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Dependency of tensile strength of ductile cast iron on strain rate and temperature

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Abstract. The dependency of the tensile strength $\sigma_{\mathrm{B}}^{\mathrm{smooth}}$ and the notch strength $\sigma_{\mathrm{B}}^{\mathrm{notch}}$on strain rate and temperature were investigated for conventional ferrite-pearlite type ductile cast iron (JIS-FCD500) to make clear the applicability of ductile cast iron to components for welded steel structures. High speed tensile tests were conducted on notched and smooth specimens with varying strain rate and temperature. Charpy absorbed energy was also evaluated on notched specimen with varying temperature. It is found that the tensile strength is in a good relationship with strain rate-temperature parameter *R* for the wide range of strain rate and temperature. With decreasing *R* parameter, both $\sigma_{\mathrm{B}}^{\mathrm{smooth}}$ and $\sigma_{\mathrm{B}}^{\mathrm{notch}}$ increase even when Charpy absorbed energy starts decreasing. It should be noted that the notch strength $\sigma_{\mathrm{B}}^{\mathrm{notch}}$ is always larger than the tensile strength at room temperature $\sigma_{\mathrm{B,\ RT}}^{\mathrm{smooth}}$ in the range of *R* parameter required for the welded structures. Therefore, the tensile strength $\sigma_{\mathrm{B,\ RT}}^{\mathrm{smooth}}$ is confirmed to be useful for the structural design.

1. Introduction

Ductile cast irons are widely used as structural members for automobile, railway vehicle, machine tool, and so on. In some cases, they have replaced cast steel and forging products [1]. In recent years, ductile cast irons efficiently substitute for several welded components because of their manufacturing and engineering advantages, such as broad range of mechanical properties and easy fabrication of components with complicated shapes. Furthermore, the cast products show better fatigue property than welded parts [1].

Ductile cast iron consists of nodular graphite particles and iron matrix. Spheroidal graphite is obtained by adding 0.035～0.045% Mg to molten iron. Usually, the required strength of ductile cast iron is obtained by controlling the ferrite-pearlite ratio in the matrix. Typically, ferritic ductile cast iron exhibits higher elongation and lower tensile strength, which is approximately 350 MPa, while pearlitic ductile cast iron has lower elongation and higher tensile strength ranging over 800 MPa. So that various strength levels of ductile cast iron castings were utilized in many fields.

However, for designing of structural components, we should take into account the upper limit of strain rate and lower limit of temperature because the toughness and strength of ferrous materials

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strongly depends on strain rate and temperature. Table 1 shows the example of the strain rate and temperature range required for welded structural members [2, 3]. The values for Charpy impact test is also given in Table 1 [4, 5], indicating Charpy impact test is not suitable for evaluating the property of welded structural components because the impact speed does not correspond to that in real products failure. Therefore, for example, one of the authors studied on high-speed tensile testing with varying tensile speed to investigate the impact properties of engineering plastics [6-8]. In addition, not Charpy absorbed energy but tensile strength and yield strength have been used for designing ductile cast iron products. To design the castings for welded structural members such as for architectures, it is necessary to make clear the influence of strain rate and temperature on the tensile strength of ductile cast iron.

Therefore, high speed tensile tests were conducted on smooth and notched specimens with varying strain rate and temperature to discuss the applicability of ductile cast iron to welded structural components.

Table 1. Example of strain rate and temperature range acting on welded structural components.

	Industrial field	Strain rate (s^{-1})	Temperature (°C)	R parameter (K)
Design	Weld toes of beam-column (Architectural structure)	~ 2 [2]	-18 ~ [3]	4522 ~
Test	V-notch Charpy impact test	≒ 10^2 [4, 5]	-18 (Temperature of this table)	3524

2. Experimental procedure

2.1. Test material

Conventional ferrite-pearlite type ductile cast iron having a tensile strength of ≧500MPa (JIS-FCD500) was prepared with 300kW high frequency electric furnace. Ductile cast iron melt was prepared by the Sandwich Method and cast into sand molds for JIS Type Ⅱ Y-shaped blocks [9]. All tests specimens are taken from the gray part of Y blocks as shown in Figure 1. Table 2 and Figure 2 show the chemical composition and typical microstructures of test specimens. The matrix structure is composed of 47% ferrite and 53% pearlite. Table 3 shows graphite structures of specimen evaluated according to JIS-G5502. Table 4 shows the results of tensile test on JIS No.4 test piece whose diameter = 14 mm and gage length = 50 mm. The test procedure meets JIS-Z 2241 standard [10].

