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INTRODUCTION

ISABELLE, the latest high energy physics machine, and currently under construction at the Brookhaven National Laboratory, is a 400x400 GeV Intersecting Storage-Ring Proton Accelerator. The beam will be guided and focused by superconducting magnets wound from a multifilamentary Nb-Ti braid. The layout of the beam and of the bending, dipole magnets and focusing, quadrupole magnets is shown in Fig. 1. There will be 722 dipoles and 280 quadrupoles in all.

Some details of the magnet construction are indicated in Fig. 2. The magnet windings are surrounded by a stack of soft-iron laminations to provide the return path for the magnetic flux. The magnet assembly, complete with laminations, is placed inside the stainless steel support tube. Each tube is .495 m (19.5 in) outside diameter, with a .019 m (0.75 in) wall thickness. The dipole tubes are 4.95 m long, the quadrupole tubes are 1.89 m long. It is with these tubes, and in particular the material from which they are made, that this report is concerned.

During operation, each tube and its contents will be at a temperature of 3.8 K, the magnet temperature. The strains resulting from the differential thermal contraction between the soft-iron core and the essentially austenitic tube will give rise to a tensile hoop stress in each tube of $\sim$210 MPa (30,000 psi). The refrigerant, which circulates inside each tube, is helium gas at a pressure of 2.07 MPa (300 psi), giving rise to a longitudinal stress in the

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wall of $\sim$12 MPa in addition to any frictional stress transferred to the tube from the longitudinal differential contraction relative to the core. These stresses are well below the expected yield stresses for stainless steel at this temperature.

The tubes are centrifugally cast and then machined, the material is CF8, and is chemically the casting equivalent of the wrought grade 304. Unlike the wrought material, which is entirely austenitic, the cast material may contain some δ-ferrite, the quantity depending upon the composition and rate of solidification. Within the limits of the allowed chemical composition (ASTM Standard A743 - see first row of Table I) CF8 may contain up to 40% δ-ferrite, though in practice amounts in escess of 20% are unusual. There is little published information on the mechanical properties of cast stainless steel at cryogenic temperatures, and no systematic study of the effect of ferrite content on these properties has been carried out.

The consideration which influences the specification of the steel for the magnet tubes, is that the material must not be brittle at 3.8 K, to prevent the possibility of catastrophic failure starting at undetected casting defects, machining marks or imperfect welds. The magnetic properties of the tube are unimportant, the magnetic flux is contained entirely by the soft iron core.

The presence of some δ-ferrite is beneficial in cast stainless steel. It refines the austenite grain size and enhances strength. However at high ferrite contents the inherent low temperature brittleness of the bcc phase can be expected to dominate the low temperature mechanical properties. This investigation studied the effects of δ-ferrite content on low-temperature mechanical properties.

EXPERIMENTAL

Samples of centrifugally cast stainless steel tube were supplied by three manufacturers, ACIPCO Special Products Division, Sandusky Foundry and Machine, and Kubota Ltd. These samples were chosen to give a wide range of compositions within the CF8 specification. These chemical compositions and δ-ferrite content are given in Table I. The latter quantity can be estimated from the chemistry by use of the Schaeffler diagram,[1] or its modification, taking into account the nitrogen content, the DeLong diagram.[2] It can also be measured metallographically or by the use of the Magne-gauge. From the table it can be seen that there is reasonable agreement between the estimates from the DeLong diagram and the measurements with the Magne-gauge (using the #2 magnet). These also corresponded with the results in the few cases when optical measurements were also made. The Schaeffler diagram in almost all cases leads to quite erroneous results.

All samples, with the exception of numbers 13 and 14, had been solution-treated after casting at 1040°C for sufficient period (~2 h) to dissolve all soluble carbides. 13 and 14 were supplied in the as-cast condition. Sample number 15 was CF8M, the casting equivalent of 316 containing 2-3% Mo, for comparison.

