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Temperature dependence of tensile strength and hardness for nodular cast iron and their mutual correlation

SAHACHIRO KOGOH
Saitama Prefectural Casting and Machinery Research Institute, Kawaguchi, Saitama, 333 Japan
TATSUO SAKAI
Faculty of Science and Engineering, Ritsumeikan University, Kita-ku, Kyoto, 603 Japan
KATSUTOSHI ASAMI
Musashi Institute of Technology, Setagaya-ku, Tokyo, 158 Japan

Nodular cast iron has mechanical properties which make it superior to relatively brittle pig cast iron. As a matter of fact, by using appropriate heat treatment processes, the tensile strength of nodular cast iron can be improved to such a degree that its hardness corresponds to that of carbon steels. The main aims in this study are to find the most preferable heat treatment conditions which will yield high strength levels, and to clarify the temperature dependence of mechanical properties for nodular cast iron. The estimation of tensile strength from hardness is also discussed, since tensile tests at elevated temperatures are usually more expensive and time consuming than the hardness tests. Nodular cast irons, having four different microstructures were first prepared by performing the following heat treatments: (1) as-cast, (2) annealed, (3) normalized and (4) bainitized. Tensile property and hardness were then measured for the respective cast irons under elevated temperatures. The temperature dependence of the tensile strength as well as hardness was investigated. It was found that the dependence was well represented by an expression of $\sigma = \sigma_0 \exp(-BT)$. Thus results were discussed from a view-point of the reaction rate process. The correlation between tensile strength and hardness was also examined and a significant linearity was found between them. Based on this strict correlation, an estimation procedure of the tensile strength was finally proposed.

1. Introduction

Various kinds of cast irons are widely used as structural components due to the fact that the final forms of complicated machine parts can be directly fabricated by casting. In particular, nodular cast iron is thought to have several mechanical property advantages over pig cast iron. Earnest attempts to improve the strength level of nodular cast iron have been made [1–5]. Recent research findings [4, 5] indicate that the tensile strength of such cast irons can be improved by using appropriate heat treatment processes. The resulting material has textural advantages comparable to those of carbon steels. Thus nodular cast iron is of great interest as a structural component for engineering applications.

Nodular cast iron is often used at high temperatures in the application of casting dies, heat-affected engine parts, some parts of boilers and many parts of furnaces [6]. The tensile strength of the cast iron at elevated temperatures has been investigated by the authors [6] and others [7–9]. However, the hardness of this cast iron at elevated temperatures has not yet been clarified in detail. If a mutual correlation is found between tensile strength and hardness, one can estimate the tensile strength at high temperatures from the hardness which is easily obtained by the conventional high temperature hardness tester.

In this study, nodular cast irons having four different microstructures were first prepared by performing the following heat treatments: (1) as-cast, (2) annealed, (3) normalized and (4) bainitized. Tensile property and hardness were then measured for the respective cast irons under the elevated temperatures. Thus the improvement of the strength level with respect to heat treatment was systematically investigated on the present material.

The temperature dependence of the tensile strength and the hardness is discussed from a view-point of the reaction rate process. The correlation between the tensile strength and the hardness is also examined, and an estimation procedure of the tensile strength is finally proposed on the basis of this correlation.

2. Experimental procedures

2.1. Specimens

Cast iron was melted by means of a high frequency induction furnace (frequency: 150 Hz; melting capacity: 300 kg) and a commercial additive was mixed to

TABLE I Chemical composition of cast iron used (wt%)

T.C.	Si	Mn	P	S	Mg
3.51	2.98	0.37	0.069	0.013	0.049

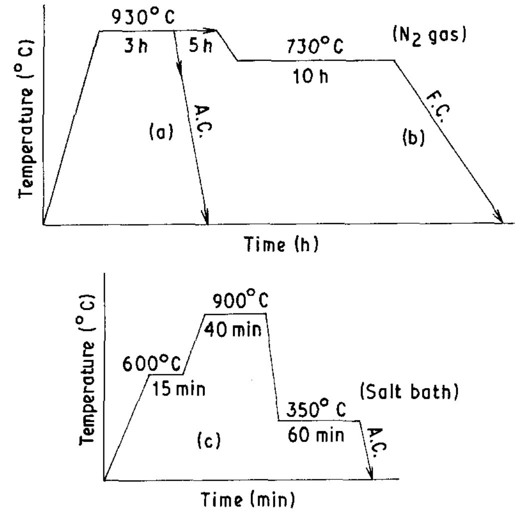

Figure 1 Heat treatment conditions of the test specimen: (a) normalizing; (b) annealing; (c) bainitizing, A.C.: air cooling; F.C.: Furnace cooling.

facilitate the spheridization of the graphite during solidification. This type of cast iron is standardized as FCD in Japanese Industrial Standard (JIS). The casting was made by using a CO_2 sand mould with a size of 60 mm × 260 mm × 210 mm. The chemical composition of the material is shown in Table I.

