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NON MAGNETIC STAINLESS STEELS FOR CRYOGENIC PURPOSES

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ABSTRACT

An investigation of the magnetic properties of the austenitic stainless steels at low temperatures has been made. Recommendations for the avoidance of ferromagnetism in these steels are made, with particular reference to those considered for the High Field Bubble Chamber.

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CONTENTS

		PAGE
I.	INTRODUCTION	1
II.	AIMS OF THE RESEARCH	4
III.	EXPERIMENTAL DETAILS	5
	a) Apparatus and techniques	5
	b) The determination of α' martensite	5
	c) Materials studied	6
	d) Heat treatments	6
	c) Cryogenic cycling treatments	7
IV.	RESULTS	7
	a) Previous reports	7
	b) Steels cooled in the absence of stress	8
	c) The production of martensite under tensile stress	12
	d) Work still to be reported	12
V.	SELECTION OF STEELS FOR LOW TEMPERATURE SERVICE	15
	a) Summary of experimental findings	15
	b) Choice of steel for the high field bubble chamber	17
ACKNOWLEDGEMENTS		21
REFERENCES		22

I. INTRODUCTION

Austenitic stainless steels are widely used as structural components at temperatures in the vicinity of $0^{o}K$ because they combine high strength with good toughness and do not show a ductile/brittle transition. Further, their welding and forming properties are good and they may be extensively cold worked at room temperature without serious increases in notch brittleness at low temperatures. They are also rustless, which is an important advantage in components which must be cycled from sub-zero to room temperature, with consequent condensation of water vapour.

Combined with these excellent mechanical properties are some very useful physical properties. The steels have low thermal conductivities which means that they can be used as thermal insulators. Their residual electrical resistance is high (~60μΩ cm at $4.2^{o}K$) thus minimising eddy current losses in field changing situations and, in addition, the fully austenitic structure of the common 18/10 steels is non-ferromagnetic so that, in principle, negligible perturbations are caused to adjacent magnetic fields.

In practice, however, it is found that the austenite phase, γ, of many stainless steels may be decomposed martensitically by cooling to and/or deformation at low temperatures. Two martensitic products are possible from this transformation: one, ε martensite, is a transitional phase and, like γ, non-ferromagnetic, but the stable product α' is ferromagnetic. The transformation to α' is not reversible until about $600^{o}C$ and steels in which martensite has formed on cooling to low temperatures do not therefore revert to austenite on warming to room temperature. The transformation to ε or α' may often be enhanced by cyclic cooling and warming, so that it is impossible to predict the extent of transformation in an unstable steel.

Reed and Mikesell[1] had studied the occurrence of this transformation in samples of commercial grade stainless steels, conforming

TABLE 1

COMPOSITIONS OF ALLOYS DISCUSSED IN THIS REPORT

Reference	wt.% C (max.)	wt.% Cr	wt.% Ni	wt.% Others
302	0.15	17 - 19	8 - 10	
303	0.15	17 - 19	8 - 10	0.15 min S
304 (L)	0.08 (0.03)	18 - 20	8 - 12	
305	0.08	17 - 19	10 - 13	
308	0.08	19 - 21	10 - 12	
309	0.25	22 - 24	12 - 15	
310	0.25	24 - 26	19 - 22	1.5 Si (max)
316 (L)	0.08 (0.03)	16 - 18	10 - 14	2 - 3 Mo
321	0.08	17 - 19	9 - 12	
347	0.08	17 - 19	9 - 13	
Incoloy 800	0.14	19	31	
FV 520	0.05	14	5.5	1.5 Mo, 1.5 Cu
Kromarc 55	0.04	16	20	9 Mn, 2 Mo, 0.2 N

NOTES:

1. All A.I.S.I. 300 steels contain 2% Mn max, 1% Si max, 0.045% P max and 0.030% S max. except where stated.

2. Compositions for Incoloy 800, FV 520 and Kromarc 55 are typical.

3. High nitrogen steels (also called hi-proof commercially) containing 0.2 wt.% N are available in the 304 (L), 316 (L) and 347 grades and are suffixed with an N in this report.

to A.I.S.I. 302, 303, 304, 308, 309, 310, 316, 321 and 347* and concluded that only steels 303 and 304 become unstable on cycling between room and low temperatures (20° or $77^{o}K$). Some experiences of the present authors[2] with a superconducting magnet former made from En 58B (A.I.S.I. 321) showed, however, that considerable transformation can occur in this steel. When samples of 304L, 310 and 347 were also examined[3], it became clear that all had significant magnetisations at $4.2^{o}K$ and that the findings of Reed and Mikesell needed to be reconsidered.