Tensile tests were carried out at room temperature (300 K), in dry ice and alcohol (195 K), in liquid nitrogen (77 K) and in liquid helium (4.2 K). Charpy V-notch impact tests were carried out at the three upper temperatures; some attempts were made at 4.2 K, but temperature control and measurement were too uncertain for them to be meaningful.

RESULTS

The results are here presented as a function of δ-ferrite content. However, this is not the only variable. In order to develop different amounts of ferrite, the chemistry must be varied, and thus the microstructures consist not only of different relative amounts of γ and δ, but of γ and δ whose chemical compositions vary from sample to sample. Thus some scatter in the results is to be expected.

Figure 1 shows the yield stress (YS) at four different temperatures. YS shows a slight increase with increasing δ-content up to about 8% δ; beyond this the strength rises noticeably with an increasing amount of the δ-phase. This rate of increase is larger at the lower temperatures. Specimen #13 shows a serious deviation from this behavior; its YS is considerably higher at all temperatures. This sample had a particularly high nitrogen content of 0.122%. The effect of nitrogen in solid solution in strengthening austenite (γ), particularly at low temperatures, is dramatically illustrated by this sample. Also shown for comparison are results typical of wrought 304 stainless (0 ferrite) and CF8M. The former is equivalent in strength to CF8 with $\sim$10% δ. The latter, with 24% δ, is weaker than would be expected by extrapolation of the CF8 results to 24% δ. All samples had a 4.2 K YS well in excess of the 210 MPa static working stress on the tubes.

The ultimate tensile strength (UTS) showed considerable scatter. This is because the UTS value is strongly affected by the formation of strain-induced martensite during the plastic deformation. Martensite formation depends upon the chemical composition of the austenite phase, and thus the UTS cannot be related in a simple way to ferrite content.

Figure 2 shows the ductility, as characterized by the percent overall elongation to fracture. Again the results show considerable scatter, but trends can be discerned. At 300 K, ductility is initially increased by up to $\sim$7% ferrite, and thereafter is reduced as the ferrite content is increased. The behavior is similar at 195 K, though the maximum ductility is observed for

$\sim$4% ferrite, and at lesser ferrite levels the ductility is higher than at 300 K. At 77 K the ductility is lower, and generally decreases with increasing ferrite content, quite rapidly at >10% δ. The 4.2 K trend is similar, with ductility everywhere reduced below that at 77 K.

Three samples deviated markedly from the above trends with seriously reduced ductility, #6, #13, and #14. The fracture surface of #6 showed the fracture to be entirely intergranular. Precipitates present in the fracture surface were identified by electron microprobe analysis as NbC. Metallographic examination revealed concentrations of NbC in a eutectic-like structure in the γ-δ interphase-boundaries. Chemical analysis showed the presence of an unusually high concentration, 0.16%, of Nb. Subsequent enquiry revealed that the particular heat from which this tube had been cast contained a high proportion of scrap containing appreciable quantities of Nb in the charge. #13, as mentioned above, had a high nitrogen content. Nitrogen, in addition to strengthening austenite, also reduces its ductility, particularly at the lower temperatures.

#14 contained 12% ferrite and was not heat treated. Heat treatment dissolves carbides, slightly reduces the amount of ferrite, and also affects the morphology of the ferrite regions, rounding them off and making them less angular. The low ductility in this sample is assumed to result from the lack of heat treatment. It is regreted that more non-heat treated samples were not available to allow of a systematic investigation of the effects of heat treatment, and of the influence of ferrite content in non-heat treated material. Again results for 304 and CF8M are shown for comparison. 304 falls in the same range of ductility as 0-ferrite CF8. CF8M shows a much higher ductility than most of the CF8, particularly at low temperatures. Molybdenum must reduce the strength and increase the ductility, especially the low temperature ductility of the ferrite phase.