Many blocks were cast in the above manner and they were divided into four groups. The material in the first group was used directly in the experiments without any additional heat treatment. For the second and third groups, the materials were heat treated following the processes indicated in Fig. 1a and b. The former corresponds to the normalizing and the latter to the annealing. The material in the remaining group was bainitized through the austempering heat process as shown in Fig. 1c.

Microstructures of the respective materials thus obtained are shown in Fig. 2. The resolution of these micrographs was adjusted such that the graphite and the microstructure of the matrix were both clearly observed. In the case of the as-cast material, a typical microstructure of the type "bull's eye" was observed as shown in Fig. 2a. Fig. 2b indicates the microstructure of the annealed cast iron, in which the matrix is completely ferrite. The matrix becomes pearlite after the normalizing heat treatment as shown in Fig. 2c. In the case of bainitized cast iron, the matrix has a typical bainitized structure consisting of fine acicular grains as indicated in Fig. 2d. However, the size and shape of the graphite are almost constant regardless of the heat treatment conditions, and the sphericity aspect is also kept relatively constant within approximately 85%.

The configuration of the tensile specimen is depicted in Fig. 3. This shape was employed here for the sake of convenience to use the fatigue testing machine explained in the next section. After machining into the shape of Fig. 3, all of the specimens were polished using emery paper. The mesh number of the final finishing is 1200. Fig. 4 indicates the shape and the dimension of the specimen for the hardness test at elevated temperatures. The top surface was similarly polished with emery papers of 240–1200, after which this surface was finished by buff-polishing with the aid of alumina fine powders. Thus mirror-like surfaces were obtained for the hardness testing.

2.2. Experimental procedure

The static tensile tests were performed by means of an electro–hydraulic servo fatigue testing machine with a capacity of 9.8 kN. An electrical furnace (capacity: 3 kW) was attached to this machine and specimens were gradually heated up to the respective testing temperatures under a constant heating speed of 5 °C min^{-1}. After the testing temperature was reached, the temperature was held for 5 min, after which a tension load was applied under a constant cross-head speed of 5 mm min^{-1}. The temperature was measured and controlled by using a thermocouple installed at the specimen surface.

On the other hand, hardness at the elevated temperature was measured by using a conventional type of Vickers hardness tester. Testing conditions are listed in Table II. All of the hardness tests were carried out inside the argon gas chamber, and the temperature was measured by inserting a thermocouple into the bottom hole of the specimen in Fig. 4.

3. Results and discussion

3.1. Tensile property at elevated temperature

The tensile test was performed repeatedly three times for each kind of cast iron under the respective testing

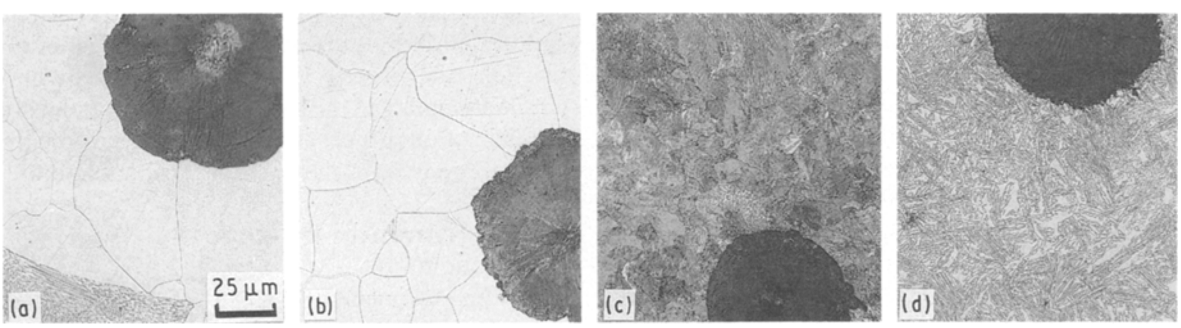

Figure 2 Microstructures of as-cast and heat-treated materials: (a) as-cast; (b) annealed; (c) normalized and (d) bainitized.