The problems of martensitic transformations in stainless steels were of direct relevance to the High Field Bubble Chamber Project at the Rutherford High Energy Laboratory since the H.F.B.C. was designed with stainless steel as its principal constructional material. In all about 100 tons of stainless steel were to be used in three principal ways: for the bubble chamber itself, for the cryostats and associated fittings, and as an interleaved support strip in the magnet's superconducting windings.

An important design restriction on these items was that the uncertainty of the field within the fiducial volume of the bubble chamber should be less than 0.1%. Taking into account the total number of factors contributing to this uncertainty, a maximum permeability of 1.03 at the design field of 80 kOe could be tolerated. A second restriction was placed on the material of the coil reinforcing strip, which could not be allowed to undergo any permanent dimensional changes after being wound into the coil pancakes. A stable austenitic steel is thus essential, to avoid the growth problems associated with the transformation $\gamma \rightarrow \alpha$.

In principle, the decomposition of austenite to martensite can be avoided by increasing the alloy content of the steel. Considerable doubt was thrown on this practice, however, by some observations of the present authors on the magnetic behaviour of two higher alloy steels,

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* Specifications of all steels described in this report are given in Table I.

A.I.S.I. 310 and Incoloy 800. Both of these remained structurally stable at low temperatures, but were found to be reversibly ferromagnetic on cooling to 4.2^{o}K in the case of 310 and to 77°K in the case of Incoloy 800. In view of the design restrictions outlined above, a programme of research of direct relevance to the H.F.B.C. project was, therefore, initiated and the results of this research are described in the following sections of this report.

II. AIMS OF THE RESEARCH

A programme of research was initiated which would examine the occurrence of martensite and low temperature magnetism in the austenitic stainless steels, with direct attention being paid to those steels which in other respects (strength, fabrication properties, etc.) were considered suitable for inclusion in the H.F.B.C. At the same time, however, a wider view was taken since the problems outlined above are common to many experiments undertaken at low temperatures. The programme of research reported here, therefore, had two main aims:

1. Stainless steels of direct relevance to the H.F.B.C. project were examined, with specific attention being paid to guaranteeing stable low permeabilities in fabricated components at the service temperatures of the H.F.B.C.

2. In order to fully carry out (1) a wide range investigation of the structural and magnetic properties of the austenitic stainless steels was initiated, with a view to determining a general framework within which the properties of arbitrary steels could be predicted.

III. EXPERIMENTAL DETAILS

a. Apparatus and Techniques

The principal experimental techniques used in the present work were measurements of magnetisation and metallography using light microscopy. These techniques have been described in detail[4]* elsewhere.

The magnetisation measurements were made with a DC Integration magnetometer, capable of working between about $2^{o}K$ and room temperature. Fields of up to 50 kOe could be generated at Imperial College, while higher field measurements (up to 120 kOe) were made in the Bitter solenoids at R.R.E., Great Malvern. The limits of sensitivity of the apparatus were about $\pm$ 1 gauss for the size of specimens used (section III d), corresponding to a detection limit of considerably better than 0.1% of martensite or δ-ferrite.

b. The Determination of α' martensite

Magnetic testing for α' martensite is rapid and convenient since the measurement can be made at R.T. (Curie points are around $600^{o}C$) and, in contrast to metallography, little preparation is needed. Nevertheless a measurement of magnetisation does not necessarily give an unambiguous determination of α', since some of the high temperature form of ferrite, δ, can also be retained at low temperatures. (See report described in section IV a.) These two constituents can be separated by metallography, but it was also shown during the course of this work that, provided the steel has not been cold-worked or stressed externally, metallography is not necessary. This arises from an earlier study in which it was shown that the M_s temperature† could be predicted from the chemical composition of the steel. For all steels conforming to A.I.S.I. 304(L), 316(L), 321 and 347 the M_s temperatures are below R.T. Hence, if a sample of these

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* A copy of this thesis is in the possession of the High Field Bubble Chamber Group.