2.2. High speed tensile test

Figure 3 shows the specimens for high speed tensile test. The smooth specimen was prepared to investigate influence of strain rate and temperature on the tensile strength σ_B^{smooth}. Furthermore, to enhance sensitivity to strain rate and temperature, the notched round bar specimen was also prepared to obtain the notch strength σ_B^{notch}. The notch has the same shape and dimension as the Charpy V-notch specimen. The tensile test was carried out in the range of stroke speed, υ = 8.5 × 10^{-3} ~ 2.7 × 10^2 mm/s, at temperature T = -130 ~ 22 °C by using electrohydraulic servo testing machine. Then, the tensile strength σ_B^{smooth} and the notch strength σ_B^{notch} were calculated by using equation (1).

$$\left.\begin{aligned}\sigma_B^{smooth} &= 4P_{max} / \pi d^2 \\ \sigma_B^{notch} &= 4P_{max} / \pi d^2\end{aligned}\right\} \quad (1)$$

Where P_{max} = maximum load (N), d = test specimen diameter (mm). The strain rate $\dot{\varepsilon}^{smooth}$ and $\dot{\varepsilon}^{notch}$ were calculated for the smooth specimen and notched specimen respectively by using equation (2).

Table 2. Chemical composition of test specimens (mass %).

Material	C	Si	Mn	P	S	Cu	Mg
JIS-FCD500	3.75	2.08	0.40	0.021	0.013	0.24	0.039

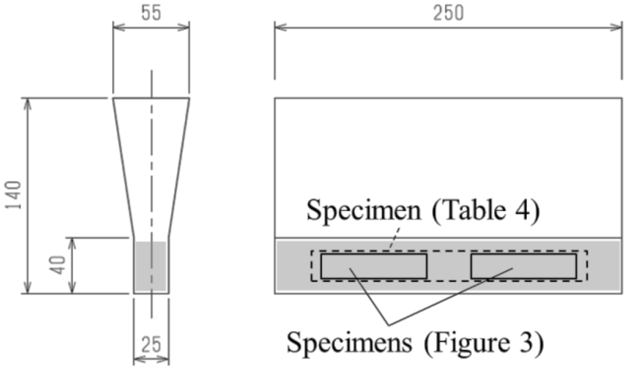


Figure 1. Schematic view of JIS Type II Y-shaped block.

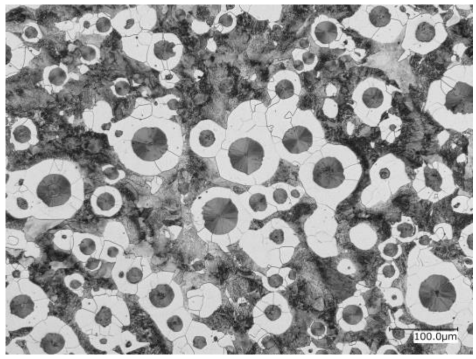


Figure 2. Microstructure of test specimen.