Impact values involve a combination of both strength and ductility. Figure 3 shows the results of Charpy V-notch impact tests at 300 K and 77 K. Room temperature impact values show a slight increase with increasing ferrite content up to $\sim$10% δ, and thereafter a decrease. At 77 K, there is little variation in impact values up to $\sim$10% δ, beyond which there is a decrease. Again samples #6, #13, and #14 are atypical. #6 and #14 are both low, the factors which reduce ductility lend to lower impact values. #13 has an exceptionally high room temperature impact value; in this instance the strengthening effect of the nitrogen has overcome the reduction in ductility. CF8M is seen to be generally superior to CF8. Also plotted in Fig. 3 is the ratio of the impact values at 77 K to 300 K. This shows a continuous decrease with increasing ferrite content, and is perhaps the best illustration of how the tendency to brittleness of the ferrite phase can influence the low temperature mechanical properties.

CONCLUSIONS

It is concluded that the low temperature ductility of cast duplex stainless steels can be reduced by high ferrite content, excessive amounts of nitrogen or strong carbide forming elements, and lack of heat treatment particularly at higher ferrite levels. While all samples investigated, with the exception of #14 (non-heat treated 12% δ), had mechanical properties more than adequate for the intended service, it was felt advisable to modify the specifications for the tube steels. The requirement is for CF8 as per ASTM specification number A743 with the following modifications: nitrogen content must not exceed 0.08%; niobium content must not exceed 0.1% and total of all carbide formers (Nb, Ti, V, W) must not exceed 0.2%; ferrite content of the casting, as determined from the heat chemistry using the DeLong diagram, must not exceed 10%. A743 already calls for suitable solution heat treatment.

REFERENCES

1. A. L. Schaeffler, Metal Progress 56, 180 (1949).

2. W. T. DeLong, Welding Journal Research Supplement 52, 281S (1973).

CHEMICAL COMPOSITION OF SPECIMENS

Sample Number	Chemical Composition (wt %)												Percent δ		
													Calculated		Measured
	C	Mn	P	S	Si	Cr	Mo	Ni	V	Cu	W	N	Schaeffler	DeLong	
STD ACI	.08 max	1.50 max	.04 max	.04 max	2.00 max	18-21		8-11							
1	.05	1.1	.04	.02	.36	18.0	0.7	11.0				.053	0	3.8	0
2	.04	1.0	.03	.02	.47	18.0	.07	13.0				.042	0	0	0
3	.04	1.0	.02	.02	.57	18.0	.19	12.0				.055	0	0	0
4	.02	1.0	.04	.04	.72	18.0	.10	11.0				.044	0	2.8	0
5	0.4	1.3	.03	.02	.99	20.0	.17	11.0				.038	5.0	10	3.7
6*	.06	..35	.039	.017	1.46	17.3		10.1				.033	4	3	1
7	.05	.37	.03	.02	1.12	18.6	.06	9.5	.05	.08	.01	.033	8	8.4	3.2
8	.05	1.07	.011	.009	1.21	19.38		10.				.009	8	10.8	8
9	.05	1.06	.014	.013	1.28	19.52		10.35				.024	8	12.5	9
10	.06	1.01	.013	.01	1.25	20.16		10.23				.019	9	11.6	11.5
11	.07	.74	.02	.02	1.57	20.10	.04	8.2	.03	.10	.08	.014	15	7.5	7.7
12	.06	.19	.02	.02	1.62	19.6	.08	8.4	.05	.08	.01	.049	18	15.3	14.5
13	.06	1.55	.02	.02	.47	18.7	<0.1	10.7				.122	0	0	0.4
14	.05	.689	.019	.017	.966	20.889	.106	8.476		.059		.085	18.3	14	12
15+	.06	.78	.03	.02	.93	21.2	2.22	10.4		.09	.007	.032	15	25.4	24

