, MJS-S55C and MJS-SUS304 specimens were photographed with a scanner after leaving them for a year and a half from the experiment as shown in Fig. 12. Their curvature radii were measured as 3.5, 4.5 and 8.9 m, respectively, based on the full size output of Fig. 12. For reference, the curvature radii 2.53, 3.91 and 1.45 m in mean, maximum and minimum were obtained from the measured values of typical 11 swords by Tawara [8]. A part of the JS and MJS-S55C specimens was polished and Nital etched to check their macro pattern as shown in Fig. 12.

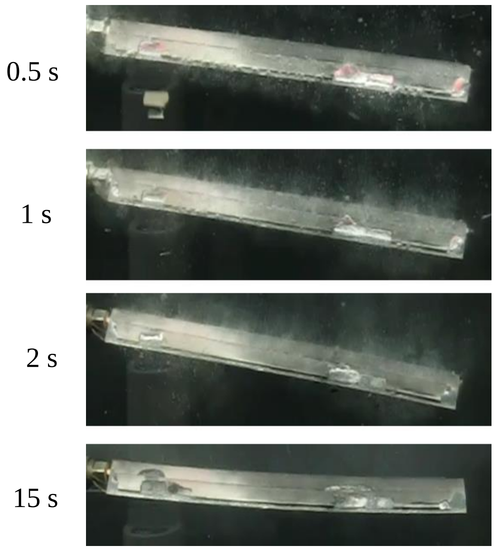

Figure 11: Appearance of JS specimen during quenching.

Figure 12: Appearance of quenched JS and MJS specimens.

Temperature Change

Temperature changes shown in Fig. 13 were measured with sheath thermo-couples inserted into A, B and C holes of the specimens in Fig. 6 (b). The JS specimen had a problem to measure the temperature at the hole A. It is revealed that the location at the hole A cools faster than at the holes B and C because of thin clay coating on the near-edge region.

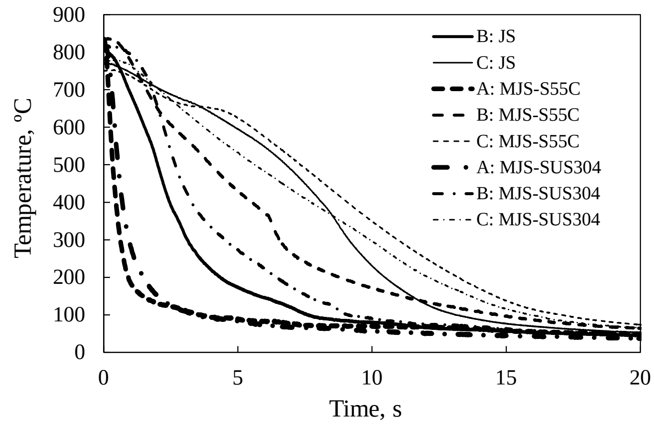

Figure 13: Temperature change at holes A, B and C.

Hardness

Hardness along the bilateral symmetry axis in the cross-section of the specimens before and after quenching were measured and plotted as shown in Fig. 14. It is revealed that the near-edge region in the JS and MJS-S55C specimens was hardened due to quenching. While hardness distributions of the specimens are flat before quenching. The MJS-SUS304 specimen shows a flat distribution of hardness before and after quenching.

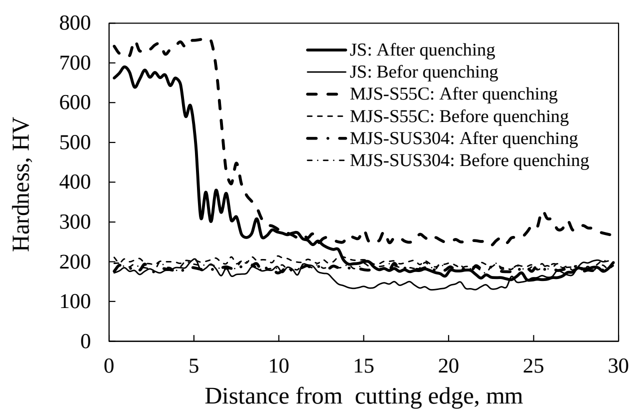

Figure 14: Hardness distribution along symmetry axis.

