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SUMMARY

Of major technical and cost impact to Magnetic Fusion Energy development are the materials for the magnet structure. Likened to gas pressure, the magnetic field lines try to expand the structure with equivalent pressures up to 1000 atm. Not only are large tensile forces produced, but significant bending forces may also be present. To withstand these forces in the restricted spaces available, materials of exceptional strength and toughness are required. In this regard, the low-temperature environment of superconducting magnets can be an advantage because many materials exhibit enhanced properties at reduced temperatures.

Those materials and fabrication techniques that are attractive to fusion magnets are discussed and relative comparisons made. Considerations such as strength, toughness, and joining techniques are balanced against recommended design criteria to reach an optimum design. Several examples of material selection are cited for large fusion magnets such as Baseball II, the Mirror Fusion Test Facility, the Toroidal Fusion Test Facility, and the Large Coil Project.

1. INTRODUCTION

The technical and economic viability of magnetic fusion energy is greatly dependent upon the manufacture of large, high-field superconducting magnets for plasma confinement. A few such magnets like Baseball-II at Lawrence Livermore Laboratory (LLL) [1] and IMP at Oak Ridge National Laboratory (ORNL) [2] were constructed in the early 1970's. However, size must be greatly expanded and field strength increased on the path to fusion power. For example, consider that the Mirror Fusion Test Facility (MFTF) magnet [3] will weigh 700 tons, its predecessor Baseball-II only 15 tons. At the same time, the field will increase from 6 T to 7.8 T. In the future, further expansion in size is envisioned with field strengths exceeding 12 T [4]. Tokamak magnets must grow from the 1-m bore, 4-T performance of the Russian T-7 to 10-m bores and perhaps 12 T for an Experimental Power Reactor [5].

Almost half the cost and technical difficulty of a large magnet is associated with its force-restraining structure. Magnetic field contours can be thought of as pressure surfaces with 12 T corresponding to a pressure of 570 atm; the usual design pressure for steam boilers is 200 atm. While pure tension geometries are possible for both tokamaks [6] and mirrors [7], inevitably practical manufacturing and fault considerations cause bending stresses to be present as well.

No code or standard guidance exists for the design of magnet structures. Instead, one usually resorts to following a portion of various codes like Secs. III or VIII of the ASME Boiler and Pressure Vessel Code or depends upon one's own intuitions and calculations. However, it is easy to show that blind obedience to existing codes can result in either excessively heavy or dangerously fracture-prone structures. For example, paragraph UA-500 of the ASME code recommends that the lower 1/4 of the tensile strength or 5/8 of the yield strength be used for design. For some stainless steels like 304, the resulting design stress would be limited by yield strength and be excessively conservative, considering the very high tensile strength and toughness at low temperature. For other materials, the Charpy impact tests at 77 K are not at all representative of the toughness and crack growth properties at 4 K, so that insufficient fracture resistance might result.

While it is premature to adopt a code, Table I summarizes our recommendations for the design of superconducting magnet structures. The criterion that results in the lowest stress should be used. Note that the percents of yield and tensile strength are higher than those recommended in UA-500 for two reasons: sophisticated electromagnetic computer codes can resolve the forces on magnetic structures, and the environment is benign and noncorrosive. More restrictive, however, is the design stress dependence upon fracture mechanics at 4.2 K due to the tendency of materials to embrittle at low temperature in a neutron flux. Here, the plane-strain constant, K_{IC}, must be known and be compatible with the permissible flow size, a. More difficult to obtain is the crack growth rate, da/dn, but such data are critical during cyclic loading conditions. Linear elastic fracture codes like FLAGRO-II can be used to predict cyclic life with crack growth data from compact fracture specimens [8].

To withstand the magnetic forces in the cryogenic and nuclear environment, unusual structural material selection criteria must be satisfied. Because of limited space for structure, the material must have both high yield and tensile strength in liquid helium at 4.2 K. It must also have a high elastic modulus and a compatible thermal expansion coefficient to keep from overstraining the superconductor. The material must be tough and have a low fatigue-crack growth rate so that critical flaw sizes will not be exceeded, causing brittle fracture. It should be relatively inexpensive, easily machined, and weldable without post-weld heat treatments. Table II summarizes such desirable material properties.