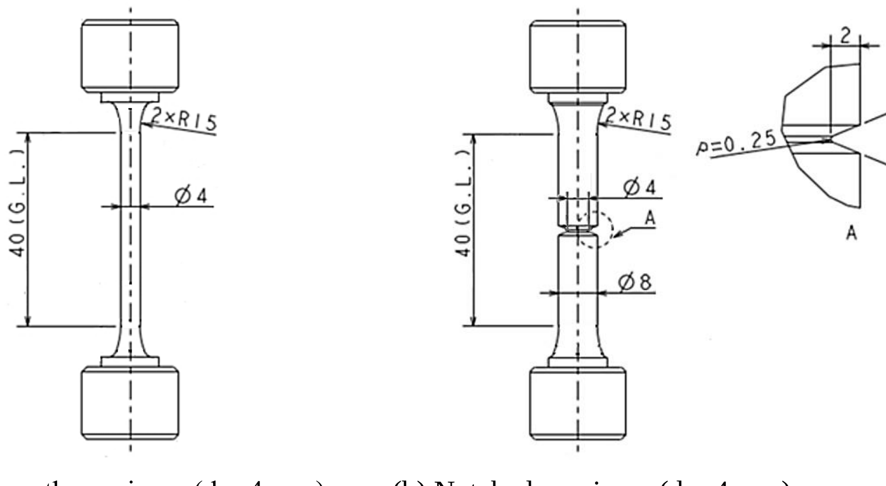
Table 3. Quantitative analysis of graphite nodules structures of as cast sample.

Nodule count (mm^{-2})	Average nodule diameter (μm)	Nodularity (%)	Graphite area fraction (%)
191	27.0	93.2	10.8

Table 4. Tensile property of test specimen.

σ_B (MPa)	$\sigma_{0.2}$ (MPa)	ε_B (%)
566	323	11

σ_B: Tensile strength, $\sigma_{0.2}$: 0.2 % proof stress, ε_B: Fracture strain



(a) Smooth specimen (d = 4 mm) (b) Notched specimen (d = 4 mm)

Figure 3. Configuration of test specimens (in mm).

$$\left.\begin{aligned}\dot{\varepsilon}^{\text{smooth}} &= u(\text{t}) \,/\, t\,\text{l} \\ \dot{\varepsilon}^{\text{notch}} &= u(\text{t}) \,/\, t\,\text{l} \times K_{\text{t}\dot{\varepsilon}}\end{aligned}\right\} \tag{2}$$

Where u(t) = stroke displacement (mm), t = time (s), l = gauge length, 40 mm. Strain rate concentration factor $K_{\text{t}\dot{\varepsilon}}$ [6-8] was used to calculate $\dot{\varepsilon}^{\text{notch}}$ because measuring the strain rate at the notch root is too difficult. The $K_{\text{t}\dot{\varepsilon}}$ value is 9.49 for the notched specimen in Figure 3.

2.3. *Charpy impact test*

Charpy absorbed energy was evaluated on V-notched specimens at 213 ～ 353 K using a Charpy impact machine with the maximum energy capacity 300 J [11]. The impact speed is estimated as 5.18 × 10^3 mm/s. The total absorbed energy in the fracture process E is determined according to JIS-Z 2242 standard [12].

3. Results and discussion

3.1. *Tensile strength*

Based on Bennett and Sinclair's theory on the influence of strain rate and temperature on yield phenomena of BCC metals [13], strain rate-temperature parameter, R parameter given by the following equation (3), has been introduced to explain the combined influence of strain rate and temperature on the yield stress of steel and ductile cast iron [14-16]. A good correlation between tensile strength and R parameter was also reported on these materials [16, 17].

$$R = T \times \ln(\text{A} / \dot{\varepsilon}) \tag{3}$$

Where T = temperature (K), A = 10^8 s^{-1} [13, 16], $\dot{\varepsilon}$ is strain rate (s^{-1}); $\dot{\varepsilon} = \dot{\varepsilon}^{\text{smooth}}$ for smooth specimen, $\dot{\varepsilon} = \dot{\varepsilon}^{\text{notch}}$ for notched specimen. As shown in Figure 4, there is a good correlation between $\sigma_{\text{B}}^{\text{smooth}}$ and R parameter. In Figure 4, the range of R parameter required for the welded structures is also shown as the hatched lines. This required range of R parameter was calculated from the strain rate and temperature for the welded toes of beam-column in Table.1. It is seen that $\sigma_{\text{B}}^{\text{smooth}}$ of JIS-FCD500 continuously increases with the decrease in R parameter over the range of R parameter required for welded structures. Here, decreasing R parameter means increasing strain rate or decreasing temperature, or both. The result of ductile cast iron is consistent with previous research reports on steel [18].

