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Magnetic Properties of Iron and Low-Carbon Steel for Soft Magnet Application

by
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AUGUST 1983

**NAVAL WEAPONS CENTER
CHINA LAKE, CALIFORNIA 93555**

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FOREWORD

This investigation of magnetic properties of iron and low-carbon steel was authorized by the Naval Air Systems Command under Task Assignment No. A5140204/0086/3000/000001. The experimental work was performed during the period 1980-81. The purpose of the investigation was to compare the magnetic properties of several soft-magnet materials and determine their suitability for use in various magnetically-actuated control devices. No further work is anticipated in this area.

This report has been reviewed for technical accuracy by professional reviewers provided by the American Society for Testing and Materials (ASTM).

Approved by
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8 July 1983

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(U) *Magnetic Properties of Iron and Low Carbon Steel for Soft Magnet Applications*, by James L. Stokes, China Lake, Calif., Naval Weapons Center, August 1983, 10 pp. (NWC TP 6455, publication UNCLASSIFIED.)

(U) An investigation was conducted to assess the relative merits of five soft magnet materials proposed as alternatives to ARMCO Electromagnet Iron (EMI), which is no longer available.

(U) Four irons and an SAE J403 (1005) (Unified Numbering System [UNS] G10050) steel were considered. When annealed in 94% nitrogen-6% hydrogen at 843°C (1550°F) for 4 hours and aged at 100°C (212°F) for 400 hours, two of the irons were found to be equivalent to EMI with regard to both coercive force and magnetic stability. A third iron exhibited similar magnetic properties after annealing, but required a higher annealing temperature to reduce the coercive force to an acceptable value. The fourth iron and the 1005 steel met the coercive force requirement after annealing at 843°C (1550°F) in 94% nitrogen-6% hydrogen, but suffered significant increases in coercive force during aging at 100°C (212°F).

CONTENTS

INTRODUCTION

The availability of iron for soft magnet applications has been rather uncertain ever since the ARMCO Steel Corporation stopped producing electromagnet iron (EMI) in 1976. Low carbon steels have been substituted in some applications, but the magnetic stability of steel is variable[1] and may not be adequate for critical applications in which small changes in magnetic properties cannot be tolerated. The present investigation was conducted to assess the relative merits of five alternate materials that have been proposed for soft magnet applications.

All magnetic properties were measured in units of oersteds and gausses (cgs system), but have been converted to SI units.

SPECIFICATION REQUIREMENTS

Soft magnetic materials used by the Naval Weapons Center are normally purchased in accordance with a U.S. Air Force Specification titled "Iron, Electromagnet," (AF 71A45549). This document requires that the coercive force Hc be less than 119 A/m (1.5 Oe), at a maximum induction Bm of 1.5T (15 kG), when tested in accordance with the ASTM Test for Direct-Current Magnetic Properties of Materials Using Ring Test Procedures and the Ballistic Methods (A 596). Before testing, the specimen is required to be annealed at 843°C (1550°F) for 1 hour in a 90% nitrogen-10% hydrogen atmosphere. These requirements were used as a general guide in this investigation.

MATERIALS AND PROCEDURES

Materials and sources of materials are shown in Table 1. The chemical analyses of the as-received materials are listed in Table 2. All analyses, with the exception of nitrogen, were performed at the Naval Weapons Center. The nitrogen analyses were performed by Durkee Testing Laboratories, Gardena, Calif. All materials were purchased as cold-drawn bar with the exception of the SAE J403 (1005) steel (Unified Numbering System [UNS] G10050) and the ingot iron. The steel was hot-rolled bar and the ingot iron was in the form of 6.35-mm (¼-inch) cold-rolled plate.

Magnetic test specimens were fabricated in accordance with ASTM Test A 596. Figure 1 is a sketch of the specimen. Before testing, the toroidal specimens were wound with 200 turns of Awg 34 (0.160-mm) transformer wire (secondary) followed by 30 turns of Awg 19 (0.91-mm) transformer wire (primary).

[1]Knight, D. J. and Adzema, P. J., *Transactions of the American Society for Metals*, Vol. 54, No. 3, Sept. 1961, pp. 355-361.

TABLE 1. Materials for Magnetic Property Evaluation.

Alloy Designation	Producer	Vendor
Electromagnet iron (EMI)	ARMCO Steel Corp. Middletown, Ohio	...
Magnet iron	Advanced Metals Corp. Waterbury, Conn.	Lang Metal Services Glendale, Calif.
Core iron (Consumet®)	Carpenter Technology Corp. Reading, Pa.	...
Electrical iron	Carpenter Technology Corp. Reading, Pa.	...
Ingot iron (commercial quality)	...	Specialty Metal Sales Westminster, Calif.
SAE J403 (1005) steel	...	Specialty Metal Sales Westminster, Calif.