Austenitic stainless steels (Table III) are the most widely used structural materials in superconducting magnets. These materials show useful combinations of toughness, stiffness, and strength at 4 K. High construction costs and the need for careful composition control to ensure microstructure stability under operational conditions are the principal drawbacks.

2. MICROSTRUCTURAL STABILITY

Materials for construction of superconducting magnets must resist microstructural transformations during fabrication and service, since such transformations involve formation of brittle phases, produce volume changes and/or dimensional distortions, create localized high residual stresses, and cause the development of significant ferromagnetic behavior in previously paramagnetic materials. Many austenite stainless steels are neither fully austenitic nor fully paramagnetic after welding and/or cold-forming followed by exposure to 4 K. Three phases which can form the problems mentioned above are δ ferrite, ε martensite, and α' martensite. Both the δ ferrite and α' martensite are ferromagnetic [9], and the presence of increasing amounts of δ ferrite degrades the 4 K fracture toughness (Fig. 1).

3. MECHANICAL PROPERTIES

An exhaustive analysis of the cryogenic mechanical properties of austenitic stainless steels is beyond the scope of the paper, and the reader is referred to a recent review paper [10]. For comparison of material strength versus fracture resistance, a plot of 4 K plane-strain fracture toughness K_{IC} versus yield strength σ_y (Fig. 2) is invaluable.

All the K_{IC} values are conversions from the values determined by the elastic-plastic J-integral test [11]. Note that the relatively weak (σ_y < 100 ksi) but tough (K_{IC} > 250 ksi $\sqrt{in.}$) compositions are those with less than about 0.05% N_2 and carbon levels below 0.03% [12-15]. For intermediate yield strength in the range 100-150 ksi, with fracture toughness in the range 180-250 ksi $\sqrt{in.}$, additions of N_2 to the 304L and 316L bases, in the amounts of 0.10-0.16% raise σ_y [14-15] as well as stabilize the austenite against both thermal- and strain-induced martensite formation [9]. Type 304LN is being used as the structural material for the General Dynamics-Convair large coil and the Lawrence Livermore Laboratory MFTF magnet case, and type 316LN is being used for the General Electric Company's large coil structure.

The low carbon content (C < 0.03%) L grades are used to minimize grain-boundary carbide precipitation during welding thermal cycles, or "sensitization," and the resulting loss in toughness. Sensitization of 310S steel results in a 38% loss in fracture toughness with no change in yield strength (Fig. 2) [15].

For yield strengths above 150 ksi, it has been found that it is difficult to procure 304L or 316L bases with the necessary nitrogen levels of 0.15-0.20% from domestic steel suppliers, due to problems including production of pore-free ingots at high N_2 contents and embrittlement of ingots and blooms by grain-boundary precipitation of Cr_2N during solidification and hot working [16]. Hence, for yield strengths beyond 150 ksi, Cr-Mn-Ni-N_2 austenitic stainless steels are available, wherein increased levels of Mn are used to increase N_2 solubility and raise the 4 K yield-strength to levels in excess of 200 ksi. Unfortunately, some of these materials suffer decreases in fracture toughness at 4 K to levels below 100 ksi $\sqrt{\text{in.}}$ As discussed by Read and Reed [17] for the Nitronic 50 alloy, this loss of toughness is associated with incomplete solution of a grain-boundary phase.

Improper melting practices and/or thermomechanical processing [18] have been thought to cause similar behavior in the Nitronic 40 alloy. In addition to these problems, the unavailability of welding consumables with matching 4 K yield strengths and adequate fracture toughness has lessened further consideration of these materials for fusion magnet structures at this time.