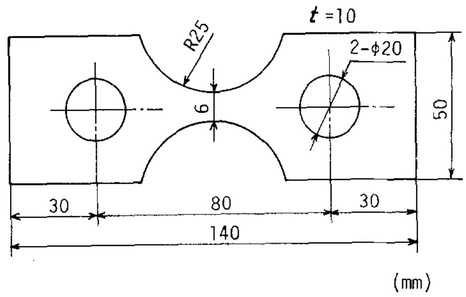

Figure 3 Shape and dimension of tension test specimen.

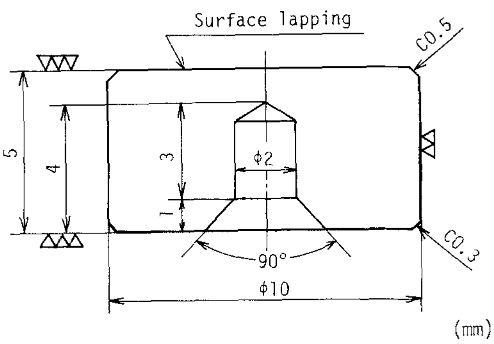

Figure 4 Shape and dimension of Vickers hardness test specimen.

TABLE II Conditions of Vickers hardness test at elevated temperatures

Testing machine	Type AVK-HF
Test load	5 kgf
Load application speed	65 $\mu m\, s^{-1}$
Load holding time	30s
Indenter	Diamond Vickers
Heating speed	20 °C min^{-1}

temperatures. Tensile strengths thus obtained under room and elevated temperatures are tabulated in Table III, in which each result indicates the mean value of three times measurements ($n = 3$). It is found that the tensile strength tends to decrease with an increase in the testing temperature for every kind of microstructure. How can we interpret this aspect on the temperature dependence? The deformation and the fracture of metallic materials are basically caused through movement of a large number of dislocations in the crystal grains. The movement of a dislocation along a crystalline plane implies a change from one stable state of packed atoms into another stable atomic state. Accordingly, the above temperature dependence of the tensile strength is discussed here from a view-point of reaction rate process.

The reaction rate of an elementary process, r, is provided as follows [10, 11]

$$r = A\exp(-U/kT) \qquad (1)$$

where U is the activation energy, k is the Boltzmann constant, T is the absolute temperature and A is the frequency factor. By combining this concept with the stochastic process, Yokobori attempted a theoretical explanation on the temperature dependence of the proof stress and the delayed fracture strength of carbon steels [12]. If the internal stress is negligible for

TABLE III Tensile strength at room and elevated temperatures (MPa)

Materials	Temperature (°C)					
	RT	100	200	300	400	500
As-cast	503	485	465	452	430	360
Annealed	462	440	420	396	376	288
Normalized	798	770	740	718	687	540
Bainitized	905	880	855	834	813	680

the material, the proof stress, σ, at the temperature T and the strain rate $\dot{\varepsilon}$ is given by

$$\frac{\sigma}{\sigma_0} = \left(\frac{\dot{\varepsilon}E\tau_0}{mkT\sigma_0}\right)^{mkT} \qquad (2)$$

where σ_0 is the proof stress at $T = 0$ K, E is Young's modulus, τ_0 is the characteristic value for the dislocation and m is the material constant.
Taking logarithms of both sides

$$\ln(\sigma/\sigma_0) = mkT[\ln(\dot{\varepsilon}E\tau_0) - \ln(mk\,\sigma_0) - \ln T] \qquad (3)$$

The third term on the right hand side takes a value sufficiently smaller than that of the first or second term for the usual material. In such a case, Equation 3 can be reduced into

$$\ln(\sigma/\sigma_0) = mk[\ln(\dot{\varepsilon}E\tau_0) - \ln(mk\sigma_0)]T = -BT \qquad (4)$$

where

$$B = mk[\ln(mk\sigma_0) - \ln(\dot{\varepsilon}E\tau_0)] \qquad (5)$$

Equation 4 can be rewritten in the form of

$$\sigma = \sigma_0\exp(-BT) \qquad (6)$$

Equations 4 and 6 imply that a linear relationship exists between the non-dimensional strength $\ln(\sigma/\sigma_0)$ and the temperature, T.

