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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 σ_B^{smooth} and the notch strength σ_B^{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 σ_B^{smooth} and σ_B^{notch} increase even when Charpy absorbed energy starts decreasing. It should be noted that the notch strength σ_B^{notch} is always larger than the tensile strength at room temperature $\sigma_{B, RT}^{\text{smooth}}$ in the range of R parameter required for the welded structures. Therefore, the tensile strength $\sigma_{B, RT}^{\text{smooth}}$ 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



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 ≥ 500 MPa (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, $v = 8.5 \times 10^{-3} \sim 2.7 \times 10^2$ mm/s, at temperature $T = -130 \sim 22$ °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).

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

Where P_{max} = maximum load (N), d = test specimen diameter (mm). The strain rate $\dot{\epsilon}^{\text{smooth}}$ and $\dot{\epsilon}^{\text{notch}}$ 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

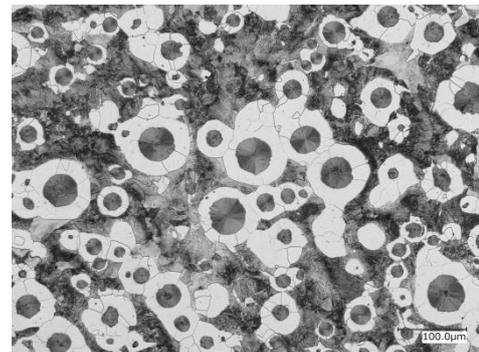
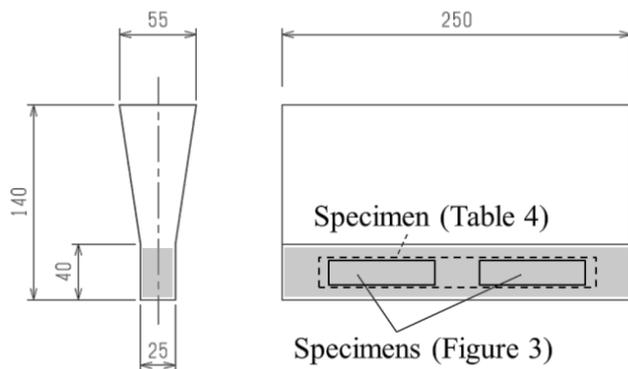


Figure 1. Schematic view of JIS Type II Y-shaped block. Figure 2. Microstructure of test specimen.

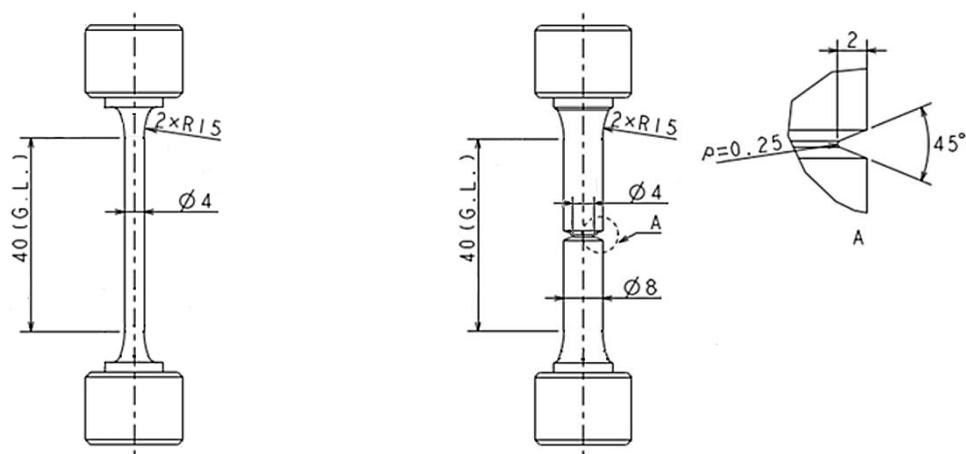
Table 3. Quantitative analysis of graphite nodules structures of as cast sample.

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).

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

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

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

Where T = temperature (K), $A = 10^8 \text{ s}^{-1}$ [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 σ_B^{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 σ_B^{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].