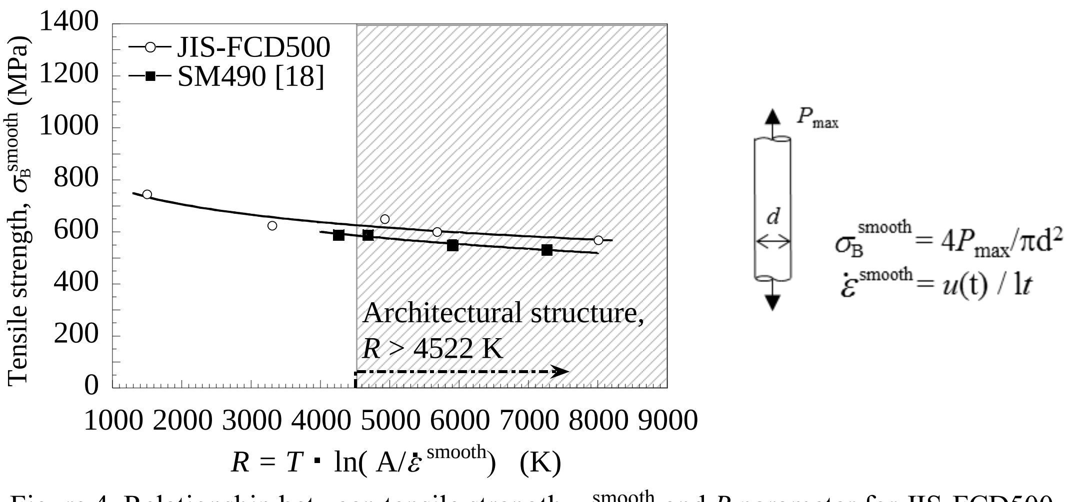


Figure 4. Relationship between tensile strength $\sigma_{\text{B}}^{\text{smooth}}$ and R parameter for JIS-FCD500 and SM490 [18].

3.2. Notch strength

The dependency of notch strength σ_B^{notch} of JIS-FCD500 specimens on *R* parameter is shown in Figure 5. With decreasing *R* parameter, σ_B^{notch} keeps increasing until *R* value of 2500, and then it starts decreasing. The σ_B^{notch} values is 100～130 MPa higher than σ_B^{smooth} over the *R* parameter range required for architectural structure shown by hatched lines.

As the higher strain rate and the lower temperature also give similar effects on the toughness of ductile cast iron [19, 20], we tried to correlate Charpy absorbed energy *E* to *R* parameter [11]. Figure 6 shows the relationship between *E* and *R* parameter for JIS-FCD500 specimens. The absorbed energy *E* starts dropping at the critical *R* parameter indicated by the black arrow. However, it is clear that σ_B^{smooth} and σ_B^{notch} keep increasing even when Charpy absorbed energy starts decreasing.

Figure 7 shows comparison of σ_B^{notch} and the tensile strength at room temperature $\sigma_{B,\ RT}^{smooth}$. It should be noted that σ_B^{notch} is always larger than $\sigma_{B,\ RT}^{smooth}$ in the range of *R* parameter required for architectural structure. Therefore, tensile strength $\sigma_{B,\ RT}^{smooth}$ is confirmed to be useful in designing ductile cast iron for the welded structural components.

