Analysis of Ductile Cast Iron for Spent Fuel Cask

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INTRODUCTION

Recently the usage of Ductile Cast Iron (D.C.I.) is expanding in many fields in Japan, and the production of D.C.I. whose thickness is more than 200 mm has already started. Although BAM regulation in Germany and ASTM-A-874 in U.S.A. for D.C.I. were settled, Japan Industrial Standard (J.I.S.) or any other rules in Japan was not decided for heavy section D.C.I. whose thickness is more than 200 mm.

But the needs of standardization of such heavy section D.C.I. was growing stronger. In this report the authors tried to analyze statistically mechanical properties, manufacturing processes and metallurgical conditions for the sake of standardization of D.C.I. as J.I.S..

PROCEDURE

143 data were prepared from 12 D.C.I. castings whose thicknesses ranged from 350 mm up to 560 mm, whose sizes and shapes were similar to those of casks in Japan and which were manufactured by 6 Japanese foundries. These data were analyzed by the Multiple and Singular Regression Analysis of Macintosh.

The data were separated into three groups which were mechanical properties, metallurgical conditions and manufacturing processes. The relationship between each mechanical property, the relationships among the three groups were investigated. The independence of each factor was guaranteed by using the factors whose singular regression coefficient was less than 0.30 (i.e., the contribution ratio was less than 0.10). The factors and their ranges are presented at Table-1. The Significance Check is performed by t-Value ≥2.00 or F-Value ≥4.00.

RESULTS

(1) The results of singular regression analyses of each other mechanical properties are shown as Fig. 1 ~ Fig. 7. And the proposal ranges of J.I.S. are shown in those figures for reader's convenience.

Supposing that the proposal is as following, Tensile Strength ≥300 MPa, Yield Strength ≥200 MPa, Minimum Elongation ≥8%, Average Elongation ≥12%, Minimum Charpy Absorbed Energy at 233K ≥4J, and Average Charpy Absorbed Energy at 233K ≥6J, all data of Tensile Strength and Yield Strength are sufficient enough for the proposal (Fig. 1), but those of Elongation and Charpy Absorbed Energy are slightly insufficient. (Fig. 2 ~ Fig. 7).

Fig. 6 indicates that Charpy Absorbed Energy will satisfy the proposal when Yield Strength is less than 230 MPa. And Fig. 3 also indicates that Yield Strength less than 230 MPa gives sufficient Elongation.

(2) The relationships among mechanical properties, metallurgical conditions and manufacturing processes and between metallurgical conditions and manufacturing processes are shown in Table 2 ~ Table 9.
   a) Tensile Strength is expressed as a function of Graphite Number and Graphite Nodularity (Table 2).
   b) Yield Strength (0.2% Proof Stress) can be expressed as a function of Graphite Number, Graphite Nodularity and Ratio of Ferrite, but better expression can be got by function of [Si]% and [Ni]% and its multiple regression coefficient is 0.92 (Table 3 ~ 4).
   c) Elongation is approximated by Ratio of Ferrite, Graphite Number and Graphite Nodularity (Table 5).
   d) Charpy Absorbed Energy at 233K can be expressed as a function of Graphite Number and Ratio of Ferrite (Table 6), but cannot be found to have any relation to manufacturing processes.
   e) Graphite Number correlates to [C]% (Table 7), Graphite Diameter is expressed as a function of [C]%, [Si]% and [Mn]% (Table 8), and Graphite Nodularity is given by a function of [Mn]% and Casting Temperature (Table 9). But any good correlation about Ratio of Ferrite could not be found by this analysis.

DISCUSSION

(1) Mechanical Properties of Heavy Section D.C.I.
The proposal of J.I.S. is quite reasonable and if manufacturer can control Yield Stress between 200 and 230 MPa, there is no difficulty to satisfy the proposal. And Yield Strength is easy controllable by [Si]% and [Ni]%.

(2) Tensile Strength
Tensile Strength of Heavy Section D.C.I. is approximated by Graphite Number and Graphite Nodularity and this fact means that fining graphite and nodularization contribute to rising Tensile Strength. And the fact indicates that the position of crack initiation of Tensile Fracture is the matrix area where stress concentration is brought by Graphite.

(3) Yield Strength (0.2% Proof Stress)
Graphite Noduraility have good correlation to Yield Strength, and it shows that the stress concentration around Graphite is effective on Yield Strength. Negative Correlation of Ratio of Ferrite means positive correlation of Ratio of Pearlite, and Negative correlation of Graphite Number means the stress concentration. But correlation of [Si]% and [Ni]% to Yield Strength is very strong as $r = 0.92$. This result means that Solid Solution Effect of [Si]% and [Ni]% is the most important for Yield Strength. Therefore, the control of Yield Strength is very easy.

