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IRON COBALT VANADIUM ALLOY

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ABSTRACT OF THE DISCLOSURE

Described herein is a novel and improved alloy containing cobalt, iron and vanadium and controlled quantities of carbon.

This invention relates to an improved alloy useful in electrical applications because of its magnetic properties. More particularly, the invention concerns an improved version of the cobalt, vanadium, iron alloy known commercially as, "Vanadium Permendur." This alloy contains 47.5 to 50.5% cobalt, 1.7 to 2.1% vanadium and the balance essentially iron.

The vanadium, cobalt and iron-containing alloy is finding increasing use as a rotor and stator material in electrical generators for aircraft because of its high magnetic flux carrying capacity which makes it possible to achieve a considerable reduction in weight of the units in which components of the alloy are employed. As a result of the high operating speeds, i.e., 8,000 to 20,000 r.p.m. of these generators, it is also important that the material have high mechanical strength as well. Although specific requirements may vary, some applications require a minimum .2% offset yield strength of 70,000 p.s.i. coupled with the minimum tensile elongation of 5% and relatively little deterioration in magnetic properties. Unfortunately, the presently commercial version of this alloy develops a yield strength of only approximately 55,000 p.s.i. when annealed for four hours at 1385° F., which is a standard pilot test procedure.

The present invention provides a composition which possesses significantly improved strength while retaining satisfactory magnetic properties. In accordance with this invention, there is provided an alloy consisting essentially of 47.5 to 50.5% cobalt, 1.7 to 2.1% vanadium, a controlled carbon content of 0.025 to 0.1%, preferably 0.03 to 0.08%, and the balance essentially iron. Laminations or strips made of alloys in accordance with the invention possess increased yield strength and relative insensitivity to normal variations in annealing conditions, i.e., temperature and time at temperature, and good ductility as well. In particular, alloys in accordance with the invention may be made which possess a minimum yield strength of 70,000 p.s.i. while retaining satisfactory magnetic properties.

In the production of alloys containing vanadium, cobalt and iron, the element carbon is usually regarded as an undesirable impurity because it is considered damaging to magnetic properties. Carbon concentration is usually reduced to the lowest level which is economically or technically feasible during melting and/or during annealing at a subsequent stage of solid state processing. It has now been discovered, however, that the deliberate increase of carbon concentration in alloys containing cobalt, iron and vanadium has the beneficial result of altering the recrystallized microstructure to effect a substantial increase in yield strength while producing little or no detriment to ductility and magnetic properties.

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As presently melted and made available commercially, Vanadium Permendur contains less than 0.02% carbon and usually less than 0.01% carbon. I have found that when the carbon is increased to the range of 0.025 to 0.1%, the yield strength of the alloy is materially improved. Carbon contents above about 0.1% result in relatively little additional refinement of recrystallized grain size and, hence, relatively little strength increase. The additional carbide particles formed by increasing the carbon concentration to greater than 0.1% have a disproportionately harmful effect on magnetic properties particularly the alternating current properties. As the examples below indicate, in the fully recrystallized condition, the yield strength for Co-V-C-Fe alloys increases only slightly with increasing carbon content up to a threshold concentration of about .020% carbon. Yield strength then increases very rapidly with increasing carbon content up to a concentration in the range .025–.030% carbon. As carbon is increased above this level yield strength again increases rather gradually. The yield strength level attained in the range .025–.030% carbon is approximately 70,000 p.s.i.

The following examples will illustrate the practice of the invention and the critical effect of carbon on properties.

Alloys of the composition described in Table I were prepared in ingot form and reheated to 2250° F., thereafter hot rolled to 0.080-inch thickness. The resulting hot rolled strip was annealed at 1450° F. and brine quenched to render it sufficiently ductile for cold rolling. It was determined metallographically that the grain size of the quenched 0.080-inch strip containing 0.028% or more carbon was distinctly finer than that of the 0.0045% carbon material. After descaling by sand blasting, sample sections of the annealed and quenched 0.080-inch strip from each of the four heats were cold rolled to 0.014" and 0.010" respectively, without intermediate heat treatment. This processing duplicated as nearly as possible the practices used in the commercial production of Vanadium Permendur.

TABLE I

Heat	C	Co	V	Fe
3835	0.0045	49.05	2.05	Balance.
3839	0.028	48.80	2.05	Do.
3837	0.055	48.95	2.07	Do.
3838	0.10	48.90	2.05	Do.
73205	0.0133	48.90	2.02	Do.
82228	0.007	49.60	1.84	Do.

