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INFLUENCE OF THERMAL HISTORY ASSUMING FIRE DAMAGE ON MECHANICAL PROPERTIES OF STEELS FOR BRIDGE HIGH PERFORMANCE STRUCTURE

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ABSTRACT

Many cases of bridge fires have been reported in Japan and overseas. When bridges are taken out of service due to fire, it is feared that economic activities will be greatly affected. Therefore, fire-damaged bridges must be recovered to service as soon as possible. It is important to accurately diagnose the degree of fire damage by estimating the thermal history of the damaged members and inspecting the external appearance of the bridge during a detailed investigation. Although data on mechanical properties of fire-affected steel materials is being accumulated, the mechanical properties after fire heating for newly developed high-performance steel materials are unknown. This study aims to investigate the influence of thermal history assuming fire damage on the mechanical properties of Steels for Bridge High Performance Structure (SBHS), standardized by JIS in 2008. A series of experiments were conducted to clarify the change in mechanical properties of SBHS400 and SBHS500 by heating and cooling. The heating up to 600℃ and cooling after that kept the mechanical properties of SBHS within the JIS standard. The heating up to 900℃ and cooling after that changed the mechanical properties of SBHS significantly. Furthermore, a method by using a portable hardness tester for estimating the change in mechanical properties after heating and cooling was proposed. The results indicated the possibility of quick investigation on after-fire site.

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KEYWORDS

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Fire;
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Leeb hardness test

1. Introduction

Many cases of bridge fires caused by traffic accidents and lost fires have been reported [1-5]. Regardless of the cause of the fire, bridges may be taken out of service for a long time depending on the degree of damage. In this case, there is concern that transportation networks and logistics will be interrupted and economic activities will be greatly affected. Therefore, it is important to aim for the early resumption of service when bridges are damaged by fire.

In order to quickly and safely put bridges damaged by fire back into service, it is necessary to clarify the process of surveying the damage, diagnosis, and judgement for necessity of repair. In 2015, the Japan Society of Civil Engineers (JSCE) presented the "Guidelines for Diagnosis and Repair Method of Steel Bridge exposed to Fire" [6], which systematically outlines the process required to put fire-affected steel bridges back into service. According to this guideline, it is important to accurately diagnose the degree of fire damage by conducting visual inspections of the external appearance such as deformation and estimating the temperature of members in the fire-affected steel bridge. For steel members, the temperature of member by fire is often estimated from the damage to the coating film. If it is determined that the temperature has exceeded a predetermined acceptance level, material tests may be conducted by extracting samples from the fire-affected area to directly investigate the change in mechanical properties. In previous studies [7, 8], it has been reported that no change in mechanical properties occurs after heating up to 600℃ and cooling for structural steels such as SS400, SM490, SM570, and high-strength bolts. In contrast, the above-mentioned guideline [6] defines 400℃ as the standard with safety margin for the temperature of member at which fire-affected bridges can be put back into service without the need for a detailed investigation. Since there are some materials among the members of steel bridges that have not been the subject of previous studies [7, 8], data on the change in mechanical properties of various steel materials after heating and cooling assuming fire are being accumulated [9, 10]. However, the mechanical properties after fire heating for newly developed high-performance steel materials are unknown. In particular, Steels for Bridge High Performance Structure (SBHS), which has been JIS-standardized since 2008, lacks data on the change in mechanical properties after fire heating. SBHS is a steel material with high strength, excellent weldability, workability, and toughness achieved by the application of Thermo-Mechanical Control Process (TMCP). It is supposed to be important to clarify how the mechanical properties of SBHS change when subjected to unintended thermal history due to fire and extinguishing. In order to expand the application of SBHS to steel structures, it will be useful to clarify the change in mechanical properties of SBHS subjected to heating and cooling history from the viewpoint of guaranteeing the performance of steel after fire. In addition, tensile test is the most basic and obvious method for investigating the material performance of fire-affected steel, but it takes time and effort to extract the steel from fire-damaged areas and process test specimens. Therefore, for early resumption of service, it is desirable to establish an investigation method that is easier to conduct than tensile test and can quickly estimate the change in mechanical properties due to fire.

This study aims to investigate the influence of thermal history assuming fire damage on the mechanical properties of SBHS. Heating and cooling experiments and various material tests were conducted to clarify the change in mechanical properties of SBHS400 and SBHS500 by heating and cooling. It was also investigated whether the change in mechanical properties of SBHS could be estimated by the Leeb hardness test with a portable device.