(4) Elongation
Elongation of Heavy Section D.C.I. is related strongly to Ratio of Ferrite and slightly to Graphite Number.

(5) Charpy Absorbed Energy at 233K
Charpy Energy has negative correlation to Graphite Diameter and positive correlation to Ratio of Ferrite. Negative correlation to Graphite Diameter indicates positive correlation to Mean Graphite Spacing. Therefore the larger Mean Graphite Spacing gives the higher fracture energy in Impact Fracture.

(6) Metallurgical Condition and Manufacturing Processes
All of the correlations can be thought theoretically reasonable.

CONCLUSION

143 data from 12 Heavy Section D.C.I. Cast Bodies of 6 manufacturer in Japan were investigated and statistically analyzed about Mechanical Properties, Metallurgical Conditions and Manufacturing Processes. The following results were concluded.

(1) The Mechanical Properties of J.I.S. are reasonable, reliable and reasonably achievable.
(2) The Mechanical Properties of D.C.I. are reasonably achievable.
(3) The Mechanical Properties of D.C.I. are easily controllable through metallurgical method.
(4) D.C.I. (JIS G5504-92) is applicable to the material for spent fuel cask.

Table 1. Data Range of Multiple Regression Analysis

Factor	Unit	Data No.	Min.	Av.	Max.
0.2% Y.S	MPa	164	200.1	226.8	306.0
T.S	MPa	164	307.9	355.3	468.0
Elongation	%	164	7.0	19.3	30.0
Reduction Area	%	155	4.9	18.4	31.3
Cp (RT)	J	125	5.3	17.8	25.5
Cp (233K)	J	94	3.8	6.3	12.2
[C]	%	164	3.35	3.48	3.85
[Si]	%	164	1.76	2.04	2.46
[Mn]	%	164	0.09	0.22	0.38
[P]	%	164	0.006	0.016	0.054
[S]	%	164	0.001	0.004	0.014
[Ni]	%	154	0.00	0.16	0.83
[Cr]	%	159	0.02	0.03	0.09
[Cu]	%	154	0.01	0.016	0.023
[Mg]	%	164	0.038	0.054	0.088
Inoculation Temp.	°C	144	1,325	1,342	1,385
Pouring Temp.	°C	149	1,270	1,322	1,345
Heat Treatment	—	164	Not	—	Done
Graphite Dia.	μm	141	37.6	151	314
Graphite No.	No./mm^2	136	3.6	30	324
Graphite Nodularity	%	138	70	80.0	97.6
Ratio of Ferrite	%	114	89.0	98.4	100

Table 2. Results of Multiple Regression Analysis (T.S)

	Graphite Number (No./mm^2)	Graphite Nodularity (%)	Multiple Correlation	Standard Error	F Value
Correlation	0.543	0.352	0.648	14.490	37.675
Regression Coefficient	0.215	1.156			
t Value	7.282	4.723			
Regression Formula (MPa)	T.S = 0.21525 [Graphite No.] + 1.15656 [Graphite Nodularity] + 256.241706				

Table 3. Results of Multiple Regression Analysis (Y.S)

	Graphite Number (No./mm^2)	Graphite Nodularity (%)	Ratio of Ferrite (%)	Multiple Correlation	Standard Error	F Value
Correlation	−0.073	0.571	−0.172	0.659	11.383	18.979
Regression Coefficient	−0.370	1.569	−2.776			
t Value	−2.392	7.240	−2.909			
Regression Formula (MPa)	Y.S = −0.37040 [Graphite No.] + 1.56907 [Graphite Nodularity] − 2.77642 [Ratio of Ferrite + 374.34619					

Table 4. Results of Multiple Regression Analysis (Y.S)

	Si (%)	Ni (%)	Multiple Correlation	Standard Error	F Value
Correlation	0.689	0.525	0.920	6.438	290.52
Regression Coefficient	67.351	34.944			
t Value	19.776	15.954			
Regression Formula (MPa)	Y.S = 67.35126 [Si]% + 34.94485 [Ni]% + 79.46603				

Table 5. Results of Multiple Regression Analysis (El)

	Graphite Number (No./mm^2)	Graphite Nodularity (%)	Ratio of Ferrite (%)	Multiple Correlation	Standard Error	F Value
Correlation	0.219	–0.063	0.599	0.662	4.782	19.285
Regression Coefficient	0.178	–0.207	2.827			
t Value	2.740	–2.277	7.051			
Regression Formula (%)	El = 0.17828 [Graphite No.] – 0.20734 [Graphite Nodularity] + 2.82725 [Ratio of Ferrite] – 245.66393					

Table 6. Results of Multiple Regression Analysis (Cp (233K))

	Graphite Number (μm)	Ratio of Ferrite (%)	Multiple Correlation	Standard Error	F Value
Correlation	–0.415	0.384	0.516	1.077	9.828
Regression Coefficient	–0.006	0.281			
t Value	–2.961	2.633			
Regression Formula (Joule)	Cp (233K) = –0.00637 [Graphite Dia.] + 0.28145 [Ratio of Ferrite] – 20.82257				

Table 7. Results of Multiple Regression Analysis (Graphite No.)