† The M_s temperature is here defined as the temperature at which α' martensite first forms on cooling in the absence of external stress. There is a corresponding but higher temperature M_d at which it first becomes possible to nucleate martensite by deformation.

steels is tested at R.T. before sub-zero cooling, any ferromagnetic magnetisation will be due to the presence of δ-ferrite. Subsequent changes on cryogenic cycling will then be due to the formation of α' martensite. These magnetisation measurements may then be converted to absolute quantities of δ or α' by the method of Curtis and Sherwin[6], also discussed elsewhere[7].

c. Materials Studied

A wide range of alloys totalling about 100 different casts or materials were examined. These can be conveniently classed into three groups:

1. Standard grade austenitic Fe-Cr-Ni stainless steels: A.I.S.I. 302, 304(L) (N), 305, 309, 310, 316(L) (N), 321 and 347 and Incoloy 800. Also examined were casting alloys corresponding to 316 and 347 and FV 520 and the high manganese casting alloy Kromarc 55.

2. In order to obtain a more systematic variation of magnetic and deformation properties in the Fe-Cr-Ni system, some 40 special Fe-Cr-Ni alloys were arc melted. In addition, three non-standard steels, 18Cr/13Ni, 18/17 and 18/20, specially supplied by the Swindon Laboratories of the British Steel Corporation were also examined.

3. The programme was concluded by testing some commercial non-ferrous materials, including Monel 400 and common copper and aluminium alloys.

d. Heat Treatments

Magnetisation measurements were generally performed on samples of steel 3 cm long and 4 mm diameter, cut from plate or bar stock. In the case of all the standard grade Fe-Cr-Ni steels, the pure Fe-Cr-Ni alloys and the special casts of steel received from

Swindon Laboratories, a standard fully softening heat treatment was given. This treatment consists of an anneal at 1075°C for ½ hour, followed by a water quench. The treatment was performed in silica capsules at a R.T. pressure of about 1/10 atmosphere of argon.

None of the casting alloys was heat treated since such heat treatments would not be performed in practice.

The fully softening treatment described above is a standard anneal for austenitic steels and returns them to a strain-free austenitic structure with carbides in solution. For the purposes of the present experiments, it also served as a reproducible standard state, since the martensitic transformation can be a sensitive function of the stress level existing within the steel. It has generally been found [8,9] that small plastic strains enhance the transformation to martensite on subsequent cooling, while large strains inhibit the transformation. The behaviour of machined and fabricated structures on subsequent exposure to cryogenic fluids is thus rather complex.

e. Cryogenic Cycling Treatments

Specimens of steel were cycled either between R.T. and 77°K or R.T. and 4.2°K. Since the martensitic transformation occurs both athermally and isothermally, a composite treatment involving a rapid quench to temperature and a slow warm up was employed. The details of these treatments are also discussed elsewhere[10].

IV. RESULTS

a. Previous Reports

Two informal reports have already been communicated to the H.F.B.C. group. These are entitled:

1. The alloying balance in the austenitic stainless steels - a survey of the different alloying balances needed to maintain an austenitic structure at high and low temperatures.

2. Monel 400 - a report on the magnetic and structural properties of this material between R.T. and 4.2°K with reference to its suitability as a bolting material.

b. Steels Cooled in the Absence of Stress

(i) Low field measurements

Before cryogenic cycling and after quenching from the temperature of the fully softening heat treatment described in section III (d), the magnetisation of all samples was measured at R.T. to check for the presence of δ-ferrite. Small quantities of δ-ferrite were found in six out of twelve samples of 304 and 304L (0.15% max.) and five out of nine samples of 316 and 316L (0.5% max.).

No traces of δ-ferrite were found in any of six samples of 304N or four of 316N or in the single samples of 305 or Kromarc 55.