2. Steel specimen

The chemical composition and mechanical properties (mill test report) of SBHS400 and SBHS500 used in this study are shown in Tables 1 and 2. As shown in Fig. 1, all specimens were 12 mm thick, and they were cut into 300 mm × 200 mm pieces for the heating and cooling experiments.

Table 1
Chemical composition of steel specimen (mass%, mill test report)

	C	Si	Mn	P	S	N
SBHS400	0.12	0.36	1.44	0.009	0.001	0.005
JIS standards	<0.15	<0.55	<2.00	<0.020	<0.006	<0.006
SBHS500	0.10	0.22	1.53	0.009	0.002	0.0025
JIS standards	<0.11	<0.55	<2.00	<0.020	<0.006	<0.006

Table 2
Mechanical properties of steel specimen (mill test report)

	Yield stress (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)
SBHS400	473	550	25
JIS standards	>400	490 - 640	>15
SBHS500	587	679	30
JIS standards	>500	570 - 720	>19

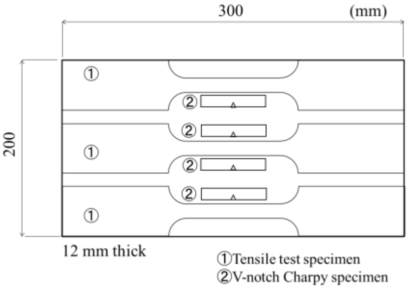


Fig. 1 Geometry of steel specimen

3. Heating and cooling experiments

3.1. Experimental method

Heating and cooling experiments were conducted to subject the specimens to a thermal history assuming fire. This method was basically the same as the conditions in previous studies [9, 10], for the purpose of comparison and examination with other steels.

The heating temperatures were based on 600℃ and 900℃. The former has been frequently reported as the upper limit of the temperature of members in steel bridge fire cases [1-5]. The latter was assumed to be the temperature of members in a large-scale fire. These also mean lower and higher temperature than the A_1 transformation temperature (about 727℃) at which microstructural changes occur in steel. The specimens were heated up to 600℃ or 900℃ in an electric furnace to heat them uniformly. Once the target temperature was reached, the steel was held for a sufficient time (approximately 12 hours) until the temperature of the steel became uniform. After heating, the steel was cooled by two different methods of air cooling and water cooling. In the case of air cooling, the heated steel was taken out from the furnace and left in the air. In the case of water cooling, the heated steel was immersed in a container filled with water at room temperature immediately after being taken out from the furnace. Water cooling is assumed fire extinguishing activities.

The steel of the same dimensions as the specimens was prepared for temperature measurement. They were dummy specimens. A hole was made in the center of the side surface that reached to the center of the steel. A thermocouple was inserted into the hole, and heated and cooled together with the specimens. Since temperature differences are expected to occur depending on the position of the steel in the furnace, the temperature history was measured by placing the specimens between two dummy specimens, as shown in Fig. 2. When the temperature of the dummy specimens reached the target temperature, it was assumed that the specimens between them also reached the same temperature. In the case of 600℃ heating, the temperature of the dummy specimens was between 620℃ to 630℃. In the case of 900℃ heating, the temperature was between 920℃ to 940℃. After confirming that the target temperature was reached, the specimens were cooled.

3.2. Experimental results

Fig. 3 shows the temperature history of each steel during the heating and cooling processes. The metallurgical structures of steel used in heating and cooling experiments were observed under an optical microscope (400x magnification), and the results are shown in Fig. 4.

Without heating and cooling, a layered ferrite-pearlite microstructure was observed in SBHS400, while like a bainite microstructure was observed in SBHS500. After heating up to 600℃ and air and water cooling, the pearlite structure disappeared in SBHS400. However, no significant changes in the metallurgical structure were observed for any of the steel or cooling conditions. This is thought to be due to the fact that the heating temperature was lower than the A_1 transformation temperature at which the metallurgical structure changes.

When heated up to 900℃, a ferrite-pearlite microstructure was observed in both steels when air cooling, while a bainitic microstructure was observed when water cooling. For both steels, the ferrite-pearlite microstructure became coarser when the steels were heated up to 900℃ and then air cooling than that without heating and cooling. The microstructure that appeared to be bainite in water cooling was coarser crystal grains than that of SBHS500 without heating and cooling. For SBHS400, after heating up to 900℃ and water cooling, a fine martensite-like structure was observed in some parts. Furthermore, the microstructures were slightly different between the surface and inside of the steel in water cooling. In both cooling methods, the fine metallurgical structure of SBHS adjusted in steelmaking might be changed by heating at temperature higher than the A_1 and A_3 transformation temperatures (about 911℃).

