STRUCTURAL ALLOYS FOR SUPERCONDUCTING MAGNETS IN FUSION ENERGY SYSTEMS

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SUMMARY

The behavior of selected alloys for superconducting magnet structures in fusion energy systems is discussed with emphasis on the following austenitic stainless steels (AISI grades 304, 310S and 316), nitrogen-strengthened austenitic stainless steels (types 304LN, 316LN and 21Cr-6Ni-9Mn) and aluminum alloys (grades 5083, 6061 and 2219). The mechanical and physical properties of the selected alloys at 4K are summarized. The available information suggests that there are enough experimental data and fabrication experience to provide reasonable assurance that the alloys have sufficient strength, ductility and toughness in the liquid helium environment; that the alloys can be fabricated into support structures for superconducting magnets; and finally, that the fabricated structure will retain adequate properties during operation of the fusion energy device. It should be realized, however, that the depth of understanding, the degree of characterization, and the extent of related experience for these alloys in the fusion-magnet environment are extremely limited. More work is needed on material behavior at 4K, particularly in the areas of material variability, processing effects on properties, and the fabrication and mechanical behavior of large, complex, thick-section components.

Key Words: Aluminum alloys, cryogenics, elastic properties, fabrication, fatigue, fracture, fusion energy, stainless steel, superconducting magnets, tensile properties, thermal properties, welding.

1. Introduction

Alloys will be used for the main structural members of the superconducting magnet systems needed for fusion devices. Designs of tokamak and mirror machines that require superconducting magnets are currently in the conceptual stage (except for the Magnetic Fusion Test Facility), but many design features that strongly influence materials selection are reasonably well established. The principal features governing alloy selection for structural applications are the enormous size and stored energy of the magnet systems, the extremely high forces exerted by the magnets, the massive structural elements needed to restrain these forces, the limited space available for the structure, and the need for accessibility to install and periodically remove the blanket and shield systems--systems that are completely surrounded by magnets and the support structure. These features result in the need for alloys with sufficient strength and stiffness to perform the required structural functions within the space available, sufficient fatigue and fracture resistance to operate safely, and sufficient fabricability to permit manufacture and assembly of the components. The choice of materials is further restricted by exposure to low temperatures and high magnetic fields and by considerations related to experience, cost and availability. Currently, the leading candidates are the austenitic stainless steels and aluminum alloys. In this paper, the properties of the alloys considered most suitable for liquid helium applications are presented with emphasis on their properties at 4K. This paper is a summary of a forthcoming review on the same subject [1].

2. Annealed Austenitic Stainless Steels

Austenitic chromium-nickel stainless steels, including the nitrogen-strengthened grades discussed in more detail in Section 3, are the most widely proposed alloys for structural applications in superconducting magnet systems. These steels have the best combination of strength, stiffness and toughness at 4K. The physical properties also offer advantages over competing materials. Specifically, the modulus is high, the thermal expansion is close to that of the copper-stabilized conductor, magnetic permeability is low, and the electrical and thermal conductivities are low. The principal disadvantages are the high cost of construction and problems arising from microstructural stability and control.

The American Iron and Steel Institute (AISI) designation of the most promising grades are 304, 304L, 310S, 316 and 316L. These alloys can be compared with respect to AISI-304, the basic 19Cr-9Ni stainless steel. AISI 316 contains 2-3% Mo and slightly higher nickel and thus has greater austenite stability than AISI 304. AISI 304L and 316L are low-carbon modifications of 304 and 316 respectively; low carbon is desirable to avoid sensitization, the grain boundary precipitation of Cr-carbides. Type 310S is a 25Cr-20Ni alloy that has lower carbon (0.08%C) than AISI 310 (0.25%C). The high alloy content provides austenite stability and greater strength, and thus 310S is useful where dimensional stability, nonmagnetic behavior and higher strength are desirable.