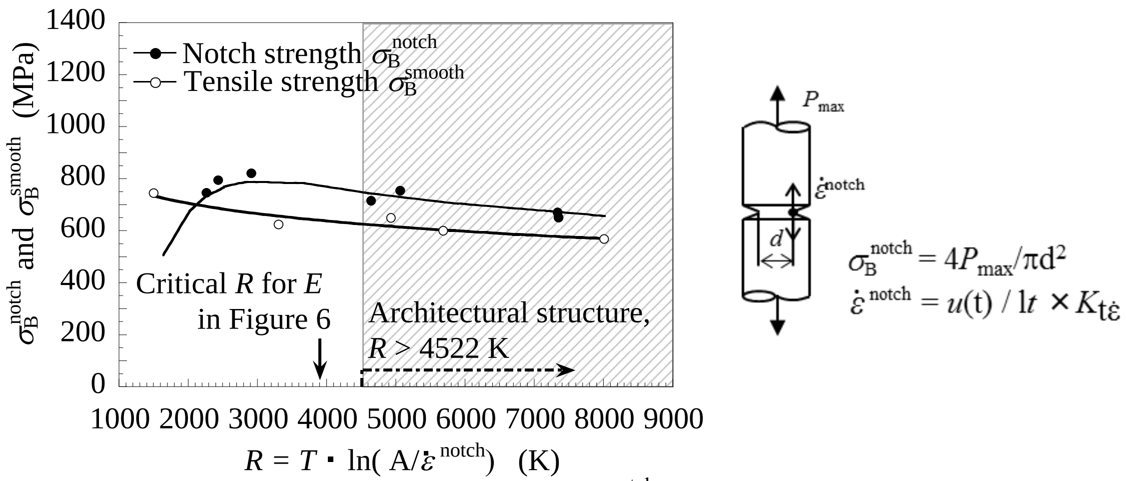


Figure 5. Relationship between notch strength σ_B^{notch} and *R* parameter for JIS-FCD500.

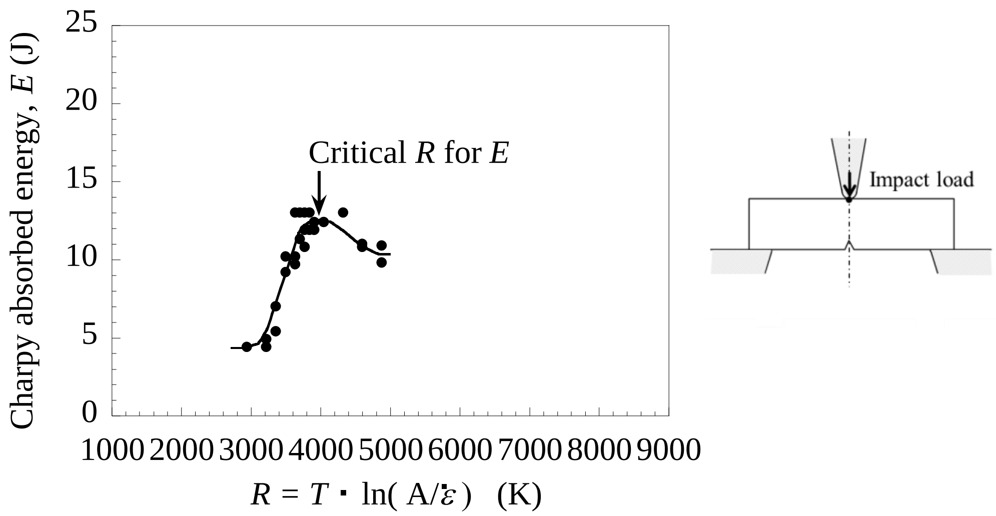


Figure 6. Relationship between Charpy absorbed energy *E* and *R* parameter for JIS-FCD500 ($\dot{\varepsilon} = 10^2$ s^{-1} [4, 5]).