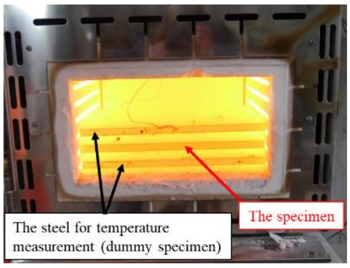
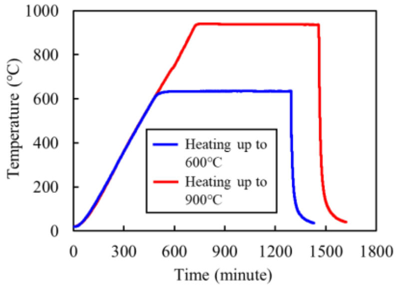
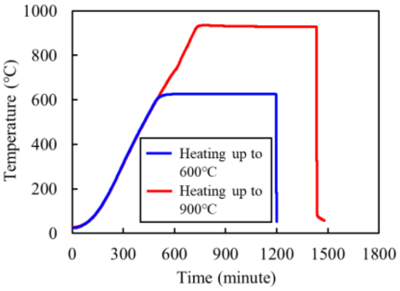


Fig. 2 Condition inside an electric furnace (heating up to 900℃)



a) Air cooling



b) Water cooling

Fig. 3 Temperature histories obtained from heating and cooling experiments

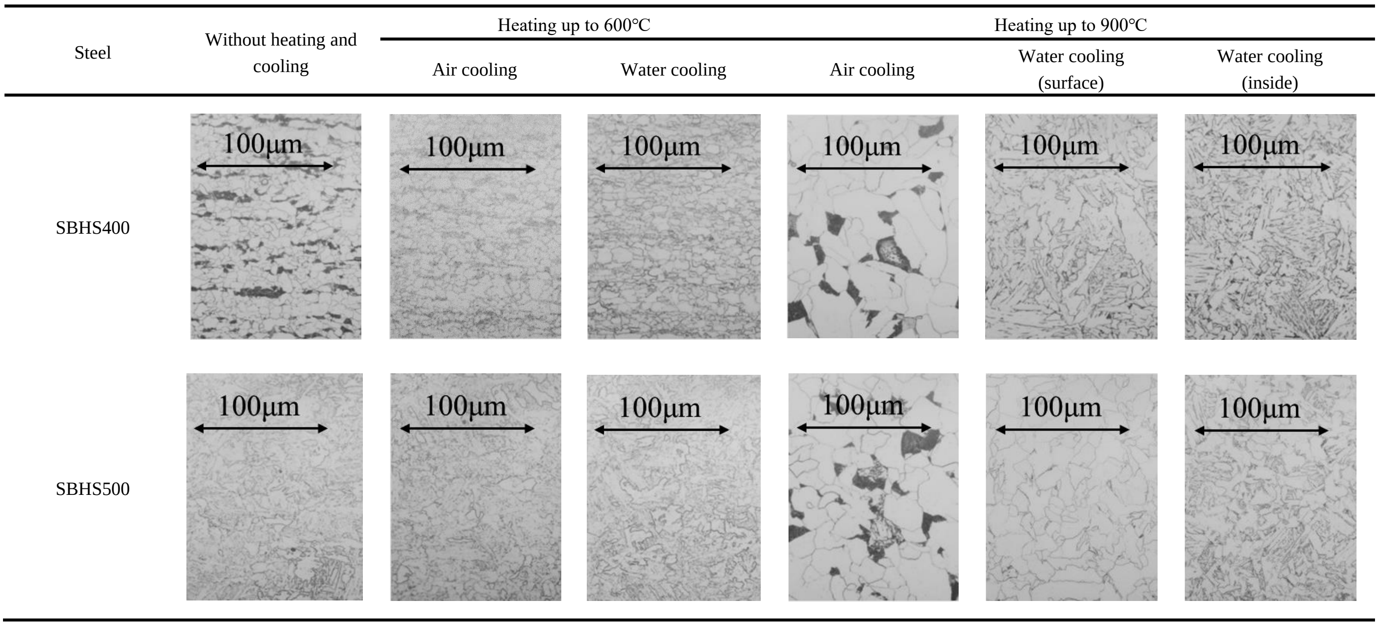


Fig. 4 Results of metallographic observation (400x magnification)

4. Mechanical properties of SBHS subjected to thermal history

4.1. Tensile test

4.1.1. Test method

Three specimens of JIS Z 2241, No. 14B were extracted from each steel used in the heating and cooling experiments, and tensile tests were conducted. Strain gauges were attached to the front and back surfaces of the mid span of the specimens. Young's modulus was determined from the strain gauge values in the elastic region. The displacement was measured with a clip-type displacement transducer attached between the reference points. In cases where the yield shelf did not clearly appear, the 0.2% proof stress was defined as the yield stress. The data obtained from the tensile tests were used to calculate nominal stress and nominal strain, and stress-strain curves were illustrated.