The austenitic stainless steels, with and without nitrogen strengthening, are readily weldable by all of the common welding processes, providing the appropriate consumables and procedures are used. The strength of stainless steel welds at 4K generally exceeds the corresponding base metal strength, but toughness is usually significantly lower. Three phenomena that affect the strength and toughness of the as-deposited weld metal take on added significance at cryogenic temperatures: sensitization, ferrite content, and nitrogen

pickup. Toughness is improved by using low-carbon filler metals to avoid sensitization, by balancing weld metal chemistry to avoid ferrite, and by using low-nitrogen consumables and welding practices.

2.1 Tensile Properties The yield and ultimate strengths of AISI grades 304, 310 and 316 are compared in Figure 1 for temperatures ranging from 4 to 300K. Notice that type 304 has the lowest yield strength and the highest ultimate strength at all temperatures. This is due in part to the martensite transformation which occurs more readily in 304 than in 316 or 310. Since the transformation is strain induced, the yield strength is not significantly influenced by martensite, but the ultimate strength is increased. Type 304 exhibits a slightly greater increase in strength than type 304L as temperature is reduced. The loss of strength associated with reduced carbon content is considered to be characteristic of all the stainless steels. The ductility of the annealed 300-series stainless steels is generally excellent at cryogenic temperatures. Elongation and reduction-of-area tend to drop with decreasing temperatures, but values generally exceed 30%.

2.2 Toughness The austenitic stainless steels retain excellent toughness at cryogenic temperatures. The Charpy V-notch impact toughness does decrease with temperature; but in all cases known to the authors, the toughness far exceeds the 0.38mm lateral expansion requirement of the ASME Boiler and Pressure Vessel Code, and a ductile-to-brittle transition is not exhibited. The minimum temperature for Charpy testing is about 20K, because adiabatic heating causes specimen temperatures in excess of 20K even when the test temperature is 4K. Slow-strain-rate tests using notched tensile specimens indicate that notch sensitivity does not develop at 4K.

Tobler [2] used J-integral methods to measure the fracture toughness of AISI grades 310 and 316 at temperatures to 4K. The toughness, $K_{Ic}(J)$, at 4K is $230 \text{ MPa}\sqrt{\text{m}}$ for 310S and $460 \text{ MPa}\sqrt{\text{m}}$ for 316, and in both alloys the toughness at 4K exceeds the toughness at room temperature. The ratio of toughness to yield strength is sufficiently high to assure gross ductile deformation prior to fracture.

2.3 Fatigue Strain-cycling fatigue properties at 300, 76 and 4K have been measured for AISI grades 304L and 310 by Nachtigall [3], and for grades 304L and 316 by Shepic and Schwartzberg [4]. The fatigue resistance of 310 and 316 was superior to that of 304L, particularly in low-cycle fatigue (less than 10^4 cycles). For each alloy, the fatigue resistance at low temperatures is superior to the fatigue resistance at room temperature except at the highest strain ranges where failure occurred in less than 1000 cycles.

The fatigue crack growth behavior of AISI grades 304, 304L, 310S and 316 has been determined at 295, 76 and 4K by Tobler and Reed [5]. The growth rates at 76 and 4K are essentially the same and slower than those at room temperature. The best-fit lines through the 304L data at 295K and at 76 and 4K form the approximate scatter bands for the data on 304, 310S and 316 at 295, 76 and 4K. Thus, it can be concluded that alloy content and temperature have minimal influence on the fatigue crack growth behavior of the 300-series stainless steels with nitrogen contents less than 0.08%.

3. Annealed Nitrogen-Strengthened Austenitic Stainless Steels

Nitrogen has a pronounced effect on the yield strength of austenitic stainless steels, particularly at cryogenic temperatures. For example, the yield strength of 304N (AISI 304 with deliberate additions of nitrogen) is approximately three times greater than the yield

strength of 304 at 76K, the ultimate strengths are approximately equal, and the elongation of the 304N is superior at temperatures below 220K [6]. This remarkable improvement in mechanical properties occurs in many nitrogen-strengthened grades. Consequently, significant interest is developing in these alloys for future applications in superconducting magnet systems. The nitrogen-strengthened stainless steels have essentially the same fabrication characteristics and physical properties as the conventional grades.