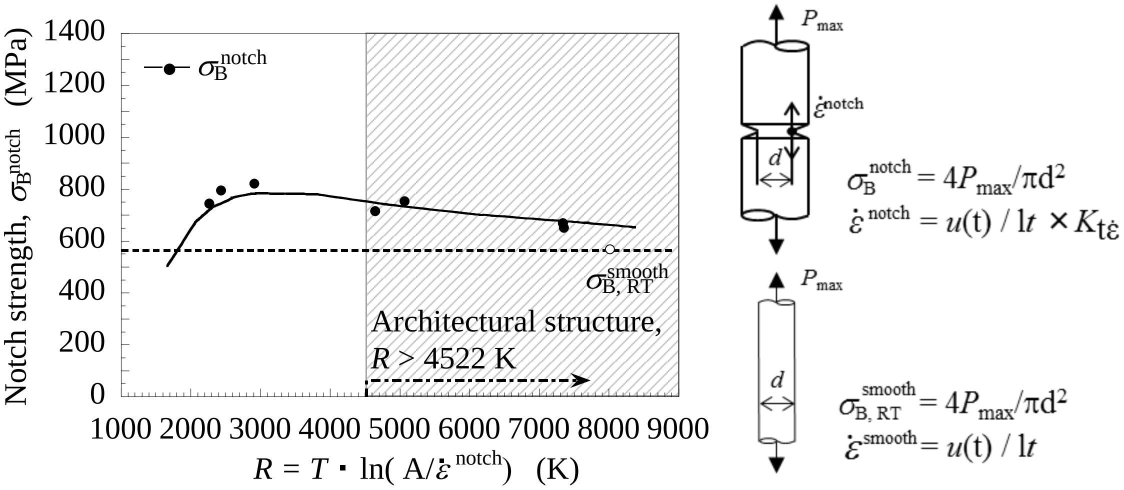


Figure 7. The comparison of $\sigma_{\mathrm{B}}^{\mathrm{notch}}$ and $\sigma_{\mathrm{B,\ RT}}^{\mathrm{smooth}}$ in R parameter required from the welded structural design.

4. Conclusions

High speed tensile test was carried out on the notched and smooth ductile cast iron specimens with 47%ferrite-53%pearlite matrix in the range of stroke speed υ = 8.5 × 10^{-3} ~ 2.7 × 10^{2} mm/s, at temperature T = -130 ~ 22 °C. The experimental data were correlated to R parameter, and following conclusions are obtained.

(1) With decreasing R parameter, the tensile strength of both smooth and notched specimens, $\sigma_{\mathrm{B}}^{\mathrm{smooth}}$ and $\sigma_{\mathrm{B}}^{\mathrm{notch}}$, continuously increases over the range of R parameter required for architectural structures. Therefore, ductile cast iron has wide application potentiality to components for welded steel structures.

(2) The notch strength $\sigma_{\mathrm{B}}^{\mathrm{notch}}$ is consistently larger than the room temperature strength $\sigma_{\mathrm{B,\ RT}}^{\mathrm{smooth}}$ in the range of R parameter required for architectural structures. Therefore, $\sigma_{\mathrm{B,\ RT}}^{\mathrm{smooth}}$ can be safely used for structural design of architectural components.

References

[1] S.Harada and T.Kobayashi 1999 *Kyujyokokuen-Chutetu no Kyodo Hyoka* (Tokyo: AGNE Gijyutu-Ctnter)
[2] Okashita K, Ohminami R, Michiba K, Yamamoto A, Yomimatsu M, Tanji Y and Miki C 1998 Investigation of the Brittle Fracture at the Corner of P75 Rigid-Frame Pier in Kobe Harbor Highway During the Hyogoken-Nanbu Earthquake *The Journal of Japan Socity of Civil Engineers* **591** pp 243-261
[3] Toyoda M 1996 Lessons Learned from Great Hanshin Earthwuake for Steel Framed Structures with Particular Reference to Materials/Welding *Materia Japan* **35** No.4 pp 370-379
[4] Sakui S, Nakamura T and Ohomori 1963 The Effects of Grain Size and Deformation Rate on the Tensile Proparties of Mild Steel at Low Temperature **49** No.7 pp 996-1003
[5] Sugiura N, Kobayashi T, Yamamoto I, Nishido S and Hayashi K 1995 Comparison of tensile and 3-point bend properties under impact loading in an AC4CH-T6 aluminum casting alloy *Journal of Institute of Lite Metals* **45** No.11 pp 638-642