4.1.2. Test results

The stress-strain curves of SBHS400 and SBHS500 obtained from the tensile tests for each heating and cooling condition are shown in Figs. 5 and 6. The stress-strain curves were similar for the same three specimens, so the one of them was extracted. The results for yield stress, tensile strength, Young's modulus, and elongation at break are shown in Figs. 7 and 8, along with the JIS standards. The figure shows the average and standard deviation of the data obtained from three specimens.

For SBHS400, the heating up to 600°C and cooling after that showed no change in Young's modulus and elongation, but yield stress and tensile strength decreased by 4-8% and 3-8%. Yield shelf appeared in SBHS500 caused the decrease in tensile strength by 6-8% and the increase in Young's modulus by 5%. In addition, elongation increased by around 15%. However, the values of yield stress, tensile strength, Young's modulus, and elongation were almost the same compared to the mechanical properties without heating and cooling. The yield stress, tensile strength, and elongation of both steel satisfied the standard values specified by JIS.

The yield stress and tensile strength of SBHS400 were 30% and 15% lower than those without heating and cooling in heating up to 900°C and air cooling. The elongation decreased by 6%, and Young's modulus was unchanged. Water cooling caused the decrease in yield stress by 17% and the increase in tensile strength by 14%, and the decrease in elongation by 24%. Young's modulus did not change. When SBHS400 was heated up to 900°C and then air-cooled, the yield stress and tensile strength did not satisfy the JIS specification. When the specimens were water-cooled, the yield stress was equal to the JIS standard value, and the tensile strength increased. For SBHS500, heating up to 900°C and air cooling caused the decrease in yield stress by 38% and the decrease in tensile strength by 30% compared to the case without heating and cooling. This result was significantly lower than the specified values by JIS. Young's modulus increased by 6% and the elongation increased by 52%. When water cooling, the yield stress decreased by 33% and did not satisfy the specification by JIS. Although the tensile strength decreased by about 7%, it was within the range specified by JIS. Young's modulus and the elongation were almost the same as those without heating and cooling.

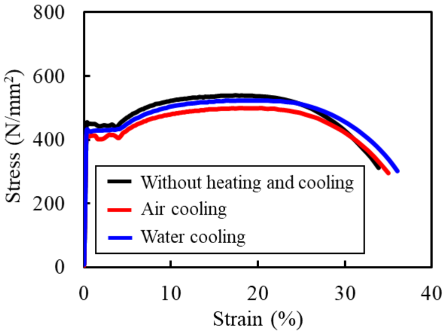
4.2. Charpy impact test

4.2.1. Test method

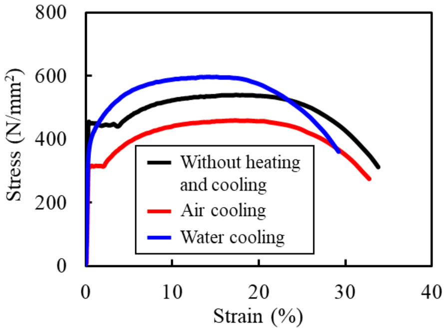
V-notch specimens of 55 mm × 10 mm × 10 mm, as specified in JIS Z 2242, were extracted from both steels used in the heating and cooling experiments. Charpy impact tests were conducted at 0°C for SBHS400 and -5°C for SBHS500 as test temperature specified by JIS. The number of specimens was basically three, but up to six specimens were tested for those with large variations in test results. For SBHS400, four specimens were used when air cooling after heating up to 900°C, and six specimens were used when water cooling after heating up to 900°C. For SBHS500, six specimens were used when water cooling after heating up to 600°C and 900°C. Charpy absorbed energy was evaluated by the average value of all specimens used in the test.

4.2.2. Test results

The Charpy absorbed energy values obtained from the test under each condition are shown in Fig. 9, along with the JIS standards. The figure shows the average and standard deviation of the test results. The fracture patterns of each steel after the test are shown in Fig. 10. For SBHS400, the absorbed energy decreased by about 16 J when air-cooled after heating up to 600°C and by about 34 J when water-cooled. The energy decreased from the case without heating and cooling was about 10% at maximum. For SBHS500, the energy increased about 95 J when air-cooled and about 72 J when water-cooled. Absorbed energy increased by more than 30% compared to that without heating and cooling. This was a different trend from SBHS400.