Two basic types of nitrogen-strengthened stainless steels are suitable for cryogenic service: the Cr-Ni-N and the Cr-Ni-Mn-N alloys. The Cr-Ni-N alloys are 300-series stainless steels with deliberate additions of nitrogen. In the U.S. specifications, the nitrogen range is 0.10 to 0.16% for 304N and 316N. The corresponding European specifications permit nitrogen levels to 0.25%. The manganese in Cr-Ni-Mn-N alloys provides austenite stability and can thus be used to replace part of the Ni content. Manganese also increases the solubility of nitrogen in austenite and thus permits higher nitrogen levels--0.4% maximum nitrogen is typical.

3.1 Tensile Properties The yield and ultimate strengths of the Cr-Ni-N 300-series stainless steels are summarized in Figure 2. The solid lines and the broken lines represent the data of Randak et al. [7] for 304LN and 316LN, respectively. The various symbols depict the data for seven other investigations [1], each on one of the following alloys: 304LN, 304N and 316LN. As is the case for 304 and 316 (Figure 1) alloys 304N and 304LN have approximately 20% greater ultimate strength at cryogenic temperatures than alloy 316LN. All three alloys have essentially the same yield strength at and below room temperature. There is relatively little scatter in the yield strength data considering that data on 17 heats from a variety of sources are plotted. The nitrogen contents of the 17 heats range from 0.09 to 0.17%.

Of the nitrogen-strengthened Cr-Ni-Mn stainless steels, the 21Cr-6Ni-9Mn alloy has been most thoroughly evaluated [8]. This alloy typically has about 25% greater yield strength than the Cr-Ni-N alloys. Representative tensile data on the other nitrogen-strengthened Cr-Ni-Mn alloys that have been tested at 4K indicate that yield strength increases and ductility decreases with decreasing temperature; and thus, fracture resistance must be considered when selecting these alloys for liquid helium service.

3.2 Toughness The nitrogen-strengthened stainless steels have excellent toughness at room temperature. However, significant toughness losses generally occur as the temperature is reduced [9]. Read and Reed [9] observed significant variations in the toughness of a single piece of 21Cr-12Ni-5Mn alloy. As-received, mill-annealed material having an intergranular micro-constituent had a plane strain fracture toughness at 4K at $111 \text{ MPa}\sqrt{\text{m}}$. A high temperature (1177 C, 1.5 h) anneal dissolved the microconstituent and increased the toughness to $176 \text{ MPa}\sqrt{\text{m}}$. Thus, certain nitrogen-strengthened grades can be used at 4K, but care should be taken to assure that the alloy selected has satisfactory toughness at 4K for the applicable melting practice, product form and heat treatment.

3.3 Fatigue The strain cycling fatigue behavior of 21Cr-6Ni-9Mn has been measured at 295, 76 and 4K by Shepic and Schwartzberg [4]. The results at 4K indicate that the 21Cr-6Ni-9Mn alloy has fatigue strength better than 304L but not as good as 316. Thus, the significantly higher strength of the nitrogen-strengthened grade does not result in a comparable improvement in fatigue life.

The fatigue crack growth behavior of several nitrogen-strengthened grades has been studied at cryogenic temperatures [8,9]. The results for the high nitrogen Cr-Ni-Mn alloys depend largely on the relative austenite stability of the alloys. For the least stable alloy evaluated, 18Cr-3Ni-13Mn, the fatigue crack growth rates at 4K are 50 times faster than those for the most stable alloy evaluated, 21Cr-12Ni-5Mn, and 10 times faster than the growth rates for 21Cr-6Ni-9Mn. For the 21Cr-12Ni-5Mn alloy, the fatigue crack growth rates fall within the same scatter band as the 300-series ($N < 0.08\%$) alloys at 4K. For the Cr-Ni alloys, comparison of 304 and 304L with 304N and 304LN shows that the nitrogen-strengthened alloys have growth rates at 4K about 4 to 5 times higher than the lower nitrogen grades. In contrast, the 316 alloy, which has greater austenite stability than 304, has essentially the same growth rates at 4K as the 316LN alloy.