TABLE 2. Chemical Analyses of Magnet Materials As-Received.

Alloy	Element, % by Weight											
	Carbon	Nitrogen	Manganese	Sulfur	Silicon	Copper	Chromium	Nickel	Vanadium	Aluminum	Titanium	Iron
EMI	0.016	0.009	0.16	0.018	0.10	0.14	0.04	0.11	<0.01	0.05	0.03	Remaining
Magnet iron	0.020	0.008	0.33	0.013	0.02	0.10	0.02	0.06	<0.01	0.02	<0.01	Remaining
Core iron	0.016	0.007	0.02	0.005	0.03	0.01	0.06	0.04	<0.01	0.01	<0.01	Remaining
Electrical iron	0.013	0.008	0.18	0.008	0.16	0.04	0.03	0.04	0.04	<0.01	<0.01	Remaining
Ingot iron	0.024	0.006	0.05	0.015	0.04	0.04	<0.01	0.01	<0.01	<0.01	<0.01	Remaining
SAE J403 (1005) steel	0.062	0.009	0.35	0.014	0.03	0.04	0.004	0.009	<0.01	<0.01	<0.01	Remaining

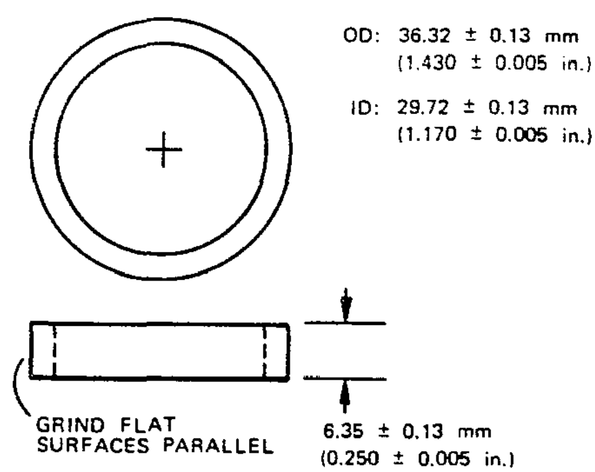

FIGURE 1. Toroidal Specimen for Magnetic Testing Made in Accordance With ASTM TEST A 596.

Magnetic testing was done on a Model 1020 Hysteresisgraph manufactured by Walker Scientific, Inc., Worcester, Mass. This device was used to plot B-H or hysteresis loops from which were measured the coercive force Hc, the residual induction Br, and the maximum induction Bm for each specimen. The accuracy of all magnetic property measurements was approximately ± 1 percent.

Specimens of each composition were subjected to four annealing cycles:

(a) 482°C (900°F) - 1 hour
(b) 843°C (1550°F) - 1 hour
(c) 843°C (1550°F) - 4 hours, and
(d) 1100°C (2012°F) - 4 hours.

Annealing was done in a closed furnace with 94% nitrogen-6% hydrogen (forming gas) flowing at a rate of five times the furnace volume per hour. The dew point of the gas was approximately -68°C (-90°F). After annealing, the specimens were furnace-cooled at approximately 50°C (122°F) per hour to 50°C (122°F) before removing them from the furnace.

After annealing at 843°C (1550°F) for 4 hours, the "best" (lowest coercive force) specimen of each composition was aged at 100°C (212°F) for 200 hours and 400 hours in air. Because of its apparent instability, the 1005 steel was aged an additional 104 hours.

RESULTS AND DISCUSSION

Magnetic properties after the four annealing cycles are listed in Table 3. The data show that for the core iron, magnet iron, ingot iron, and 1005 steel, optimum magnetic properties were obtained by annealing at 843°C (1550°F) for 4 hours. The EMI had a slightly lower coercive force after 1 hour at 843°C (1550°F). Only one material, electrical iron, did not meet the coercive force requirement of 119 A/m (1.5 Oe) maximum after annealing at 843°C (1550°F). This material required 4 hours at 1100°C (2012°F) to bring the coercive force below 119 A/m (1.5 Oe). It must be pointed out, however, that the producer recommends that this alloy be annealed in wet hydrogen to achieve optimum magnetic properties.

Table 4 lists carbon and nitrogen analyses of the materials as-received and after annealing at 843°C (1550°F) for 4 hours in forming gas. These data show that except for EMI the carbon content was reduced significantly by annealing. Nitrogen, however, remained essentially unchanged in all materials. The stability of the carbon in EMI is apparently the result of the titanium and aluminum which are intentionally added to this material to stabilize the impurities.

TABLE 3. Magnetic Properties of Soft Magnet Materials After Annealing in 94% Nitrogen-6% Hydrogen.