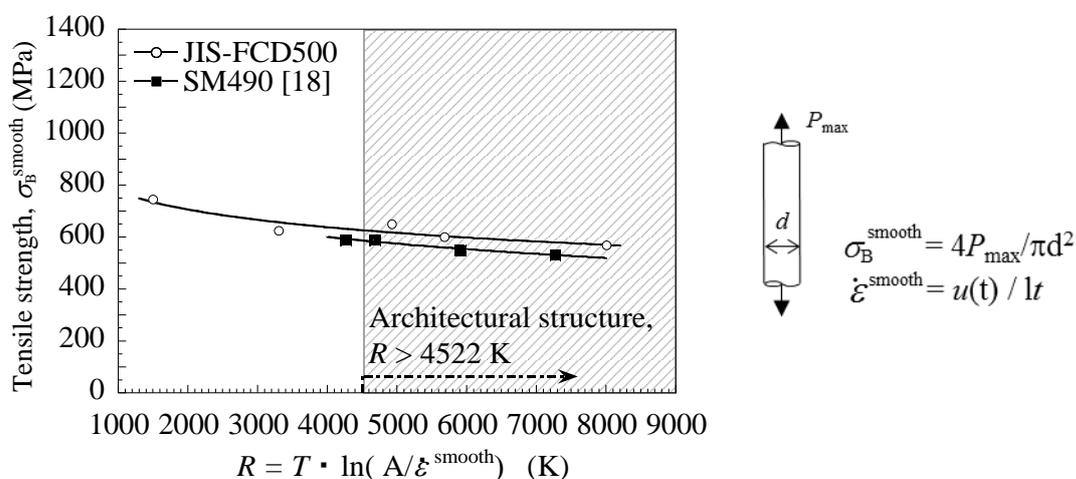


Figure 4. Relationship between tensile strength σ_B^{smooth} and R parameter for JIS-FCD500 and SM490 [18].

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

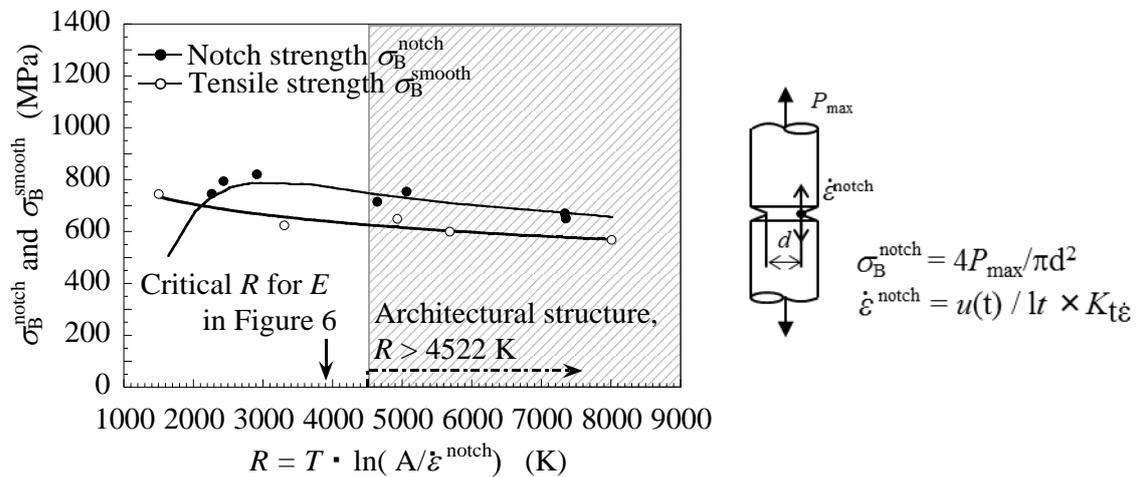


Figure 5. Relationship between notch strength σ_B^{notch} and R parameter for JIS-FCD500.