*Also contained 0.16% Nb.
+CF8M

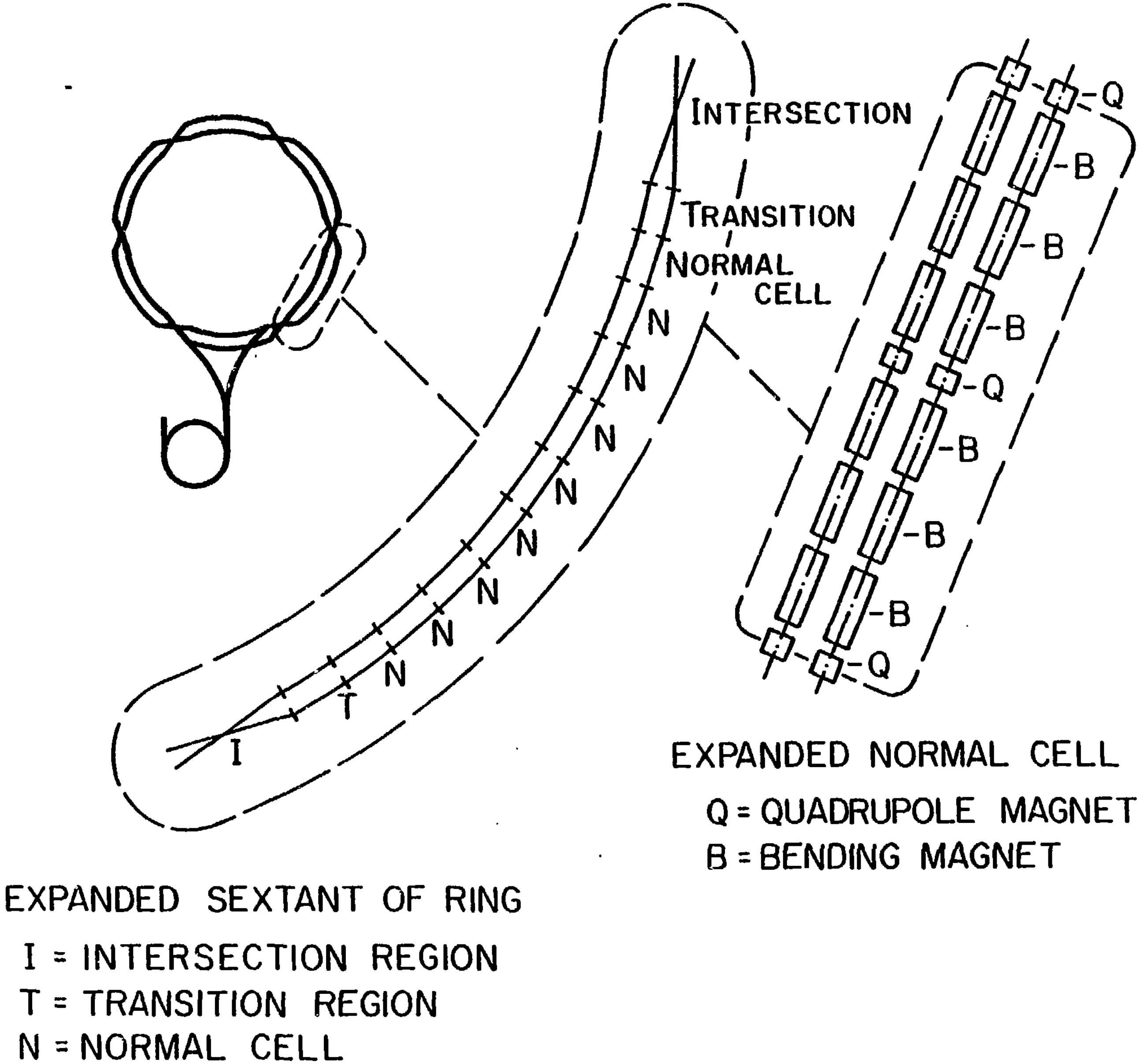

Figure 1. Schematic layout of beam line, one sextant of the ring, and disposition of magnets in normal cell, for ISABELLE.