Metallic Microstructure

Metallic microstructure observation was performed on the specimens before and after quenching. Ferrite and pearlite mixture was observed entirely before quenching, and martensite was detected only in the near-edge region after quenching in the JS specimen as shown in Fig. 15.

The presence of similar microstructures to the JS specimen was observed at the specific locations of the MJS-S55C specimen. As for the MJS-SUS 304 specimen, no change was observed in the microstructure before and after quenching.

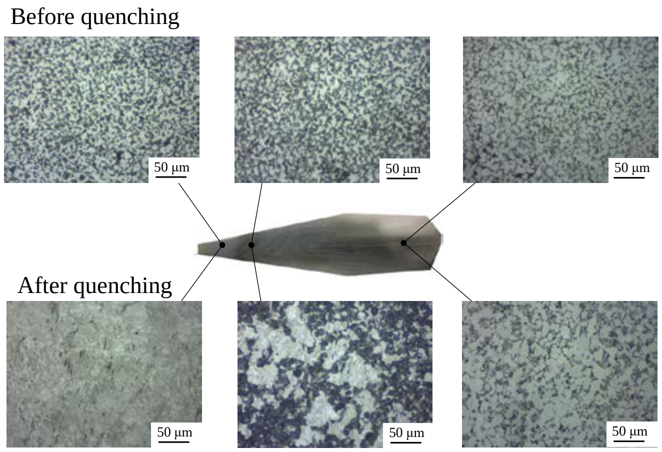

Figure 15: Metallic microstructure observation in JS specimen.

Residual Stress

The residual stress of the specimens was measured with Rapid X-Ray Stress Analyzer: PSPC-MSF, Rigaku Corp. at three points located at the 2, 10 and 25 mm distances from the edge on the surface along the transverse line at the specimen center as shown in Fig. 16. The length and width direction of residual stress components are designated as X and Y directions in this study, respectively. Oxide film on surface of the specimens was removed by electrolytic polishing before the measurement.

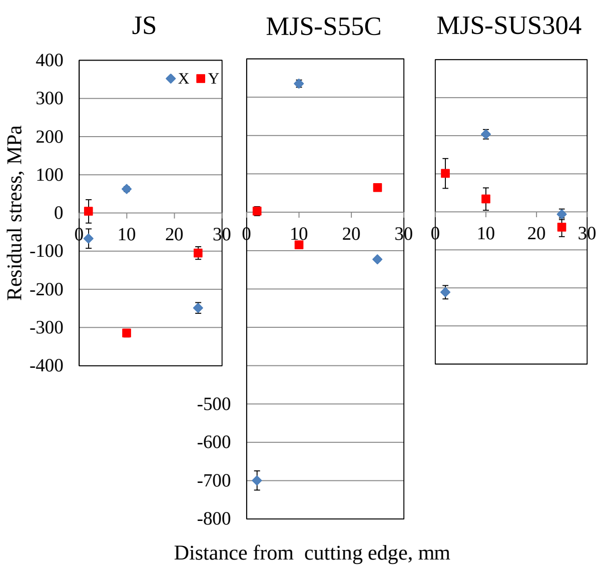

Figure 16: Residual stress of specimens measured along transverse line at specimen center.

The residual stress measured at the JS specimen was tensile only in the X direction at the 10 mm distance point, and values at the other points were compressive. As for the MJS-S55C specimen, it is noticeable that the X direction component is a large compression value of about -700 MPa at the 2 mm distance point and a tensile value of about 300 MPa at the 10 mm distance point, however no significant value occurs under the other conditions. The residual stress of the MJS-SUS304 specimen was similar to that of the MJS-S55C specimen, except the X direction residual stress was about -200 MPa at the 2 mm distance point and about 200 MPa at the 10 mm distance point.

Conclusions

All Japanese sword and model Japanese sword type specimens including the austenite stainless steel specimen were curved after quenching. During early cooling, the Japanese sword type specimen showed the reverse curving phenomenon, although the model Japanese sword type specimens did not exhibit it clearly. The origin of the blade curving will be explained clearer in our scheduled simulation works. The described experimental study was supported by the research group under the Japan Society for Heat Treatment.

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