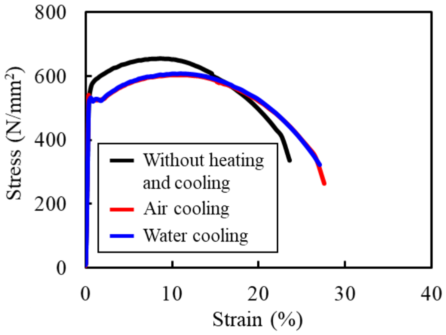


a) Heating up to 600°C

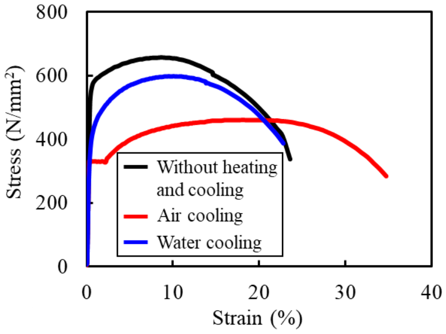


b) Heating up to 900°C

Fig. 5 Stress-strain curves of SBHS400



a) Heating up to 600°C

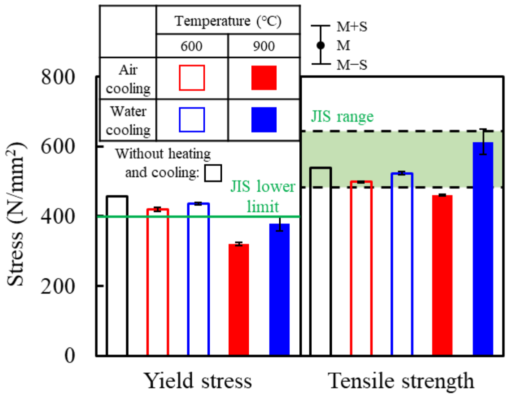


b) Heating up to 900°C

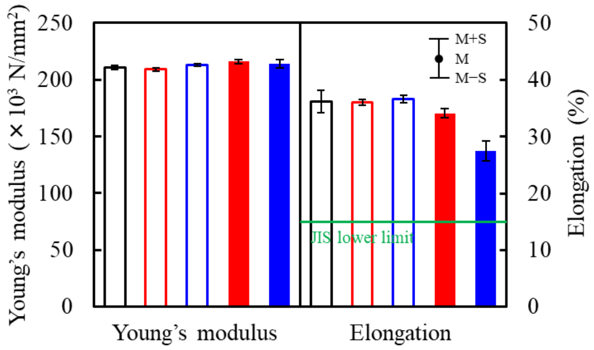
Fig. 6 Stress-strain curves of SBHS500

Observation of the fracture surface showed that both steels had the ductile fracture in the cases without heating and cooling, air cooling after heating up to 600°C, and water cooling.

When SBHS400 was heated up to 900°C and then air-cooled, there was almost no change in absorbed energy compared to the case without heating and cooling, while that of SBHS500 increased by 47%. When water-cooled, that decreased by 67% for SBHS400 and 41% for SBHS500, and the values were close to JIS value. Observation of the fracture surface as in the 600°C case showed that a ductile fracture was dominant in both steels in air cooling after heating up to 900°C. Water cooling after heating up to 900°C resulted in brittle fracture with the brittle fracture surface ratio of about 70%. Therefore, the toughness of SBHS might be decreased.