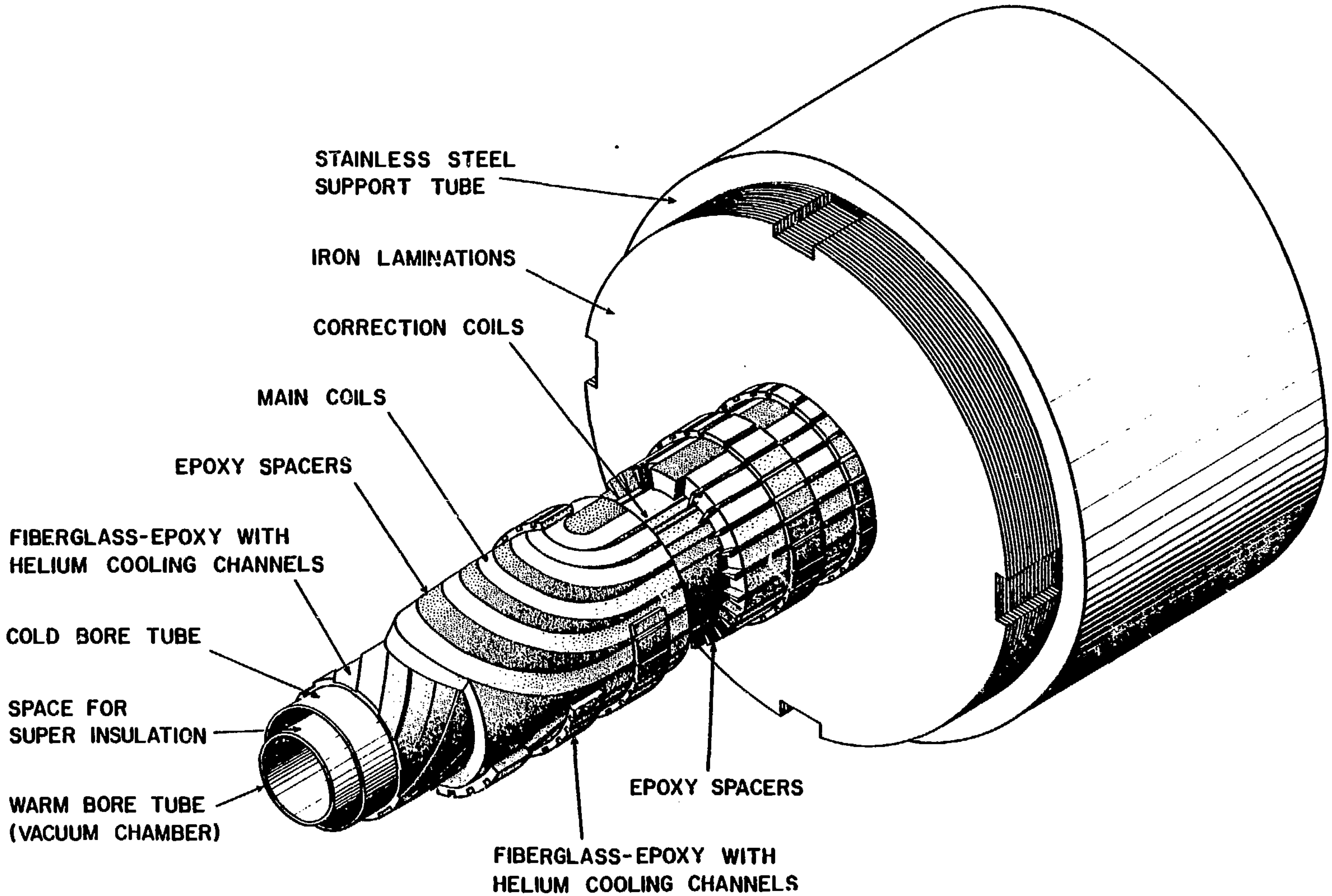

Figure 2. Detail of construction of a dipole magnet for ISABELLE.