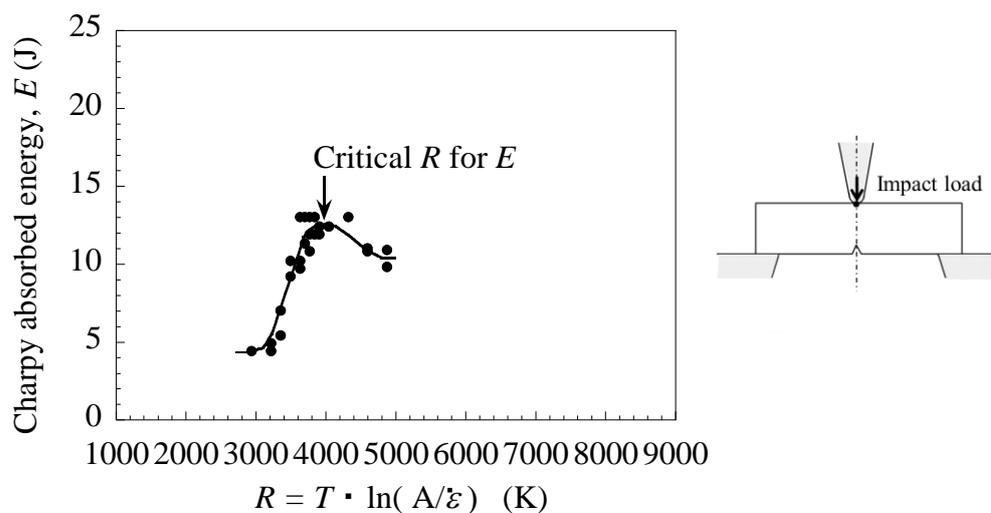


Figure 6. Relationship between Charpy absorbed energy E and R parameter for JIS-FCD500 ($\dot{\epsilon} = 10^2 \text{ s}^{-1}$ [4, 5]).

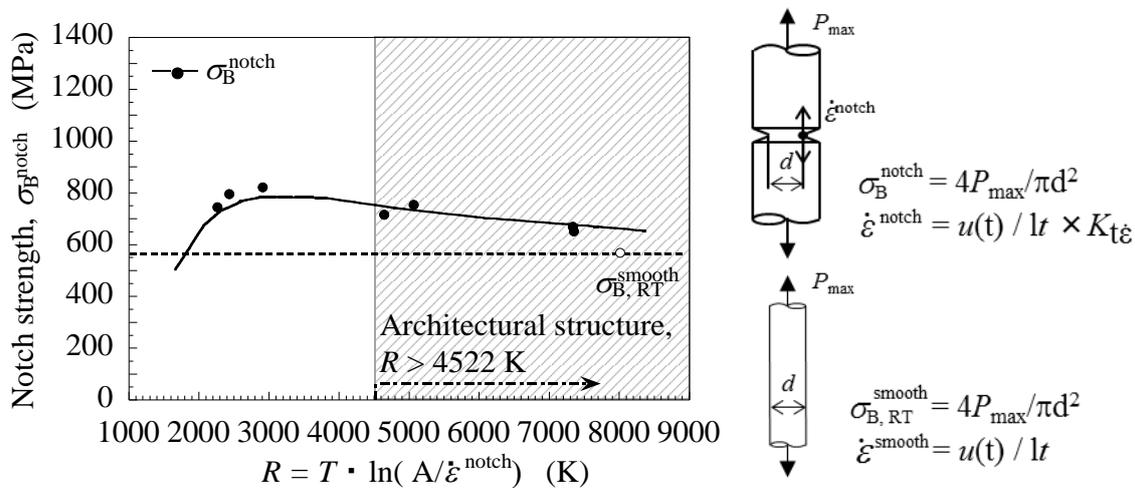


Figure 7. The comparison of σ_B^{notch} and $\sigma_{B,RT}^{\text{smooth}}$ in R parameter required from the welded structural design.

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 $v = 8.5 \times 10^{-3} \sim 2.7 \times 10^2$ mm/s, at temperature $T = -130 \sim 22$ °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, σ_B^{smooth} and σ_B^{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 σ_B^{notch} is consistently larger than the room temperature strength $\sigma_{B,RT}^{\text{smooth}}$ in the range of R parameter required for architectural structures. Therefore, $\sigma_{B,RT}^{\text{smooth}}$ can be safely used for structural design of architectural components.

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