The above analysis was applied by Yokobori [12] to the temperature dependence of the proof stress for steels. As cited in his work, experimental results on the temperature dependence by Eldin and Collins [13], Wood and Clark [14], McAdam and Mebs [15] and Cottrell and Churchman [16] were successfully explained by this concept when referring to a temperature range of -200– $+100$ °C. Thus it is expected that this concept is analogously applicable to the temperature dependence of the tensile strength in the present work.

From this point of view, the experimental results in Table III are plotted by taking the coordinates of $\ln(\sigma_B/\sigma_0)$ versus T in Fig. 5. Since the value of σ_0 for the present material is unknown, we put $\sigma_0 = 1733$ MPa, which is the corresponding value for iron reported [14]. The relationship between $\ln(\sigma_B/\sigma_0)$ and T for each material is well represented by the individual solid line in the region of $T < 723$ K(450 °C). This fact indicates that the temperature dependence of the tensile strength is successfully explained by a concept of the reaction rate process in the temperature range of $T < 723$ K. However, once the temperature exceeds the critical value

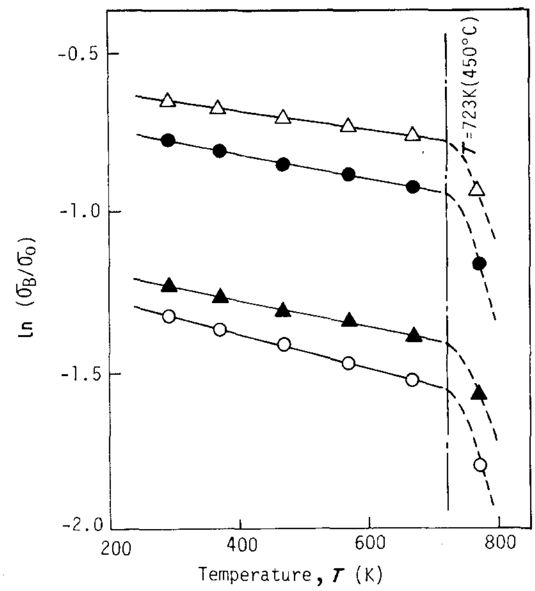

Figure 5 Relationships of $\ln(\sigma_B/\sigma_0)$ versus T: (▲) as-cast; (○) annealed; (●) normalized and (△) bainitized.

indicated by the vertical chained line, $\ln(\sigma_B/\sigma_0)$ tends to abruptly decrease as shown by dashed lines. This marked reduction in tensile strength is thought to come from the metallurgical instability of the microstructure. The slope of the regression line provides the value of the constant B in Equation 4. This B includes implicitly m, k, σ_0, $\dot{\varepsilon}$ and E as shown in Equation 5, and exact values for some of these parameters are still unknown. Therefore, the concrete value of the slope is not discussed here. The noteworthy finding in this section is the fact that an excellent linearity is established between $\ln(\sigma_B/\sigma_0)$ and the testing temperature T, and such a temperature dependence is well explained by the concept of reaction rate process.

On the other hand, in order to clarify the effect of the heat treatment on the strength level, the variation of the strength due to the respective heat treatments was calculated as a percentage of the tensile strength of the material as cast. The results are shown in Table IV. The tensile strength of the annealed ones tends to decrease 8–20% in the temperature range of RT–500 °C. However, the normalizing treatment improves the strength about 50–60%, and the bainitizing treatment further improves the strength up to 80–90%. Thus we can conclude that the strength level of the present material as-cast is a little degraded by the annealing, but it is remarkably improved by normalizing and bainitizing heat treatments as indicated by the respective marks in Fig. 5. Especially, it is noted that the tensile strength of the bainitized cast iron (marks of △) is comparable with those of high strength steels. This is a reason why cast iron as a structural component is of great interest in engineering applications.

TABLE IV Increasing or decreasing of tensile strength due to heat treatment (%)

Materials	Temperature (°C)					
	RT	100	200	300	400	500
Annealed	− 8.2	− 9.3	− 10.1	− 12.3	− 12.6	− 20.0
Normalized	58.6	58.8	58.5	58.9	59.8	50.0
Bainitized	79.9	81.4	83.1	84.5	89.1	88.8