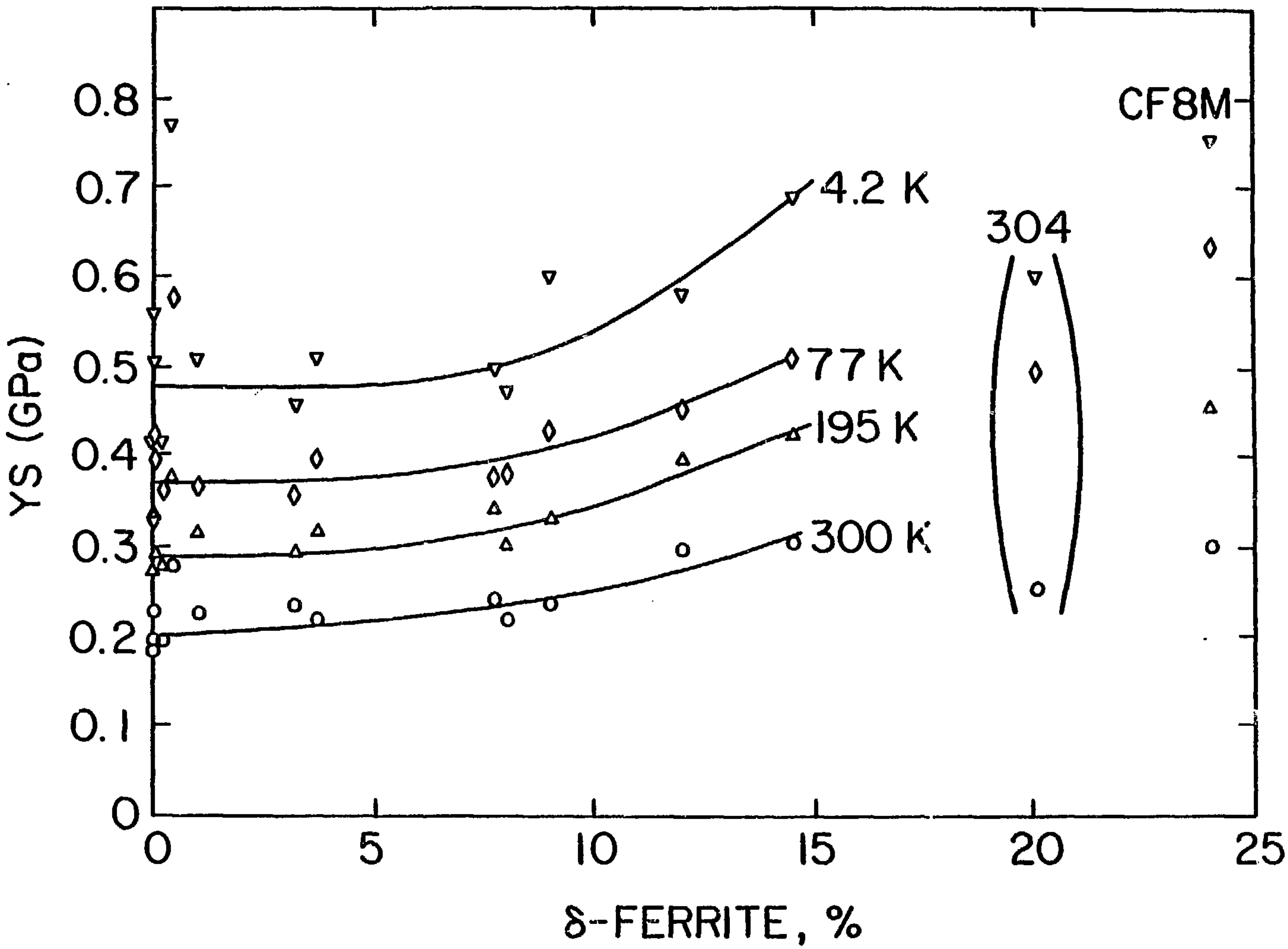

Figure 3. Yield strength versus δ-ferrite content for cast stainless steels at 300 K, 195 K, 77 K and 4.2 K.