Following these preliminary tests, the samples were cycled ten times between R.T. and 77°K and three times between R.T. and 4.2°K using the composite quenches referred to in section III (e). A detailed analysis of the results of magnetisation measurements made in the course of the cycling will be reported later but the wide range of steels within the 304 and 316 grades had been deliberately chosen since a previous study had suggested[11] that both stable and unstable casts of steel could be found within the same grades. This study, which showed that the Eichelman and Hull equation[12]* could be applied to the commercial 18/10 steels, indicated that the M_s temperature could vary over the wide limits shown in Table 2. In agreement with these predictions, both stable and unstable casts of steel within the 304L and 316L grades were found.

An important result was, however, that no sample of any high

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* This gives the M_s in terms of the C, N, Cr, Ni, Si and Mn contents:
$M_s(^{\circ}K) = 1580 - 41.7\ Cr - 61.1\ Ni - 33.3\ Mn - 27.8Si - 1667\ (C + N)$.

TABLE 2

THE VARIATION OF M_s WITHIN THE PERMITTED COMPOSITIONAL LIMITS ACCORDING TO THE EICHELMAN AND HULL EQUATION

Steel	Calculated M_s	
	Upper Limit	Lower Limit
304	216°K	-249°K
304L	266	-165
305	137	-267
316	179	-289
316L	229	-205
321	247	-90
347	214	-184

The maximum and minimum compositions are those from Table 1 together with likely lower limits of 0.5% Mn and 0.25% Si. 0.02% N has also been included. In the plain carbon grades the likely carbon variation is 0.01 - 0.03% (304L and 316L) and 0.04 - 0.08% (304 and 316). In the stabilised grades a constant 0.03% C has been assumed, but in 321 the nitrogen will be present as TiN and not available for stabilisation. No factor is known for molybdenum but if it is assumed that it behaves like silicon, the weakest depressant of the M_s, 2.5% Mo in the 316 grades would result in a further depression of 72°K to the figures in the Table. For 305 a maximum C content of 0.08% has been assumed since at contents greater than this considerable welding problems would be encountered and excess carbon would precipitate from solution.

nitrogen steel transformed martensitically during the cycling experiments. This result is again in agreement with the empirical predictions referred to above, according to which at a nitrogen content of 0.17 wt.% (cf. a nominal 0.2 wt.%), the M_s should be depressed by a further 250°K over the values given in Table 2. Since type 321 is not made in the hi-proof grade this is sufficient to make all the high nitrogen steels except 304L unconditionally stable on exposure to cryogenic cycling.

(ii) High field measurements

When some measurements were made on an earlier batch of steels comprising a rather wider range of grades than those used for the cycling experiments described above, it was observed that some complex magnetisation curves were obtained in high fields at 4.2°K. At liquid helium temperature the 18/10 grades are antiferromagnetic and thus have a small resultant magnetic moment but it was observed that at fields in the vicinity of 30 - 40 kOe a significant increase in the magnetic permeability occurred. In the higher alloy grades A.I.S.I. 310 and Incoloy 800 which are ferromagnetic at 4.2°K, no true saturation was found, the magnetisation continuing to increase with field. These effects are believed to be related to the existence of two electronic states in γ-Fe[13,14] and will be reported in detail later, but, because the operating fields of the H.F.B.C. will be in the 70 - 80 kOe range, high field magnetisation measurements were made in the Bitter Solenoids at R.R.E. The results of these experiments expressed in terms of the permeability at 80 kOe are given in Table 3 and show several interesting features:

1. Only the cast alloy FV 520 and Incoloy 800 have $\mu > 1.03$.

2. The sample of 321 containing some 4% α' martensite and the ferromagnetic 310 both have $\mu < 1.02$.

TABLE 3

HIGH FIELD PERMEABILITIES

Permeability at 80 kOe at 4.2°K

	GRADE	μ 80	Error
	304L	1.009	
	304N	1.008	
	309	1.013	
	310	1.016	
	316LN	1.009	
	321	1.017	
	347	1.008	
	Incoloy 800	1.038	
C.E.R.N. Material	304N	1.006	
	316LN	1.008	± 0.003
	316L	1.008	± 0.003
	316 cast	1.016	
	347 cast	1.012	
	FV 520 cast	1.195	
	Kromarc 55	1.006	± 0.003

The uncertainty is ± 0.002 except where stated.