Heat Treatment	*Hc*		*Br*		*Bm*	
	A/m	(Oe)	T	(kG)	T	(kG)
EMI						
482°C (900°F) − 1 h	107	(1.35)	0.82	(8.2)	1.48	(14.8)
843°C (1550°F) − 1 h	82	(1.03)	1.47	(14.7)	1.56	(15.6)
843°C (1550°F) − 4 h	85	(1.07)	1.47	(14.7)	1.55	(15.5)
1100°C (2012°F) − 4 h	95	(1.20)	1.32	(13.2)	1.52	(15.2)
MAGNET IRON						
482°C (900°F) − 1 h	143	(1.80)	1.03	(10.3)	1.55	(15.5)
843°C (1550°F) − 1 h	95	(1.20)	1.04	(10.4)	1.55	(15.5)
843°C (1550°F) − 4 h	80	(1.00)	1.45	(14.5)	1.57	(15.7)
1100°C (2012°F) − 4 h	95	(1.20)	1.20	(12.0)	1.56	(15.6)
CORE IRON						
482°C (900°F) − 1 h	85	(1.07)	0.85	(8.5)	1.55	(15.5)
843°C (1550°F) − 1 h	74	(0.93)	1.31	(13.1)	1.59	(15.9)
843°C (1550°F) − 4 h	72	(0.90)	1.48	(14.8)	1.60	(16.0)
1100°C (2012°F) − 4 h	80	(1.00)	1.16	(11.6)	1.56	(15.6)
ELECTRICAL IRON						
482°C (900°F) − 1 h	143	(1.80)	1.06	(10.6)	1.54	(15.4)
843°C (1550°F) − 1 h	127	(1.60)	1.44	(14.4)	1.56	(15.6)
843°C (1550°F) − 4 h	127	(1.60)	1.48	(14.8)	1.59	(15.9)
1100°C (2012°F) − 4 h	111	(1.40)	0.76	(7.6)	1.48	(14.8)
INGOT IRON						
482°C (900°F) − 1 h	95	(1.20)	0.92	(9.2)	1.56	(15.6)
843°C (1550°F) − 1 h	95	(1.20)	0.88	(8.8)	1.52	(15.2)
843°C (1550°F) − 4 h	95	(1.20)	1.43	(14.3)	1.59	(15.9)
1100°C (2012°F) − 4 h	191	(2.40)	1.36	(13.6)	1.48	(14.8)
SAE J403 (1005) STEEL						
482°C (900°F) − 1 h	125	(1.57)	0.83	(8.3)	1.50	(15.0)
843°C (1550°F) − 1 h	119	(1.50)	0.88	(8.8)	1.52	(15.2)
843°C (1550°F) − 4 h	88	(1.10)	1.06	(10.6)	1.54	(15.4)
1100°C (2012°F) − 4 h	111	(1.40)	1.08	(10.8)	1.52	(15.2)

TABLE 4. Carbon and Nitrogen Analyses of Magnet Materials Before and After Annealing at 843°C (1550°F) for 4 hours in 94% Nitrogen-6% Hydrogen.

Alloy	Element, % by Weight			
	Carbon		Nitrogen	
	As-received	Annealed	As-received	Annealed
EMI	0.016	0.015	0.009	0.009
Magnet iron	0.020	0.010	0.008	0.010
Core iron	0.016	0.007	0.007	0.006
Electrical iron	0.013	0.008	0.008	0.008
Ingot iron	0.024	0.009	0.006	0.008
SAE J403 (1005) steel	0.062	0.030	0.009	0.007

The results of this aging study are shown in Table 5. The data show that the EMI, magnet iron, core iron, and electrical iron were not degraded by the aging treatment. By comparison, the coercive force of the ingot iron increased from 95 (1.20) to 127 A/m (1.60 Oe) during the first 200 hours and from 127 (1.60) to 135 A/m (1.70 Oe) during the next 200 hours. Similarly, the coercive force of the 1005 steel increased from 81 (1.02) to 116 A/m (1.46 Oe) during the first 200 hours, from 116 (1.46) to 1.43 A/m (1.80 Oe) during the next 200 hours, and from 143 (1.80) to 150 A/m (1.88 Oe) during the final 104 hours.

It appears that the U.S. Air Force Specification AF 71A45549 coercive force requirement of 119 A/m (1.5 Oe) after annealing may not be adequate for applications requiring magnetically stable materials. The purchaser, therefore, should specify a maximum allowable coercive force after annealing and aging.

Table 6 lists hardnesses and grain sizes in accordance with the ASTM Method for Estimating the Average Grain Size of Metals (E 112) of the specimens annealed at 843°C (1550°F) for 4 hours. The annealed microstructures are shown in Figure 2. The EMI, magnet iron, core iron, and electrical iron exhibited relatively clean, equiaxed structures. The ingot iron and 1005 steel, on the other hand, contained appreciable amounts of inclusions. It should be noted that the materials containing inclusions were the only ones to suffer an increase in coercive force during the aging test.