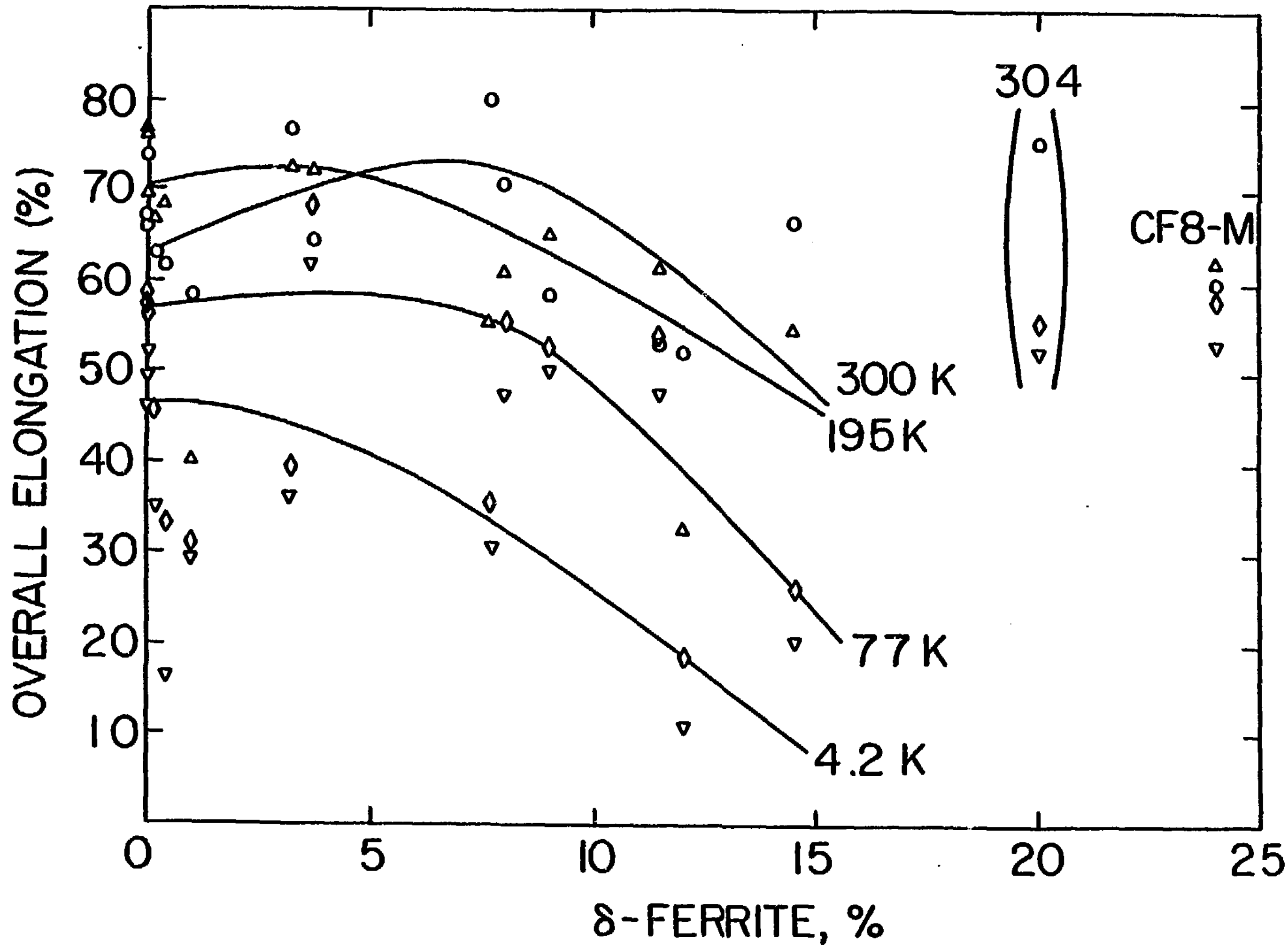

Figure 4. Ductility (% overall elongation) versus δ-ferrite content for cast stainless steels at 300 K, 195 K, 77 K and 4.2 K.