4. WELDING-RELATED ISSUES

Austenitic stainless steels with 4 K yield strengths less than 140 ksi, are readily weldable for 4 K service by all the common welding methods if appropriate procedures and welding consumables are used. Table IV summarizes composition ranges of commonly used filler materials. As shown in Fig. 3, which is a plot of K_{IC} as a function of σ_y for stainless-steel weld metals deposited by the common welding practices [15,19], the usual inverse relationship between K_{IC} and σ_y prevails. For a given yield-strength level, say 120 ksi, the attainable range of K_{IC} values is about 60-120 ksi $\sqrt{\text{in.}}$ or about 25-50% of the base metal value. This severe reduction in weld-metal fracture toughness is attributed to the presence of appreciable (above 4%) amounts of δ-ferrite present to prevent hot-cracking, and the embrittling effects of nitrogen entering the molten weld metal [20]. For some of the high-deposition-rate welding processes such as flux-cored metal-arc welding, K_{IC} is reduced to low-enough levels to obtain linear-elastic behavior in the weld-joint [21]. Present U.S. practice in welding stainless steels for magnet structures intended for 4 K operation involves the use of shielded metal-arc welding, with either 316L or 308L filler metal and the "-15" or lime electrode coating. Evaluation of ferrite-free welding consumables such as the Avesta [22] or of Sanvik [23] products such as 2RM69 is just beginning.

5. SUMMARY COMMENTS

1. The development of austenitic stainless-steel welding consumables that meet simultaneous stringent requirements of high strength, toughness, freedom from hot cracking, and low magnetic permeability when deposited by high-deposition-rate welding processes is a prerequisite to economic fabrication of high-performance austenitic stainless-steel structures with high reliability for 4 K service. Whether this is achievable through control of ferrite content in the weld metal or use of special ferrite-free welding consumables is not known at this time.

2. The rapid advances in material requirements for 4 K service may be appreciated by a comparison of the "goals of an alloy development program" as stated by one of the present authors 2-1/2 years ago [24], with some of the minimum properties of the type 304LN stainless steel being used in the MFTF magnet case at this time.

1977 "Goals"		MFTF Case Requirements
100 ksi	Yield strength	120 ksi
50 ksi $\sqrt{\text{in.}}$	K_{IC}	120 ksi $\sqrt{\text{in.}}$

6. ACKNOWLEDGMENTS

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TABLE I. Recommended design factors for superconducting magnet structures.[a]

Design stress $< 2/3$ yield (primarily tension and combined)

Design stress $< 90\%$ yield (primarily bending)

Design stress $< 1/3$ tensile

Design stress $< 1/2\ K_{IC}/\sqrt{\pi a}$

Design stress cycles < 4 lifetimes

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[a] The lowest stress value should be used.

TABLE II. Desirable material properties.

Yield strength > 100 ksi
Tensile strength > 200 ksi
$K_{IC} \geq 100$ ksi $\sqrt{\text{in.}}$
Charpy lateral expansion > 0.015 in.
Charpy impact energy > 25 ft-lb
Thermal contraction = 0.3%
Elastic modulus > 30×10^6 psi
Magnetic permeability < 1.2

TABLE III. Composition of Austenitic Stainless Steels for Liquid Helium Service.
Composition (%)[a]

Type	C	N	P	S	Si	Cr	Ni	Mo	Mn	Other
AISI 304	0.08	0.10	0.045	0.03	1.0	18-20	8-10.5	b	2.0	
304L	0.03	0.10	0.045	0.03	1.0	18-20	8-12	b	3.0	
304LN	0.03	0.10-0.16	0.070	0.015	1.0	18-20	9-12	b	2.0	P+S: 0.03 MAX
304N	0.08	0.10-0.16	0.045	0.03	1.0	18-20	8-12	b	2.0	
316	0.08	0.10	0.045	0.03	1.0	16-18	10-14	2-3	2.0	
316LN	0.03	0.10-0.16	0.045	0.03	1.0	16-18	10-14	2-3	2.0	
Nitronic 33	0.08	0.20-0.40	0.060	0.03	1.0	17-19	2.75-3.75	b	16.5-14.5	
40	0.04	0.15-0.40	0.060	0.03	1.0	19-21.5	5.5-7.5		8-10	
50	0.06	0.10-0.40	0.040	0.03	1.0	20.5-23.5	11.5-13.5	1.5-3.0	4-6	Cb: 0.1-0.3 V: 0.1-0.3
Kromarc 58	0.02-0.08	0.14-0.20	b	b	12-5	14-17	18-24	1.75-2.75	8-13	V: 0.12-0.24

[a] Maximum unless range is given

[b] Not stated

TABLE IV. Compositions of austenitic stainless steel welding consumables for liquid helium service.