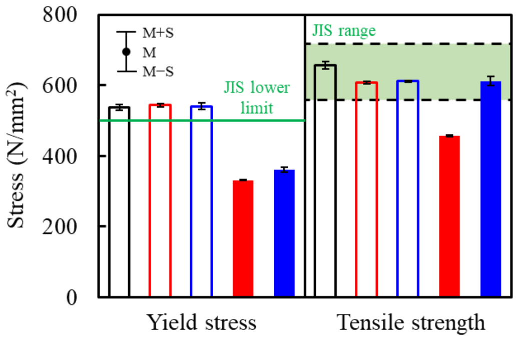


a) Yield stress and tensile strength

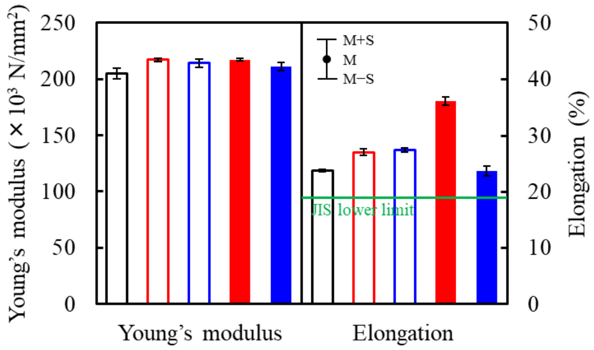


b) Young's modulus and elongation

Fig. 7 Tensile test results of SBHS400

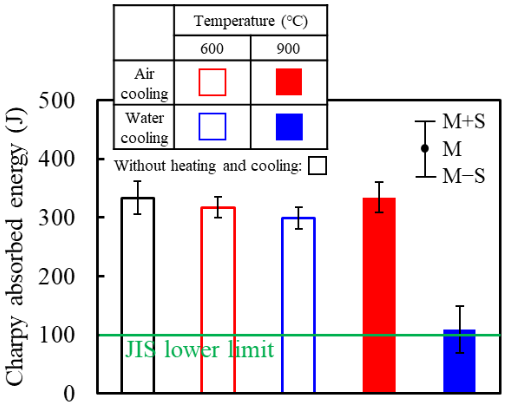


a) Yield stress and tensile strength

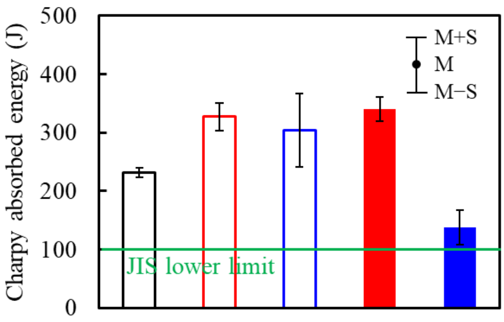


b) Young's modulus and elongation

Fig. 8 Tensile test results of SBHS500



a) SBHS400



b) SBHS500

Fig. 9 Charpy impact test results

5. Estimation of changes in mechanical properties of SBHS by Leeb hardness test

5.1. Estimation method

It is known experimentally that there is a correspondence between the hardness and tensile strength of steel [11]. Based on this, the Leeb hardness test was conducted with the intention of using hardness to estimate the mechanical properties of steel subjected to fire heating. The Leeb hardness tester in this study and the test situation are shown in Fig. 11. The tester is approximately 150 mm long, 45 mm wide, and 150 g in weight, making it compact and lightweight. In the test, a small hammer inside the tester is driven into the steel surface. As shown in equation (1), the Leeb hardness *HL* is calculated by the ratio of the velocity v_i when the hammer is launched and the velocity v_r after the rebound.

$$HL = v_r/v_i \times 1000 \qquad (1)$$

As shown in Fig. 12, 18 measurement points were set on the specimen at which the surface was smoothed with a grinder. The test was conducted with grease applied between the surface plate and the steel to keep the air gap tight. The average and standard deviation were calculated from five measurements of the Leeb hardness at each measuring point of the specimen.

5.2. Relationship between Leeb hardness and mechanical properties of SBHS

It was investigated whether the change in mechanical properties of SBHS could be estimated by the Leeb hardness. The relationship between the Leeb hardness and the mechanical properties of SBHS400 and SBHS500 under each condition is shown in Fig. 13. The figure shows the average and standard deviation of each test value. The red graph shows the results for SBHS400, and the blue one shows the results for SBHS500. The figure also shows the regression line by the least-squares method and its coefficient of determination (R^2 value). The yield stresses of both SBHS400 and SBHS500 showed a correspondence with the Leeb hardness. The R^2 value of the regression line was also greater than 0.9. In contrast, for tensile strength, there were points (heating up to 900°C and water cooling) which deviated significantly from the regression line, and the R^2 became small. Although the relationship was less clear than that of yield stress, a tendency for tensile strength to increase with increase in Leeb hardness was observed.