[6] Noda N.-A, Ohtuka, H, Ando M, Sano Y, Takase Y, Shinozaki T and Guan W 2013 Analysis of dynamic stress concentration and strain rate cocentration for notched specimes used for high speed tensile test *Transactions of the Japan Society of Mechanical Engineers Series A* **79** No.804 pp 1182-1190

[7] Ando H, Noda N.-A, Kuroshima Y, Ishikawa Y and Takeda H 2014 Impact properties of polydimethylsiloxane copolymerized polycarbonate and applicaton of the time-temperature superposition principle *Transactions of the Japan Society of Mechanical Engineers* **80** No.814 DOI: 10.1299/transjsme. 2014smm0149

[8] Noda N.-A, Ohtsuka H, Zheng H, Sano Y, Ando M, Shinozaki T and Guan W 2015 Strein rate concentration and dynamic stress concentration for double-edge-notched specimens subjected to high-speed tensile loads *Fatigue & Fracture of Engineering Materials & Structures* **38** pp 125-138

[9] Japanese standards association (Eds.) 2012 *JIS G 5502 Spheroidal graphite iron castings* (Tokyo: Japanese standards association) pp 1880-1897

[10] Japanese standards association (Eds.) 2011 *JIS Z 2241 Metallic materials –Tensile testing-Method of test at room temperature* (Tokyo: Japanese standards association) pp 321-365

[11] Umetani T, Ikeda T, Sura N, Ashizuka K, Nemoto T, Takada H. and Ogi K 2014 Tensile strength, Fatigue Strength and Impact Strength of Solution Strengthend High Silicon Ferritic Ductile Cast Iron *Journal of Japan Foundry Engineering Society* **86** No.1 pp 36-42

[12] Japanese standards association (Eds.) 2005 *JIS Z 2242 Method for Charpy pendulum impact test of metallic materials* (Tokyo: Japanese standards association) pp 366-377

[13] Bennett P E and Sinclair G M 1966 Parameter Represntation of Low-Temperature Yield Behavior of Body-Centered Cubic Transition Metals *Transactions of the ASME* **65** pp 518-524

[14] Fuji E, Ohkuma Y, Kawaguchi Y and Tsukamoto M 1985 Effects of Temperature and Strain Rate on Dynamic Fracture Toughness of Steel *The society of naval architects of Japan* **158** pp 619-629

[15] Goto K, Hirasawa H and Toyosada M 1944 A Simple Estimating Method of Constiutive Equation for Structural Steel as a Function of Strain Rate and Tmperature *The society of naval architects of Japan* **176** pp 501-507

[16] Yamamoto H, Kobayashi T and Fujita H 1999 Strain Rate-temperature Dependency of Impact Tensile Properties and Ductile Fracture Behavior in Ductile Cast Iron *Tetsu-to-Hagané* **85** No.10 pp 765-770

[17] Minami F, Hashida T, Toyoda M, Morikawa J, Ohmura T, Arimochi K and Konda N 1998 *The society of naval architects of Japan* **184** 453-463

[18] Kurihara, M., Influence of strain rate on tensile properties for steel, Jounal of the Japan Welding Society, Vol.66, No.1(1997), pp.6 (in Japanese)Japanese standards association (Eds.) 2005 *JIS Z 2242 Method for Charpy pendulum impact test of metallic materials* (Tokyo: Japanese standards association) pp 366-377

[19] Yamamoto H, Kobayashi T and Fujita H 2000 Strain Rate Dependency of Ductile-Brittle Transition Behavior in Ductile Cast Iron *Journal of Japan Foundry Engineering Society* **72** No.2 pp 107-112 Minami F, Hashida T, Toyoda M, Morikawa J, Ohmura T, Arimochi K and Konda N 1998 *The society of naval architects of Japan* **184** 453-463

[20] Ikeda T, Umetani T, Kai N, Ogi K, Noda N.-A. and Sano Y 2016 Influence of Silicon Content, Strain Rate and Temperature on Toughness and Strength of Solid Solution Strengthened Ferritic Ductile Cast Iron *MATERIALS TRANSACTIONS* **57** No.12 pp 2132-2138