	Composition (%)[a]			
	Cr	Ni	C	Other
AWS type covered electrodes[b]				
E308	18-21	9-11	0.08	
E308L	18-21	9-11	0.04	
E310	25-28	20-22.5	0.20	0.75 Si
E16-8-2	14.5-16.5	7.5-9.5	0.10	0.50 Si
E316	17-20	11-14	0.08	2-2.5 Mo
E316L	17-20	11-14	0.04	2-2.5 Mo
AWS type rod and bare electrodes[c]				
LN 308	19.5-22	9-11	0.08	
LN 308L	19.5-22	9-11	0.03	
LN 310	25-28	20-22.5	0.08-0.15	
LN 316	18-20	11-14	0.08	2-3 Mo
LN 316L	18-20	11-14	0.03	2-3 Mo

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[a] Maximum unless range is given.

[b] Covered electrodes: S: .03, P: .04, Si: .9, Mn: 2.5.

[c] Rod and bare electrodes: Mn: 1-2.5, Si: .25-.60, P: .03, S: .03.

Figure captions

Figure 1. Effect of increasing ferrite content on liquid-helium plane-strain fracture toughness of shielded metal arc welds using type 316 weld metal.

Figure 2. Liquid-helium plane-strain fracture toughness as a function of 0.2% yield strength for conventional Cr-Ni, Cr-Mn-Ni-N_2, and Cr-Ni-N_2 austenitic stainless steels.

Figure 3. Liquid-helium plane-strain fracture toughness as a function of 0.2% offset yield strength for weld metals in austenitic stainless-steel weldments.

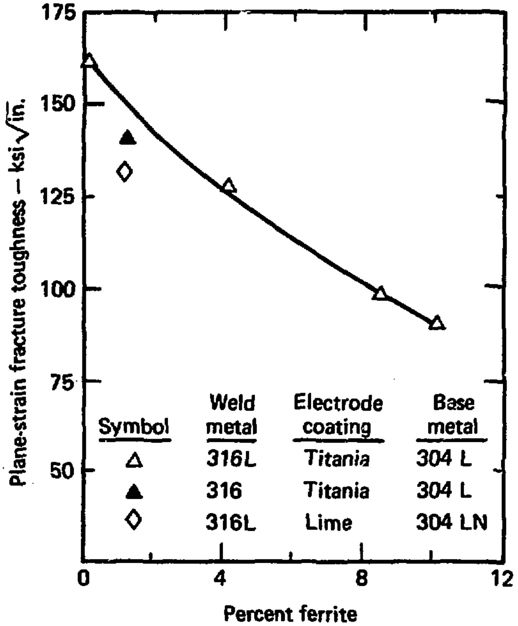
175
150
125
100
75
50
0
4
8
12
Plane-strain fracture toughness – ksi·√in.
Percent ferrite
Symbol
Weld metal
Electrode coating
Base metal
△ 316L Titania 304 L
▲ 316 Titania 304 L
◇ 316L Lime 304 LN