Ring samples (1" I.D. x 1½" O.D.) and tensile test specimens were prepared from the cold rolled experimental strip and similarly from the 0.014" and 0.010" strip, representing commercially available Vanadium Permendur (the latter designated heat 73205 and 82228 respectively). The 0.014" test samples were batch annealed (stacked laminations and tensile specimens in a welded box) at various temperatures in the range 1300 to 1550° F. and for various times in dry hydrogen (dew point of hydrogen supply was −80° F. or dryer). The 0.010" samples were continuously annealed, singly and without stacking, in a belt furnace for 10 minutes at 1400° F., 1450° F. and 1500° F. in dry hydrogen atmosphere having a dew point of about −20° F.

The tensile and magnetic tests results are disclosed in Table II for the compositions described in Table I. The results with respect to samples continuously annealed are described in Table III.

TABLE II

Heat	Anneal	Tensile tests: .2% Y.S.	Tensile tests: Percent elongation	D.C. permeability: H at 20 kb.	H at 22 kb.	B at 10 H	B at 20 H	B at 50 H	B at 100 H	B at 200 H	Core loss: 400 Hz. 15 kb.	400 Hz. 20 kb.	2,400 Hz. 10 kb.	2,400 Hz. 15 kb.
3835	1,300° F., 2 hrs	119,300	8.0	50.4	--------	2,080	16,250	19,980	21,240	21,860	121.9	230.1	510	1,107
3835	1,325° F., 1 hr	120,950	9.5	38	138	5,130	18,100	20,580	21,660	22,420	111	199	441	988
3835	1,325° F., 2 hrs	58,330	5.8	7.14	23.5	20,570	21,650	22,560	22,880	23,110	21.1	38.6	148	412
3835	1,325° F., 4 hrs	55,325	6.8	6.04	34.0	20,950	21,900	22,730	23,770	23,180	20.4	34.1	150	421
3835	1,400° F., 1 hr	60,000	6.0	6.16	38.0	20,810	21,820	22,400	22,850	23,100	18.1	31.4	149	394
3835	1,450° F., 1 hr	62,750	6.8	6.22	22.4	20,820	21,830	22,650	22,970	23,190	19.8	34.8	144	428
3835	1,550° F., 4 hrs	40,595	5.0	4.88	18.1	21,250	22,100	22,780	22,960	23,130	16.8	30.1	130	397
3939	1,300° F., 2 hrs	122,400	9.8	40	149	4,280	17,800	20,430	21,510	22,270	118	211	471	1,051
3839	1,325° F., 1 hr	126,150	8.8	35.8	137	5,530	18,400	20,580	21,660	22,380	113	204	457	1,006
3839	1,325° F., 2 hrs	68,930	5.5	7.8	27.5	20,470	21,490	22,460	22,820	23,040	24.6	46.4	150	437
3839	1,325° F., 4 hrs	67,875	6.3	7.9	33	20,400	21,450	22,400	22,760	23,000	23.4	40.6	162	437
3839	1,400° F., 1 hr	72,875	6.3	7.0	27.6	20,630	21,655	22,590	22,930	23,160	24.8	42.7	162	459
3839	1,450° F., 1 hr	71,800	5.3	7.7	30	20,530	21,550	22,480	22,870	23,130	27.5	50.1	169	489
3839	1,550° F., 4 hrs	50,020	5.5	6.6	25.6	20,680	21,750	22,580	22,970	23,140	22.5	42.5	147	407
3837	1,300° F., 2 hrs	128,150	7.5	27.8	105.4	12,070	19,250	21,020	21,890	22,530	77.6	152.1	354	851
3837	1,325° F., 1 hr													
3837	1,325° F., 2 hrs	74,310	7.3	10.3	28	19,920	21,250	22,380	22,900	23,250	36.2	71.2	206	537
3837	1,325° F., 4 hrs	73,450	5.8	8.26	33	20,350	21,360	22,400	22,820	23,040	28.9	52.3	182	499
3837	1,400° F., 1 hr	73,000	6.5	8.02	31.8	20,380	21,460	22,490	22,880	23,150	29.9	52.9	189	489
3837	1,450° F., 1 hr	74,150	6.8	8.68	32	20,280	21,360	22,390	22,830	23,110	31.6	57.4	181	505
3837	1,550° F., 4 hrs	65,755	6.8	7.9	29.4	20,380	21,510	22,500	22,850	23,100	29.1	53.4	172	474
3838	1,300° F., 2 hrs	124,800	10.0	38.6	161	4,150	18,000	20,520	21,490	22,230	95.0	218	494	1,104
3838	1,325° F., 1 hr													
3838	1,325° F., 2 hrs	73,115	7.0	14.8	55	19,070	20,550	21,720	22,280	22,660	37.0	74.0	200	542
3838	1,325° F., 4 hrs	70,225	7.0	10.3	60.0	19,900	21,100	22,280	22,760	23,000	31.8	58.1	189	517
3838	1,400° F., 1 hr	73,350	5.5	9.54	35.4	20,075	21,255	22,285	22,770	23,140	32.2	59.2	195	509
3838	1,450° F., 1 hr	71,525	5.3	10.4	39	19,980	21,100	22,240	22,770	23,050	34.0	63.2	191	521
3838	1,550° F., 4 hrs	61,440	6.0	9.52	34	20,080	21,260	22,350	22,800	22,990	31.6	57.7	173	479
73205	1,300° F., 2 hrs	110,850	13.0	44	168	2,010	17,280	20,220	21,390	22,230	125.3	214.2	494	1,054
73205	1,325° F., 1 hr	107,000	11.5	33.8	106	5,820	18,540	20,800	21,900	22,650	104	192	434	954
73205	1,325° F., 2 hrs	60,830	6.8	6.58	25	20,780	21,760	22,550	22,810	23,010	27.8	52.5	220	619
73205	1,325° F., 4 hrs	58,900	7.8	7.20	24	20,700	21,760	22,650	22,985	23,120	24.4	41.6	193	539
73295	1,400° F., 1 hr	55,425	8.5	7.24	25.2	20,670	21,740	22,640	22,940	23,170	14.9	25.0	107	281
73205	1,450° F., 1 hr	57,250	7.5	5.22	19.4	21,120	22,030	22,730	22,970	23,190	18.8	35.4	146	437
73205	1,550° F., 4 hrs	42,100	7.0	5.52	19.7	21,080	22,010	22,650	22,910	23,060	22.6	42.0	181	520