3. There is little significant difference between the samples of 304L, 304N, 316LN and 316L at this field.

4. The sample of Kromarc 55 cut from the R.H.E.L. helium bubble chamber has the very low permeability of 1.006.

c. The Production of Martensite under Tensile Stress

At the same time as the present examination of the magnetic properties of stainless steels, a parallel programme of work investigating their mechanical properties was being carried out at the Rutherford Laboratory. In particular a series of tensile tests was performed at 4.2°K and these tensile bars were then examined at Imperial College for the presence of α' martensite. In this case small discs were cut from the undeformed shoulder portions of the specimens and from the fracture neck of the broken specimens or from the centre of the gauge length of lightly strained specimens. Since the size and shape of these specimens were unsuitable for testing in the integration magnetometer, a modified Sucksmith force balance[15] was used. The quantities of α' martensite found in these steels are shown in Table 4.

It is clear from Table 4 that low temperature deformation is extremely potent in producing martensite, since in the previous cycling experiments no martensite could be found in either the high nitrogen grades or the high alloy 309. It will be noticed, however, that no martensite could be induced in the ferromagnetic 310 by tensile fracture at 4.2°K, a result supported by previous work[16,17]

d. Work Still to be Reported

Three main items of work, arising from experiments conducted during the course of the present contract remain to be reported.

1. Prediction of low temperature stability from a room temperature test

There is a temperature range above the M_s in which martensite

TABLE 4

MARTENSITE CONTENTS OF DEFORMED STEELS

All steels were tensile bars deformed at 4.2°K
at Rutherford Laboratory

Steel	Test Condition	% α'	
		On gauge length	On shoulder
304L	0.5% strain	0.1%	0.1%
	Fractured	83%	not done
304N	Fractured	65%	0
309	0.5% strain	0	0
	Fractured	~ 50%	0
310	Fractured	0	0
316L	Fractured	46%	0.5%
316LN	Fractured	52%	0
Kromarc 55	0.5% strain	0	0
	Fractured	0	0

may be formed by deformation (up to a maximum temperature M_d) and in the case of somewhat lower alloy steels than 18/10 where the M_s is around 0° - 100^oC there is some evidence[18] that the M_d lies in the range 300 - 400^oC. If the same temperature interval between M_d and M_s is maintained for steels with M_s near 0^oK, a simple room temperature deformation test will suffice to determine the low temperature properties of arbitrary pieces of steel. Some preliminary tests[19] proved promising and the experiments were thus extended utilising the same wide variety of 304 and 316 grades that were used for the cryogenic cycling experiments. Samples of these steels have been cold rolled at 0^oC and 100^oC and the results of a comparison between their behaviour under this deformation and their behaviour after cryogenic cycling will be reported shortly.

2. The thermodynamic stability of γ iron

Considerable evidence[14,20] exists to show that the magnetic energy of iron is responsible for the peculiar allotropic changes which occur in the pure element

$$\alpha \underset{}{\overset{910^oC}{\rightleftarrows}} \gamma \overset{1400^oC}{\rightleftarrows} \delta$$

where α and δ have the same body centred cubic structure. It also appears that were the ground state of α iron not ferromagnetic, a hexagonal allotrope of iron, ε, would be stable at low temperature. Kaufman et al[14] and Weiss[13] have explained certain features of the allotropic transformation in pure iron and the anomalous properties of the Invar alloys by suggesting that γ iron exists in two different electronic forms, one ferromagnetic and the other anti-ferromagnetic.

In pure γ iron neither of these two magnetic states are observed on a macroscopic scale, since γ iron is stable only between 910° and 1400^oC, well above any critical point for the destruction of long range magnetic order. The simultaneous

addition of Cr and Ni to Fe results in the stabilisation of the f.c.c. structure at the expense of α-Fe and both bulk anti-ferromagnetic and ferromagnetic states can be observed. An extremely interesting observation to emerge from the present work is that when antiferromagnetic austenites are deformed they break down to the α structure, while on the other hand, ferromagnetic austenites remain stable. These observations have been formulated as a general hypothesis:

Under conditions where macroscopic regions of both magnetic states can be retained, alloys based on the anti-ferromagnetic state are structurally unstable while those based on the ferromagnetic state retain the f.c.c. structure even after deformation at $0^{o}K$.