4. Aluminum Alloys

Aluminum alloys have been proposed for many structural applications in fusion magnet systems. Their principal advantages are: low as-fabricated cost, light weight, nonmagnetic behavior, stable microstructure, and good retention of strength and toughness at cryogenic temperatures. The main disadvantages of aluminum alloys are low strength in weldments, high electrical and thermal conductivity, and an unfavorable elastic modulus (too low) and thermal expansion (too high) for many applications.

For fusion magnet structures, the preferred aluminum alloys are 5083, 2219 and 6061. Alloy 5083 (Al-4.5Mg) is generally used in the annealed condition and has a typical yield strength of 171 MPa (25 ksi) at 4K. Alloy 2219 (Al-6.3Cu) is generally used in a heat-treated condition, and in the T-851 temper has a typical yield strength of 482 MPa (70 ksi) at 4K. Alloy 6061 (Al-1Mg-0.6Si) is usually used in the heat-treated condition, and in the T-6 temper has a typical yield strength of 380 MPa (55 ksi) at 4K. Each of these alloys is readily weldable by the gas metal arc and gas tungsten arc processes. However, only 5083 retains full strength in the welded condition and is the best choice for most large welded components. Alloy 2219 has the highest strength of the three alloys and is recommended for bolted construction where space or weight need to be conserved. Physical properties of the aluminum alloys are summarized in Table 2.

4.1 Tensile Properties The mechanical properties of alloys 5083, 6061 and 2219 at room temperature and 4K have been determined by Kaufman, Nelson and Wanderer [10]. In all cases the tensile strengths and, to a lesser extent, the yield strengths are superior at 4K, and the ductility values are not significantly changed. The alloys retain good notched-tensile properties at 4K.

Aluminum alloys having a wide range of strength levels are suitable for liquid helium applications. The yield strengths of commercially pure (CP) aluminum (types 1100-0 and 1099-H14) and the preferred alloys are shown as a function of temperature in Figure 3. The yield strengths of each alloy gradually increase with decreasing temperature. Strength increases in the following order: annealed CP (1100-0), cold-worked CP (1099-H14), solution-strengthened Al-Mg alloy (5083-0), cold-worked Al-Mg alloy (5083-H321), precipitation-hardened Al-Mg-Si alloy (6061-T651), and precipitation-hardened Al-Cu alloy (2219-T851). Still higher yield strengths are available in several other alloys including 2014-T651, 2024-T851 and 7005-T5351.

4.2 Toughness Aluminum alloys generally retain excellent toughness at cryogenic temperatures. A useful measure of aluminum alloy toughness at 4K is the notch-yield ratio, i.e., the ratio of notched tensile strength to unnotched yield strength [10]. Ratios substantially greater than one, say 1.5, indicate that the alloys retain the ability to plastically deform and resist crack initiation in the presence of sharp stress concentrations. The 5083 and 6061 alloys have notch-yield ratios greater than 1.6, and the higher-strength 2219-T851 and T87 alloys have notch-yield ratios of about 1.4. Significantly lower ratios (1.0 to 1.25) occur in other high-strength alloys such as 2014-T651 and 2024-T851 and in most 7000-series alloys (7005 is an exception), where the ratio is sometimes below 0.4 at cryogenic temperatures.

Limited toughness test data are available on aluminum alloys at 4K. Tobler and Reed [11] measured the fracture toughness of 5083-0 (4.3 cm thick plate) using J-integral procedures and found that toughness increased with decreasing temperature. The $K_{IC}(J)$ was 47 $MPa\sqrt{m}$ at 4K in the transverse (TL) orientation. Shepic [12] measured the toughness of 2219-T87 (3.8 cm thick plate) using ASTM E399 plane strain fracture toughness testing procedures. The K_{IC} for 2219-T87 at 4K was 45.5 $MPa\sqrt{m}$ in the transverse (TL), 47.7 $MPa\sqrt{m}$ in the longitudinal (LT), and 28.6 $MPa\sqrt{m}$ in the through-thickness (SL) orientations.