6. Discussions

When SBHS400 and SBHS500 were heated up to 600°C, changes in mechanical properties were small under both air and water cooling conditions. For SBHS500, the yield shelf appeared in the stress-strain relationship and there were some changes in mechanical properties, but these were within the range specified by JIS. The fracture behavior in the Charpy impact test was ductile

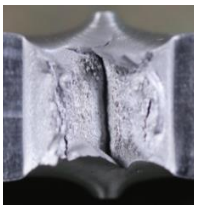
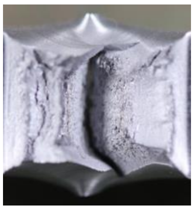
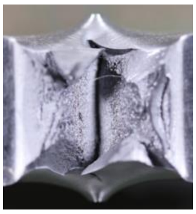
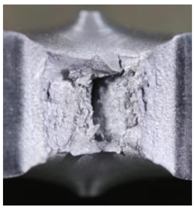
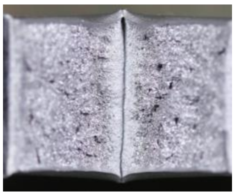
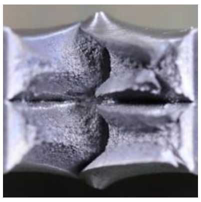
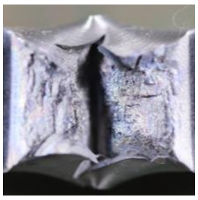
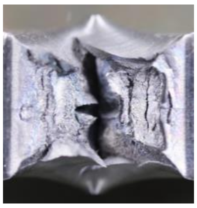
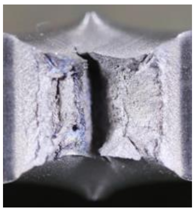
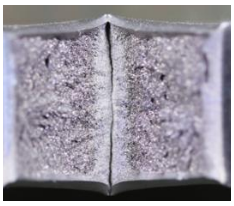
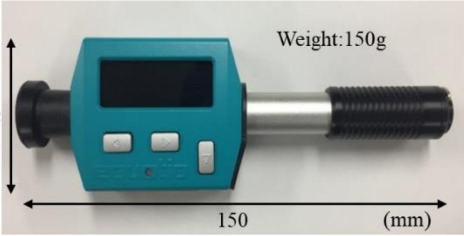
Steel	Without heating and cooling	Heating up to 600°C		Heating up to 900°C	
		Air cooling	Water cooling	Air cooling	Water cooling
SBHS400					
SBHS500					

Fig. 10 Fracture patterns of Charpy impact test specimens



a) Test device

b) Test situation

Fig. 11 Leeb hardness test device and test situation

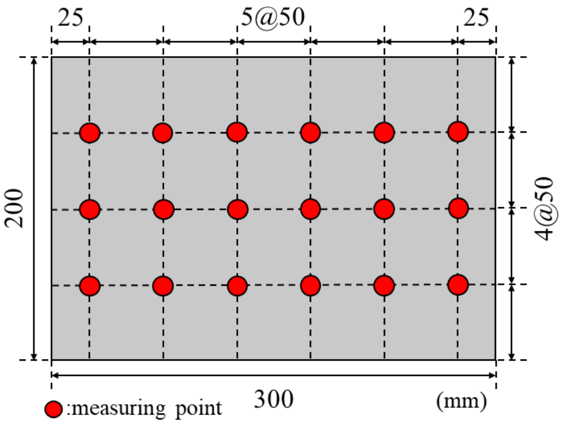
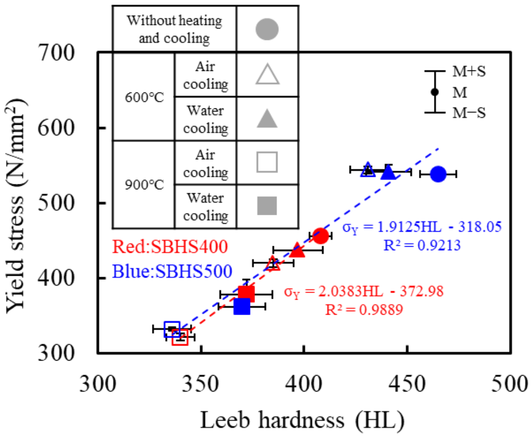
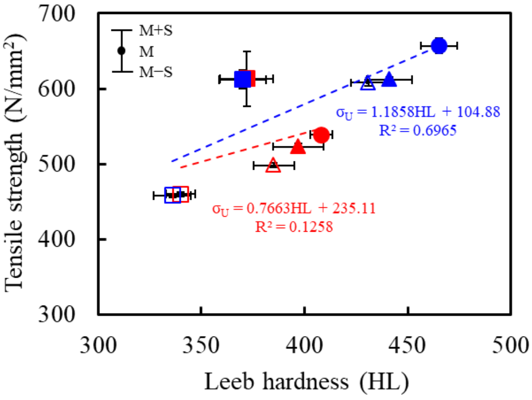