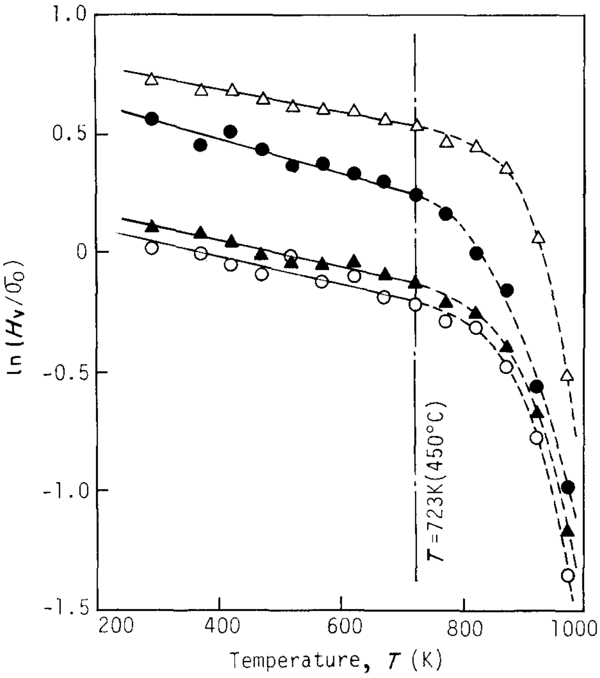

Figure 6 Relationships of $\ln(H_v/\sigma_0)$ versus T: key as for Fig. 5.

3.2. Vickers hardness at elevated temperature

Vickers hardness of the respective materials measured at room and elevated temperatures are listed in Table V, in which each value indicates the average of three measurements. These results are plotted in Fig. 6 as the function of the absolute temperature, T, in quite a similar fashion to the presentation in Fig. 5. In the region of $T < 723$ K(450 °C), excellent linearity is found between $\ln(H_v/\sigma_0)$ and the temperature, T. Consequently, the effect of temperature on hardness is also well explained from the view-point of the reaction rate process. But the value of $\ln(H_v/\sigma_0)$ tends to decrease if the temperature exceeds the critical value of the vertical chained line in Fig. 6. The temperature dependence of $\ln(H_v/\sigma_0)$ in this region is presented by dashed lines to distinguish from the linear relationships of solid portions. The marked reduction in hardness in the high temperature region, as well as the tensile strength, can be attributed to the metallurgical instability of the present material.

The effect of the heat treatment on hardness was also evaluated from the above results. Numerical data on the decreasing or increasing percentage of the hardness are listed in Table VI in the same way as in Table IV. The annealing causes a little decrease in the hardness, but the normalizing improves it about 50–60%. It should be noted that the hardness after bainitization is almost two times that of the material as-cast. Thus the over-all trend on the effect of the heat treatment is similar to the results for the tensile strength as mentioned in the previous section.

TABLE V Vickers hardness at room and elevated temperatures

Materials	Temperature (°C)													
	RT	100	150	200	250	300	350	400	450	500	550	600	650	700
As-cast	195	192	184	173	168	167	170	160	155	141	136	119	90	55
Annealed	180	176	166	160	173	156	160	146	142	132	130	110	81	46
Normalized	311	277	295	273	252	259	245	238	225	208	176	152	101	67
Bainitized	362	348	350	337	325	322	320	309	302	280	276	253	188	106

TABLE VI Increasing or decreasing of Vickers hardness due to heat treatment (%)

Materials	Temperature (°C)					
	RT	100	200	300	400	500
Annealed	− 7.7	− 8.3	− 7.5	− 6.6	− 8.8	− 6.4
Normalized	59.5	44.3	57.8	55.1	48.8	47.5
Bainitized	85.6	81.3	94.8	92.8	93.1	98.6

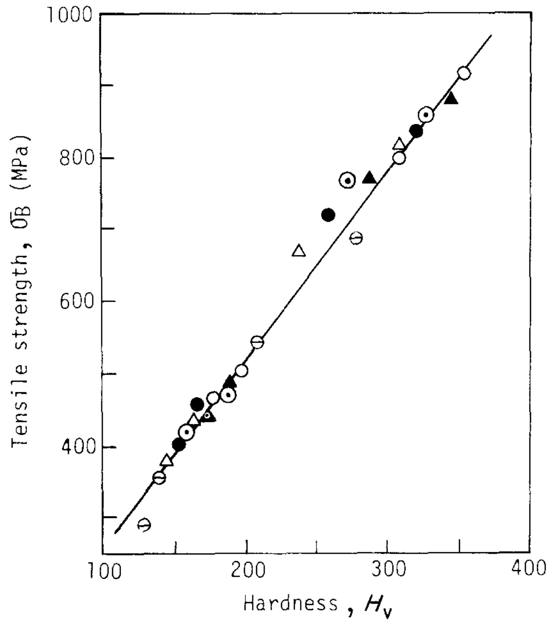

Figure 7 Correlation between tensile strength and Vickers hardness: (○) RT; (▲) 100; (⊙) 200; (●) 300; (△) 400 and (⊖) 500°C.