4.3 Fatigue Strain-cycling fatigue tests have been conducted by Nachtigall [3] on 2219-T851 and 2014-T6 alloys at room temperature, 77K and 4K. For a given strain level, the fatigue lives of both alloys were greater at 4K than at the higher temperatures for endurance greater than about 500 cycles.

The fatigue crack growth behavior of 5083-0 [11], 2219-T87 [12] and an Al-6Mg [13] alloy have been determined at 4K. In each case, the results indicate that the growth rates at 4K are slower than the rates at room temperature.

5. Alternative Alloys

Alternative alloy systems do not provide candidate structural materials for superconducting magnets in fusion energy systems. Consider the following systems:

Nickel-base alloys are ferromagnetic, expensive and frequently difficult to fabricate. However, many of these alloys have excellent combinations of strength and toughness at 4K and may be suitable for special applications [14].

Titanium alloys are brittle at 4K, expensive and difficult to fabricate [15].

Cobalt-base superalloys transmute to long half-life reaction products and are expensive and difficult to fabricate.

Carbon and alloy steels including the ferritic and martensitic stainless steels are ferromagnetic and brittle at 4K. Even the cryogenic nickel steels are brittle at 4K [16] except for a specially processed 12Ni alloy [17].

Copper alloys are acceptable, but generally not competitive with the austenitic stainless steels or aluminum alloys.

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Table 1. Physical Properties of Austenitic Stainless Steels [1]

Property	Units	AISI 304		AISI 310		AISI 316	
		295K	4K	295K	4K	295K	4K
Density	g/cm^3	7.9	---	7.9		8.0	
Young's Modulus	GN/m^2	189	204	184	199	217	234
Shear Modulus	GN/m^2	740	800	700	770	830	910
Poisson's Ratio	---	.290	.271	.307	.296	.298	.281
Thermal Conductivity	W/m.K	13	0.3	Nearly the same for 304, 310 and 316			
Expansion	$\text{cm/cm/K}^{-1} \times 10^{-6}$	15.8	10.2	Nearly the same for 304, 310 and 316			
Specific Heat	J/kg.K	480	0.5	Nearly the same for 304, 310 and 316			
Electrical Resistivity	$\mu \Omega \text{ cm}$	70.4	49.6	87.3	68.5	75.0	53.9
Magnetic Permeability (Initial)		1.02	1.09	1.003	1.10	1.003	1.02

1. Tensile and yield strengths of three austenitic stainless steels--AISI types 304, 310 and 316--at temperatures between 4 and 300K.

2. Tensile and yield strengths of nitrogen-strengthened 300-series stainless steels at temperatures between 4 and 300K.

3. Yield strengths of six aluminum alloys at temperatures between 4 and 300K.

Table 2. Physical Properties of Aluminum Alloys [1]

Property	Units	5083 (Annealed)		Precipitation Hardened 6061		Precipitation Hardened 2219	
		295K	4K	295K	4K	295K	4K
Specific Gravity	g/cm^3	2.66		2.70		2.83	
Young's Modulus	GN/m^2	71.5	80.9	70.1	77.7	77.4	85.7
Shear Modulus	GN/m^2	26.8	30.7	26.4	29.2	29.1	32.5
Poisson's Ratio		.333	.318	.338	.327	.330	.318
Thermal Conductivity	W/m.K	120	3.3	120-160	3.-6.	120-160	3.-6.
Thermal Expansion	$\text{K}^{-1} \times 10^{-6}$	23	14.1	120-160	14.1	120-160	14.1
Specific Heat	J/kg.K	900	.28	120-160	.28	.28	.28
Electrical Resistivity	$\mu \Omega \text{ cm}$	5.66	3.03	3.94	1.38	5.7	2.9