A detailed test of this hypothesis is still in progress using the specially prepared pure Fe-Cr-Ni alloys. Their magnetisation in high fields and as a function of temperature has already been measured and they remain to be deformed at $4.2^{o}K$ by Rutherford Laboratory, followed by a final examination for α' martensite and chemical analysis. These results are likely to be the last to be reported on the present contract.

3. Commercial copper and aluminium alloys

Small magnetisations are often noted due to iron impurities in many commercial alloys. In addition when operating at liquid helium temperatures, superconducting impurities (e.g. lead in free machining brasses) give a diamagnetic magnetisation which may be quite appreciable at low fields (below H_c or H_{c1}). A survey of these effects in about a dozen commercial copper and aluminium alloys has been made.

V. SELECTION OF STEELS FOR LOW TEMPERATURE SERVICE

a. Summary of Experimental Findings

The principal findings of direct relevance to the H.F.B.C.

project to emerge from the present work are:

1. The standard grade 18/10 steels lie on the borderline between retaining the austenitic structure and (partially) transforming to martensite when exposed to cryogenic temperatures. Consequently, both stable and unstable steels conforming to each of the standard A.I.S.I. grades 304(L), 316(L), 321 and 347 may be found. If the exact chemical composition of the sample of steel to be used is known, the Eichelman and Hull equation may be employed to predict the instability. The suggested order of stability for the 18/10 grades is, beginning with the most stable, 316, 316(L), 304, 347, 304(L), 321. It is therefore a matter of some concern that 321, or its now obsolete British equivalent classification En 58B(M), appears to be the most widely available grade for bar or tube. Whether this is a reflection of the actual production of stainless steel in the U.K. is unknown, since current production figures are a commercial secret[21], but the published American figures show 304 outranking 321 some 20 times[22]. Whatever the cause, a shift away from 321 for cryogenic purposes would be beneficial in all situations where non-magnetic properties are desirable.

2. No unstable sample of high nitrogen 304 or 316 steel was found. Use of the Eichelman and Hull equation suggests that at a minimum content of 0.18 wt.% N all steels in the 304(L), 304, 316, 316(L) and 347 grades will remain stably austenitic down to $0^{o}K$. Since no δ-ferrite was found in any of these high nitrogen samples either, these steels all have excellent non-ferromagnetic properties.

3. The range of high alloy steels examined was considerably smaller, principally due to the difficulties of supply. No martensite could be detected in the sample of 305, the two samples of 309, the three of 310 or the single samples of Incoloy 800 and Kromarc 55. Of these grades, 305 is really an uprated 304 (see Table 1) and not significantly more stable than the 316(L) grade, so that it cannot be considered as a guaranteed stable grade when exposed to cryogenic cycling. The 309 grade is expected to be stable under these conditions but can be decomposed to martensite by deformation at 4.2°K. The two remaining Fe-Cr-Ni steels, 310 and Incoloy 800, are stable even after low temperature deformation, a behaviour which is believed to result from their austenitic ferromagnetism. Kromarc 55 which contains some 9% Mn in addition was found to be both unconditionally stable and non-ferromagnetic at 4.2°K.

b. Choice of Steel for the High Field Bubble Chamber

When the findings outlined above are considered in the light of the design restrictions for the permeability of the chamber body itself (μ 80 = 1.03 max.), it will be observed from Table 2 that all the steels measured at 80 kOe, except FV 520 and Incoloy 800, have permeabilities comfortably less than 1.02. This is true even of the weakly ferromagnetic 310 and the sample of 321 which contained ~ 4% of α' martensite.