Figure 1

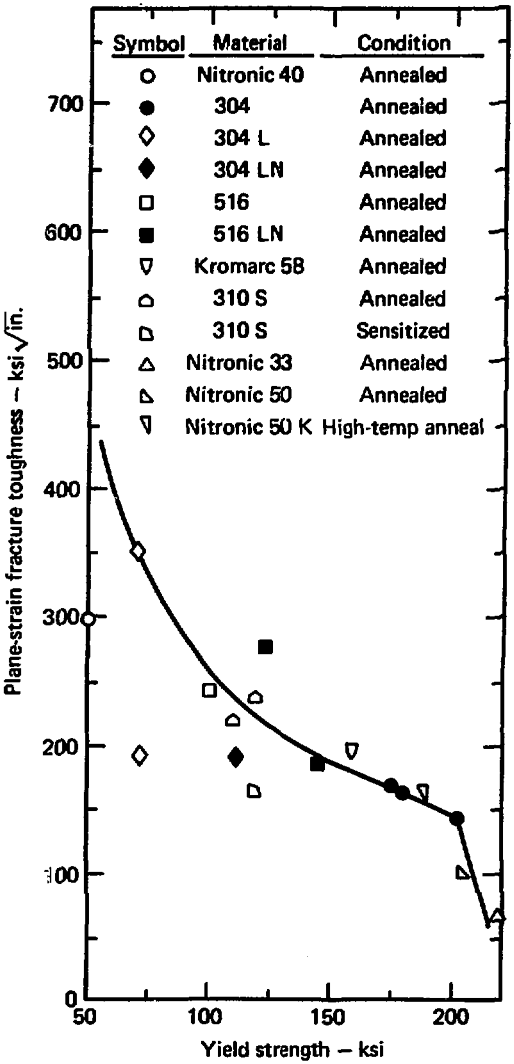
Symbol
Material
Condition
○ Nitronic 40 Annealed
● 304 Annealed
◇ 304 L Annealed
◆ 304 LN Annealed
□ 516 Annealed
■ 516 LN Annealed
▽ Kromarc 58 Annealed
⌂ 310 S Annealed
310 S Sensitized
△ Nitronic 33 Annealed
Nitronic 50 Annealed
Nitronic 50 K High-temp anneal
700
600
500
400
300
200
100
0
50
100
150
200
Plane-strain fracture toughness — ksi √in.
Yield strength — ksi

Figure 2

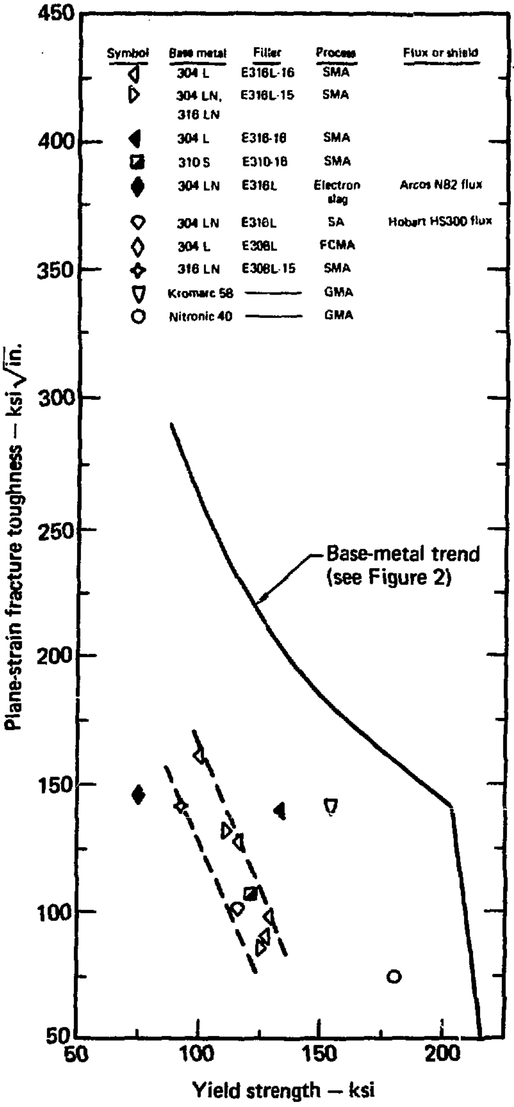
Symbol | Base metal | Filler | Process | Flux or shield
◁ 304 L E316L-16 SMA
▷ 304 LN, 316 LN E316L-15 SMA
◀ 304 L E316-16 SMA
▨ 310 S E310-16 SMA
◆ 304 LN E316L Electron slag Arcos NB2 flux
♢ 304 LN E316L SA Hobart HS300 flux
◇ 304 L E308L FCMA
✧ 316 LN E308L-15 SMA
▽ Kromarc 58 —— GMA
○ Nitronic 40 —— GMA
Base-metal trend (see Figure 2)
Plane-strain fracture toughness — ksi $\sqrt{\text{in.}}$
Yield strength — ksi
450
400
350
300
250
200
150
100
50
50
100
150
200

Figure 3