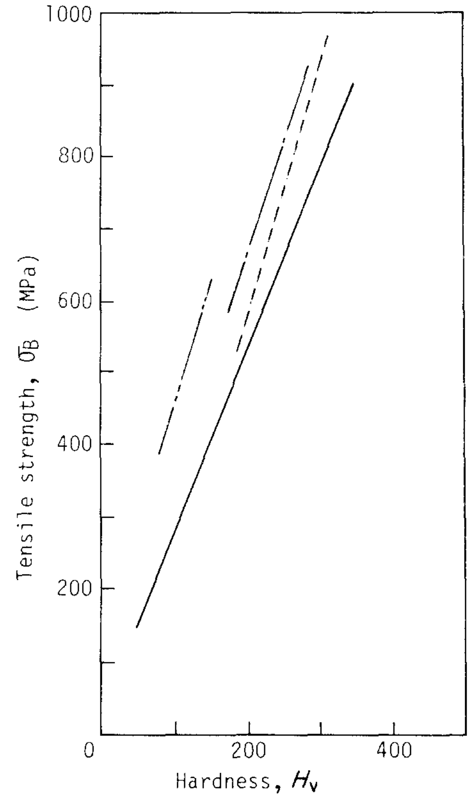

Figure 8 Correlation between tensile strength and Vickers hardness for nodular cast iron and steels: (——) FCD; (- - -) SKD 61; (— — —) SCM 435 and (– – – – –) SUS 304.

3.3. Correlation between tensile strength and Vickers hardness

As we have noted, the temperature dependence of the tensile strength and the Vickers hardness can be systematically analysed, and similar characteristics have been observed with respect to both mechanical properties. This fact suggests that a mutual correlation should be found between them. Accordingly, the tensile strength σ_B is plotted in Fig. 7 as a function of the Vickers hardness, H_v. The result at each temperature in the range of RT–500 °C is shown by the individual symbol as explained in Fig. 7. The experimental results at every temperature are closely overlapping within a narrow scatter band. Thus a regression line was determined from the pooled data. The result is given as follows:

$$\sigma_B = 2.586H_v + 2.80 \qquad (7)$$

where the correlation coefficient is $R = 0.988$.

Based on this strict linearity, one can easily estimate the tensile strength, σ_B, from the Vickers hardness, H_v, in the wide temperature range of RT–500 °C. This fact indicates that we can determine the tensile strength at elevated temperatures without performing the tensile test which is usually more expensive and time consuming than the hardness test. Tominaga *et al.* [17–19] reported a similar correlation between σ_B and H_v for steels of SUS304 (RT–1000 °C), SKD61 (RT–700 °C) and SCM435 (RT–700 °C). Regression lines for these steels are plotted in Fig. 8 along with the corresponding result for the present material. All of the regression lines yield within a narrow band. This fact suggests that the tensile strength has the same level regardless of the kind of materials if the hardness is almost the same. However, further experimental results should be systematically accumulated in the future to clarify details.

4. Conclusions

Nodular cast irons having four different microstructures were prepared through the following heat treatments: (1) as-cast, (2) annealed, (3) normalized and (4) bainitized. The tensile strength and Vickers hardness were measured for the respective cast irons under elevated temperatures. The temperature dependence of these mechanical properties was discussed and the mutual correlation between tensile strength and hardness was also investigated. Main conclusions obtained in this study are summarized as follows.

1. When the temperature is in the region of $T < 723$ K(450 °C), the temperature dependence of the tensile strength and the Vickers hardness is successfully explained from the view-point of the reaction rate process for every kind of microstructure. However, if the temperature exceeds the critical level, a marked reduction is caused on those mechanical properties due to the metallurgical instability of the present material.

2. With respect to heat treatment effect on strength level, we noted that annealing caused a slight decrease in tensile strength and hardness, but normalizing improved the mechanical properties about 50–60%. These properties were further improved by bainitizing so that the hardness is almost two times that of the material as-cast.

3. Concerning the tensile strength and the Vickers hardness, a strict correlation was found in the temperature range of RT–500 °C, and it was given by $\sigma_B = 2.586H_v + 2.80$. Based on this relationship, one can estimate the tensile strength, σ_B, from the Vickers hardness, H_v, in the elevated temperature without performing the tensile test.

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