TABLE III

Heat	Anneal	Tensile tests: .2% Y.S.	Tensile tests: Percent elongation	D.C. permeability: H at 20 kb.	H at 22 kb.	B at 10 H	B at 20 H	B at 50 H	B at 100 H	B at 200 H	Core loss: 400 Hz. 15 kb.	400 Hz. 20 kb.	2,400 Hz. 10 kb.	2,400 Hz. 15 kb.
3835	1,400° F., 10 mins	62,500	8.0	8.6	29.2	20,270	21,440	22,500	22,910	23,120	16.9	29.1	109	261
3835	1,450° F., 10 mins	58,600	7.3	8.6	32	20,310	21,430	22,420	22,730	22,970	15.8	24.0	102	243
3835	1,500° F., 10 mins	56,800	7.3	8.54	33.6	20,260	21,380	22,370	22,730	22,940	14.9	23.2	101	237
3839	1,400° F., 10 mins	73,650	7.5	9.74	37.2	20,210	21,330	22,360	22,760	22,960	22.0	36.1	120	294
3839	1,450° F., 10 mins	71,525	8.3	9.48	38	20,110	21,180	22,270	22,690	22,930	21.0	34.4	115	280
3839	1,500° F., 10 mins	69,000	7.5	9.08	35.6	20,160	21,230	22,320	22,690	22,930	20.0	36.1	118	281
3837	1,400° F., 10 mins	77,875	8.0	11.3	46.4	19,765	20,930	22,070	22,630	22,865	26.9	46.2	139	327
3837	1,450° F., 10 mins	74,000	7.5	11.2	46	19,760	20,930	22,070	22,530	22,860	26.5	43.6	133	314
3837	1,500° F., 10 mins	69,050	7.5	11	46	19,860	20,930	22,030	22,530	22,810	26.2	42.0	131	311
3838	1,400° F., 10 mins	76,650	6.0	12.6	49.4	19,515	20,730	22,020	22,640	22,930	29.7	55.2	153	374
3838	1,450° F., 10 mins	74,300	7.5	12.6	48.6	19,560	20,780	22,020	22,640	22,950	28.2	51.4	141	342
3838	1,500° F., 10 mins	72,875	6.8	12.6	48.8	19,560	20,780	22,020	22,580	22,870	28.1	49.3	140	334
82228	1,400° F., 10 mins	55,150	8.0	9.3	34.0	20,140	21,275	22,335	22,720	22,990	16.5	26.2	105	262
82228	1,450° F., 10 mins	52,700	8.3	9.2	32.6	20,140	21,320	22,410	22,820	23,090	15.6	20.2	110	257
82228	1,500° F., 10 mins	52,300	7.0	9.0	31.8	20,190	21,380	22,410	22,770	23,000	15.3	25.4	107	264