This result is a direct consequence of the high operating field of the H.F.B.C. The saturation magnetic moment of a completely martensitic 18/10 steel lies in the region of 16,000 gauss and the maximum possible permeability of such a steel at 80 kOe is thus 96/80 $\simeq$ 1.2. Such a complete transformation is extremely unlikely except under conditions of extensive low temperature deformation (when a mechanical design failure would in any case have occurred). Unfortunately, however, no definite maximum likely permeability can be suggested, for

while a maximum content of ~10% α' was found in any 18/10 steel studied in the present work, such transformation is a very sensitive function of the stress and temperature/time relationships to which the individual steel is exposed. Reed and Mikesell[1] for example found 25% α' in their sample of 304, a content which was still increasing after some 3 months of cycling between 77°K and R.T. The maximum design permeability of 1.03 corresponds to an α' content of 15%, a figure rather lower than this. Moreover, if for any reason the chamber is run at a lower field than maximum, the permeability increases proportionately, such that at 40 kOe, only 7.5% α' could be tolerated.

In principle no permeability restriction attaches to the choice of coil reinforcing strip, since the requirement is for high dimensional stability and conceivably an unstable steel could be chosen and cryogenically cycled in liquid nitrogen so as to complete most of the transformation before winding. Two additional complications would result from this latter course, however:

1. Since the support strip is now ferromagnetic, this adds an additional field to that produced by the superconducting windings. The higher local induction in the vicinity of these windings, however, ensures that the local critical current density is reduced and a lower total magnet current will be possible. Rather detailed calculations will be necessary to decide which is the dominant term.

2. A second problem arises from the large increase in eddy currents in field changing situations when ferromagnetic phases are present[2]. Two aspects of this problem again exist, the first being the production of heat and the second the occurrence of electromagnetic forces. These effects may not be large during charging of the magnet at a slow rate but in case of sudden field collapses, which will inevitably happen even if only in testing, both effects could be serious, since the sudden

heat liberation will cause serious problems with respect to sudden helium boil off and possible overpressures, while large transient stresses may result from the magnetic forces. This argument applies equally to the presence of ferromagnetic phases in the chamber body itself or in other components existing in the neighbourhood of large fields.

These considerations are, we believe, very strong ones for considering only non-ferromagnetic steels for use in the H.F.B.C. In addition to the magnetic properties of these steels, however, which were the principal concern of the present work, we also note the remaining important factors of good mechanical properties (principally good strength and low temperature toughness), ease of fabrication and supply and cost. Re-examining the steels already considered with reference to these points we find that:

1. The ingot steel prices of grades 304, 304(L), 321 and 347 fall in the range £500 - £600/ton with the 316 and 316(L) grades some 20% dearer. The high alloy grades 309 and 310 are considerably more expensive. Ingot steel prices of the hi-proof grades are very little different from their equivalent standard grades. The final mill prices for production of plate, strip, etc., may well, however, increase these prices considerably and reduce the differentials, particularly for the 18/10 grades.

2. An extensive mechanical testing programme has been carried out at Rutherford Laboratory. Without having full details of these tests, two general conclusions can nevertheless be drawn. No significant increase in strength is gained by using high alloy steels in preference to the standard 18/10 grades; on the other hand, 0.2% proof stresses of the high nitrogen grades are some 100% higher than the standard grades without any simultaneous loss of ductility at 4.2^{o}K.

3. The techniques of rolling, forging and welding stainless steel are well established and should give no insuperable problems.

Although there appears to be rather less experience available for the high proof grades, no special differences are expected. From a welding point of view it would be better to specify low carbon grades where possible so as to avoid extensive carbide precipitation. This applies particularly where thick sections must be welded, as on the chamber body itself.

A summary of these conclusions shows the hi-proof grades based on 304(L) and 316(L) to have the following advantages:

1. A stable non-ferromagnetic structure on cycling down to $4.2^{o}K$. This ensures a low permeability, dimensional stability and minimises eddy current problems.

2. Their mechanical properties are markedly superior to the standard 18/10 grades.

3. Their fabrication properties are not markedly different to those of the standard grades.

4. There is no significant cost premium over the equivalent standard grade.

Since the margin of safety against low temperature instability of the 316(LN) grade is somewhat greater than that of the 304(LN) grade, other things being equal, this grade is preferred for the critical components of the chamber body itself and the coil reinforcing strip. This grade would also be equally suitable for much of the remaining stainless steel work to be found on the chamber.

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