The effects of impurities on coercive force and magnetic aging have been discussed in some detail by Richards.[2] The data presented in this paper are consistent with Figure 3 of Richards' paper that shows that coercive force is a function of both carbon and nitrogen and that reducing the concentration of either of these elements will reduce the coercive force. The results of the present aging study, however, cannot be explained on the basis of Richards' paper, which shows that above approximately 0.004% nitrogen, magnetic aging should be a linear function of nitrogen content. Since all of the materials in the present investigation contained about the same amount of nitrogen, it appears that the magnetic instability of the ingot iron and 1005 steel cannot be due to nitrogen alone. Unfortunately, the chemical analyses of these materials provides no clue as to the cause of the observed instability.

[2]Richards, J. T., in *Proceedings of the 25th Relay Conference*, National Association of Relay Manufacturers, Elkhart, Ind., 1977.

TABLE 5. Magnetic Properties of Annealed Materials Before and After Aging [All Materials Annealed at 843°C (1550°F) for 4 hours in 94% Nitrogen-6% Hydrogen Before Aging].

Heat Treatment	*Hc*		*Br*		*Bm*	
	A/m	(Oe)	T	(kG)	T	(kG)
EMI						
Annealed	76	(0.95)	1.44	(14.4)	1.56	(15.6)
Aged 200 h at 100°C	76	(0.95)	1.44	(14.4)	1.56	(15.6)
Aged 400 h at 100°C	76	(0.96)	1.44	(14.4)	1.56	(15.6)
MAGNET IRON						
Annealed	80	(1.00)	1.48	(14.8)	1.60	(16.0)
Aged 200 h at 100°C	78	(0.98)	1.44	(14.4)	1.58	(15.8)
Aged 400 h at 100°C	78	(0.98)	1.44	(14.4)	1.58	(15.8)
CORE IRON						
Annealed	72	(0.90)	1.48	(14.8)	1.60	(16.0)
Aged 200 h at 100°C	72	(0.90)	1.44	(14.4)	1.58	(15.8)
Aged 400 h at 100°C	72	(0.90)	1.44	(14.8)	1.58	(15.8)
ELECTRICAL IRON						
Annealed	127	(1.60)	1.48	(14.8)	1.58	(15.8)
Aged 200 h at 100°C	127	(1.60)	1.48	(14.8)	1.58	(15.8)
Aged 400 h at 100°C	127	(1.60)	1.48	(14.8)	1.58	(15.8)
INGOT IRON						
Annealed	95	(1.20)	1.44	(14.4)	1.60	(16.0)
Aged 200 h at 100°C	131	(1.65)	1.44	(14.4)	1.56	(15.6)
Aged 400 h at 100°C	136	(1.71)	1.44	(14.4)	1.58	(15.8)
SAE J403 (1005) STEEL						
Annealed	81	(1.02)	1.20	(12.0)	1.56	(15.6)
Aged 200 h at 100°C	116	(1.46)	1.32	(13.2)	1.56	(15.6)
Aged 400 h at 100°C	143	(1.80)	1.36	(13.6)	1.52	(15.2)
Aged 504 h at 100°C	150	(1.88)	1.36	(13.6)	1.54	(15.4)

TABLE 6. Rockwell Hardnesses and ASTM Grain Sizes of Iron and Low Carbon Steel After Annealing at 843°C (1550°F) for 4 hours in 94% Nitrogen-6% Hydrogen.

Specimen	Rockwell Hardness, F Scale	ASTM Grain Size[a]
EMI	68.8	1
Magnet iron	65.6	1-2
Core iron	58.8	1
Electrical iron	77.6	6
Ingot iron	79.1	1-2
SAE J 403 (1005) steel	76.2	5-6

[a] In accordance with ASTM Method E 112.

SUMMARY AND CONCLUSIONS

When annealed at 843°C (1550°F) in forming gas, the magnet iron and core iron were found to be equivalent to EMI with regard to both coercive force and magnetic stability. The electrical iron exhibited similar magnetic properties after annealing in forming gas, but required a higher annealing temperature to reduce the coercive force to an acceptable value. Both the ingot iron and the 1005 steel met the coercive force requirement after annealing at 843°C (1550°F) in forming gas, but suffered significant increases in coercive force during aging.

It is concluded that magnet iron and core iron can be used as direct replacements for EMI when treated in accordance with U.S. Air Force Specification AF 71A45549. The electrical iron also can be used as an alternate to EMI, but may require a modified annealing process. The usefulness of the ingot iron and 1005 steel in soft magnet applications is questionable because of magnetic instability. (The stability of these materials might be improved by annealing in a more reactive atmosphere such as wet hydrogen. However, this was beyond the scope of the present investigation.)

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