	C (%)	Mg (%)	Multiple Correlation	Standard Error	F Value
Correlation	0.769	0.585	0.772	33.549	61.248
Regression Coefficient	334.364	608.331			
t Value	7.222	0.918			
Regression Formula (No./mm^2)	Graphite No. = 334.36475 [C]% + 608.33179 [Mg]% – 1173.59326				

Table 8. Results of Multiple Regression Analysis (Graphite Dia.)

	C (%)	Si (%)	Mn (%)	Multiple Correlation	Standard Error	F Value
Correlation	–0.591	0.428	–0.572	0.806	45.843	50.982
Regression Coefficient	–350.949	129.692	–827.721			
t Value	–7.556	4.829	–5.252			
Regression Formula (μm)	Graphite Dia. = –350.94946 [C]% + 129.69281 [Si]% – 827.72144 [Mn]% + 1318.19531					

Table 9. Results of Multiple Regression Analysis (Nodularity)

	Mn (%)	Pouring Temp. (°C)	Multiple Correlation	Standard Error	F Value
Correlation	–0.393	–0.545	0.720	4.023	56.159
Regression Coefficient	–86.659	–0.195			
t Value	–6.926	–8.882			
Regression Formula (%)	Nodularity = –86.65926 [Mn]% – 0.19576 [Pouring Temp.] + 357.04785				