Fig. 12 Measuring point of Leeb hardness test

and there was no decrease in absorbed energy. As shown in Fig. 4, this can be explained by the fact that the metallurgical structure of SBHS did not change significantly when heated below the A_1 transformation temperature. The "Guidelines for Diagnosis and Repair Method of Steel Bridge exposed to Fire" [6] stipulates that a detailed investigations are not required if the temperature of member is less than 400°C. Therefore, it was shown that the stipulations may be applicable to SBHS as well as to general structural steel.



a) Yield stress



b) Tensile strength

Fig. 13 Relationship between Leeb hardness and mechanical properties of SBHS

On the other hand, when SBHS400 and SBHS500 were heated up to 900°C and then air-cooled, the microstructures of both steels coarsened and softened. When SBHS400 was heated up to 900°C and then water-cooled, the martensite-like microstructure was observed in part due to quenching, resulting in the increase in tensile strength. The metallurgical structure of SBHS500 was coarser and tensile strength did not increase. The yield stress of both SBHS400 and SBHS500 was lower than that of the case without heating. This trend was different from that observed for general structural steel heated up to 900°C and then water-cooled. In general steel, it was confirmed that the effect of quenching increased the yield stress and tensile strength [9]. Unlike general steel, the mechanical properties of SBHS are adjusted by strictly controlling the temperature in each process during steelmaking. Under the 900°C heating conditions of this experiment, the steel was heated up to 920-940°C. This is above the A_3 transformation temperature (about 911°C) at which the metallurgical structure of the steel is completely transformed to a soft austenite structure. Therefore, the cooling from this situation invalidated the microstructure adjusted in steelmaking of SBHS, caused the decrease in strength. If there is a large fire in which the temperature of members exceeds the A_3 transformation one, the experimental results in this study suggest that the yield stress and tensile strength may be significantly decreased in SBHS.

Regarding the estimation of mechanical properties using the Leeb hardness, the case in which the specimens were heated up to 900°C and then water-cooled showed the significant deviation from the regression line. As shown in Fig. 4, the microstructural states differed between the steel surface and the inside during water cooling after heating up to 900°C. The reason might be the difference in cooling rate affecting the formation of microstructure between the surface and the inside of the steel by rapid cooling with water. In addition, the hardness is strongly influenced by the microstructural condition of the steel surface. Therefore, it is suggested that the estimation accuracy based on the Leeb hardness may decrease during water cooling after heating up to 900°C due to differences in the microstructural state.

7. Conclusions

A series of material tests were conducted to clarify the influence of thermal history assuming fire on the mechanical properties of SBHS. It was examined whether the change in mechanical properties of SBHS due to fire could be estimated by the Leeb hardness test. The obtained main results in this study are as follows.

(1) When SBHS400 and SBHS500 were heated up to 600°C and then cooled, the mechanical properties were almost the same as those without heating and cooling. In the case of a fire on a steel bridge with SBHS, 400°C might be applicable as the temperature criterion for determining whether detailed investigations are required or not. This criterion is the same for general steel.

(2) When SBHS400 and SBHS500 were heated up to 900°C and then air-cooled, there was almost no change in Charpy absorbed energy for SBHS400. The increase in Charpy absorbed energy by 47% was observed in SBHS500 compared to the case without heating and cooling. In contrast, the yield stress was 30% lower for SBHS400 and 38% lower for SBHS500, and the tensile strength was 15% lower for SBHS400 and 30% lower for SBHS500. As a result, the standard values specified in JIS were not satisfied.

(3) When SBHS400 and SBHS500 were heated up to 900°C and then water-cooled, Charpy absorbed energy was 67% lower for SBHS400 and 41% lower for SBHS500 than that without heating and cooling. The fracture patterns of these cases were brittle. The yield stress was 17% lower for SBHS400 and 33% lower for SBHS500. The tensile strength increased by 14% for SBHS400, but decreased by 7% for SBHS500. No effect of quenching was observed in SBHS with high strength provided by TMCP. This trend was different from that of general steel.

(4) Except for the case of water cooling after heating up to 900°C, the average value of the Leeb hardness measured at several points on the steel surface is possible to be used to accurately estimate the changes in yield stress and tensile strength. Although there is room for improvement in accuracy and applicable range, the Leeb hardness test has shown the potential for use in quickly estimating the mechanical properties of SBHS subjected to thermal history assuming fire.

In the future, similar studies will be conducted for latest steel such as SBHS700. SBHS700 has not yet been investigated in previous studies. Research and evaluation will be continued to accumulate data on mechanical properties of steel in bridge fires.

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