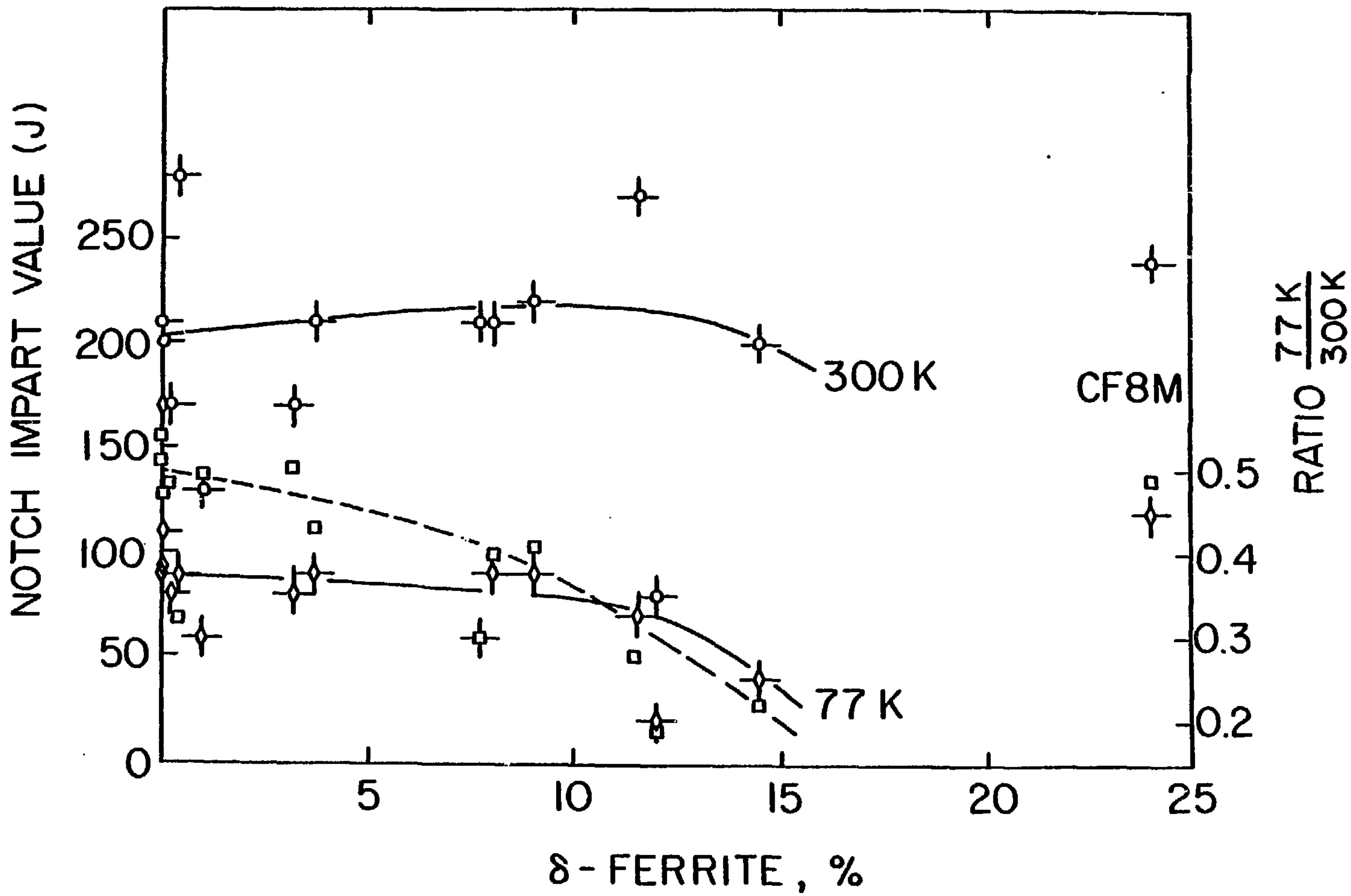

Figure 5. Charpy V-notch impact values versus δ-ferrite content for cast stainless steels at 300 K and 77 K.