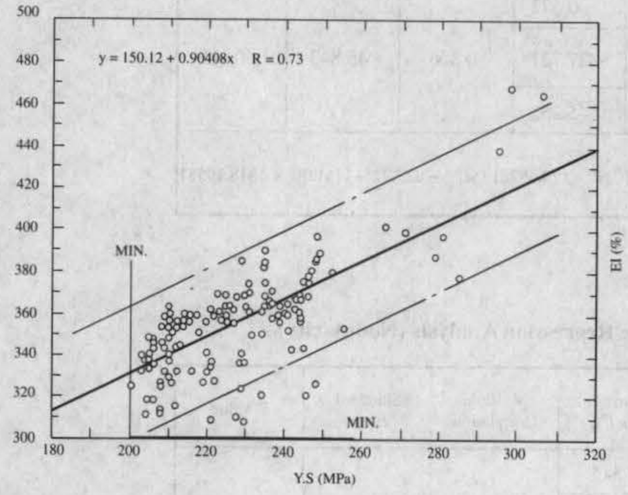

Fig. 1. Relationship between Yield Strength and Tensile Strength

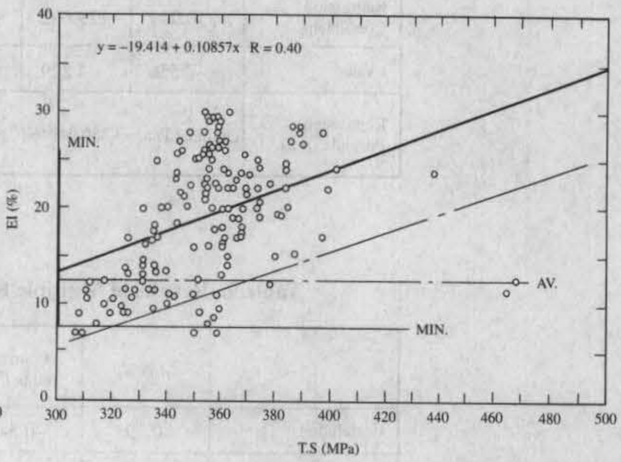

Fig. 2. Relationship between Tensile Strength and Elongation

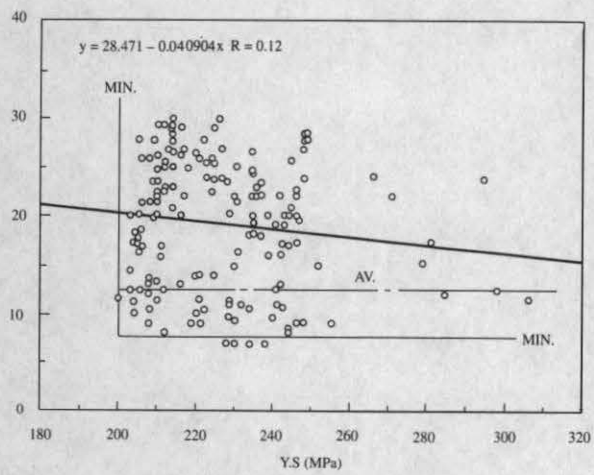

Fig. 3. Relationship between Yield Strength and Elongation

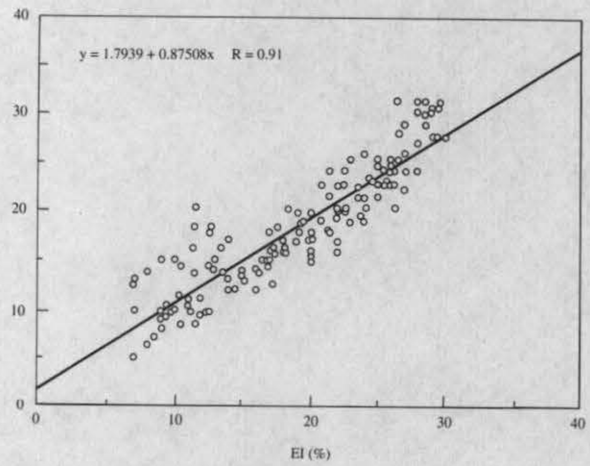

Fig. 4. Relationship between Elongation and Reduction Area

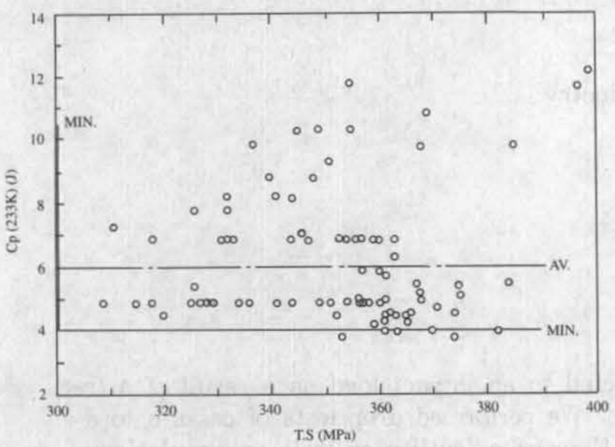

Fig. 5. Relationship between Tensile Strength and Charpy Absorbed Energy

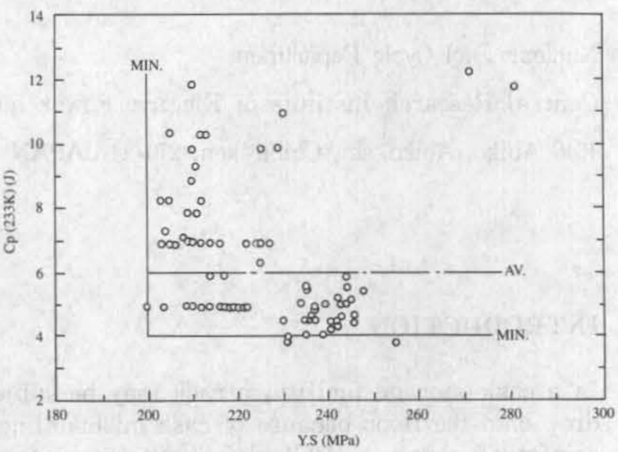

Fig. 6. Relationship between Yield Strength and Charpy Absorbed Energy

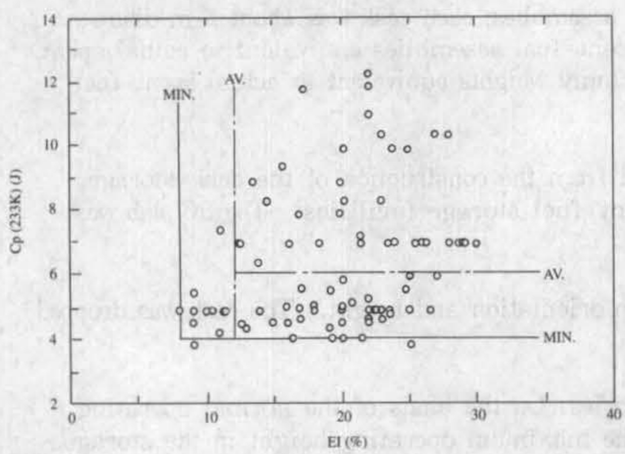

Fig. 7. Relationship between Elongation and Charpy Absorbed Energy