It was determined metallographically that recrystallization was incomplete in all of the samples annealed at 1300° F. for two hours and 1325° F. for one hour, and, although yield strengths in excess of 100,000 p.s.i. were developed, the corresponding magnetic properties were extremely poor (Table II). The 2-hour and 4-hour treatments at 1325° F. and all of the treatments at temperatures higher than 1325° F. resulted in complete recrystallization in all of the experimental heats and in the control material (Heat 73205). Each of the alloys containing 0.028% or more carbon developed yield strengths of 70,000 p.s.i. or higher (Table I) in one or more of the batch treatments which resulted in complete recrystallization. With one exception, the direct current magnetic properties, which are of primary importance in the 70,000 p.s.i. yield strength application, were within the limits generally specified for that strength level. In the recrystallizing treatments evaluated in these tests the heats containing less than 0.028% carbon developed somewhat better magnetic properties, but yield strengths were never higher than 63,000 p.s.i. The data in Tables II and III illustrate that, in the fully recrystallized condition, the materials containing 0.028% or more carbon have satisfactory and acceptable magnetic properties but at substantially higher strength levels than the materials containing less than 0.028% carbon. Similar structures and properties can be developed in short time heat treatments (10 minutes at temperature) by continuous annealing.

A useful increase in the yield strength of Vanadium Permendur can be obtained by a deliberate increase in the carbon content of the alloy. An increase in carbon concentration to higher than normal levels, i.e., greater than 0.020% carbon, results in the formation during processing of second phase particles, presumed to be vanadium carbides, which are then present in sufficient number to decrease significantly the recrystallized grain size developed during the annealing of cold rolled Vanadium Permendur strip or laminations and which effectively limit grain growth following recrystallization. The action of the second phase particles is such that the development of a stable fine-grained recrystallized structure is relatively insensitive to variations in annealing time and temperature. The second phase particles and the associate fine grain size act in combination to produce yield strengths which are substantially higher than those developed in the normal alloy by the same annealing conditions. The ductility of the recrystallized fine-grained structure, as measured by elongation in a tensile test, is acceptable but somewhat lower than that of the normal alloy. Although the presence of second phase particles causes some deterioration in magnetic properties, the associated fine-grained structure is magnetically satisfactory.

An important advantage of the invention is that the yield strength improvement associated with increased carbon concentration in Vanadium Permendur is attained in fully recrystallized structures in which grain growth following recrystallization is relatively limited. These characteristics greatly increase the range of annealing conditions which can be employed to realize the strength improvements. It is difficult to attain a strength increase in the conventional alloy by establishing a partially recrystallized or barely recrystallized structure, particularly with a batch heat treatment. In contrast, the fully recrystallized grain structure is relatively stable and, therefore, the yield strength of the higher carbon alloys, e.g., 0.055% carbon alloy, Heat 3837, remains high. A low carbon alloy (Heat 3835, .0045%C) and the normal commercial alloy (Heats 73205 and 82228) develop lower strengths in the fully recrystallized condition and show a greater tendency toward grain growth and loss of strength with increasing annealing temperature and time. The similarity of the yield strengths and magnetic properties developed by batch heat treatments (Table I) and by continuous annealing (Table II) further indicate the latitude in annealing conditions which may be employed to develop the strength improvements which are characteristic of alloys having controlled critical amounts of carbon in accordance with the invention. It should be noted that although the alloys described were relatively pure with regard to the concentrations of residual elements (Mn, P, S, Si, Cr, Ni, and Al), it is believed that strength levels may be increased still further by solid solution strengthening effects resulting from an increase in the concentra-

tions of one or more of the residual elements or by adjusting the base composition of the alloy. The strengthening effects of carbon can be superimposed on strength improvements attained by solid solution effects.

It is apparent from the foregoing that various changes and modifications may be made without departing from the invention. Accordingly, the scope thereof should be limited only by the appended claims wherein what is claimed is:

1. An improved cold worked and subsequently fully recrystallized alloy consisting essentially of 47.5 to 50.5% cobalt, 1.7 to 2.1% vanadium, the balance essentially iron and containing 0.025 to 0.10% carbon and having a yield strength of at least 70,000 p.s.i.

2. An improved alloy according to claim 1 having 0.03 to 0.08% carbon.

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