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A possibility for developing high strength soft magnetic materials in FeCo–X alloys

KOHJI KAWAHARA, MITSURU UEHARA
National Research Institute for Metals, Nakameguro, Meguro-ku, Tokyo 153, Japan

The effects of the combination of cold rolling and heat treatment upon mechanical and magnetic properties have been examined for the FeCo-based alloys with additive elements such as carbon, vanadium, chromium, molybdenum, tungsten, tantalum, niobium, and nickel. It is revealed that whenever alloys including such elements are subjected to cold rolling the yield strength can be raised to between 100 and 200 $kg\,mm^{-2}$, and that cold rolling is effective in both strengthening and in improving soft magnetic properties, even when cold rolling is followed by annealing or ageing. This suggests that these alloys can be used for lessening the weight of parts which are used as soft magnetic materials, although their properties will depend on the combinations of cold rolling and heat treatments, and/or on the added elements and the control of their amount.

1. Introduction

Equiatomic FeCo alloys, which have a high saturation magnetization, are too brittle to be fabricated, their application being confined to limited fields. It has been found, however, that a small addition of vanadium [1–3] or chromium [4–5] can improve the ductility of the alloys without lowering their magnetic properties. Much attention has been paid to the elucidation of the effectiveness of such additional elements. One of the present authors has also been concerned with this problem [6–9], and the following important phenomena have been found: (a) there are effective elements other than vanadium and chromium, namely, carbon, molybdenum, tungsten, tantalum, niobium, and nickel [6]; (b) cold rolling over a critical reduction, about 72%, is very effective for improving the ductility [9]. This effectiveness of cold rolling suggests that one requirement for increasing the strength of the alloys may be easily accomplished. In the present paper the possibility that the high strength of soft magnetic FeCo alloys is obtained by cold rolling is shown based on the results of tensile tests and magnetic measurements carried out for the FeCo–X alloys employed in the previous investigation [6–9].

2. Experimental procedures

Experimental procedures and specimens were the same as those used in the previous papers [6–9]. Ingots were prepared with high purity electrolytic iron and cobalt, additive elements, each of which has a purity of 99.9%, and a ferroalloy for the addition of vanadium. The ingots used were not consistent in shape, size, and melting process because they were manufactured for various purposes other than the present investigation. The main sample, which consisted of an FeCo–2V alloy, was melted in a high-frequency induction furnace *in vacuo* and then cast into a 17 kg ingot with a section of 90 mm square. Samples with different ratios of iron and cobalt were cast into 2.3 kg ingots; those containing carbon were cast into a 980 g ingot 35 mm in diameter for 0.5%C and into a 6.5 kg ingot with a section of 70 mm square for 2%C. Ingots containing other elements, i.e. chromium, molybdenum, tungsten, tantalum, niobium, and nickel, were arc-melted in an argon atmosphere and then cast into 120 g ingots 15 mm in diameter. All ingots used were homogenized at 1200° C for 4 h, followed by hot rolling to plates 1 to 5 mm in thickness, irrespective of the size of the ingots. Plates 5 mm thick were subjected to cold rolling after the heat treating, that is, they were heated at 800 to 1200° C and then quenched in iced brine.

Tensile tests were carried out on specimens of 20 mm in gauge length, 2 to 3 mm in width, about 0.5 mm in thickness, under a crosshead speed of 1 mm min^{-1}. The values of saturation magnetization and coercive force were determined at an applied force of 1.1 MA m^{-1}, using the vibrating sample magnetometer. The specimens for these measurements was cut as a disc of 7 mm in diameter from the piece utilized in tensile testing. Attention was paid to determine whether any anisotropy due to rolling occurred on these specimens. Hysteresis curves were taken as a function of the angle between the direction of the magnetic field and the direction of rolling of the disc-shaped specimen, and eventually no anisotropy was observed within the limits of experimental error.

For some specimens the early rising of magnetization at low magnetic field was measured by a d.c. magnetic hysteresis loop tracer, using a ring-like specimen of outer diameter 45 mm and inner diameter of 35 mm. These ring specimens, 0.5 to 1 mm in thickness, were measured singly, without stacking.

3. Experimental results

3.1. Effect of cold rolling and heat treatments upon tensile and magnetic properties in FeCo–2V alloys

It has been shown previously for FeCo–2V alloys that the tensile strength achieved by cold rolling was below about 75 kg mm^{-1} and that the yield point was unclear [8, 9]. Cold rolling increased the strength and the yield point appeared clearly, even though the specimens were heat treated after the rolling [8, 9, 10].

Table I shows the mechanical and magnetic properties of the specimens rolled to 90% and then annealed or aged. The structures of the alloys, as have been shown in the previous paper [8], depend on the quenching temperatures: a massive martensitic structure, a mixed structure consisting of martensite and ferrite, and a ferritic structure are formed by quenching from the temperature of 1100, 950 and 800° C, respectively. Subsequent ageings at below 730° C are accompanied by ordering, recrystallization, and precipitation [8].

The rolled specimens all show marked increases in yield strength with increasing coercive force, the values over 130 kg mm^{-2} being maintained even in the case of ageing at 500° C. Although the yield strength of the rolled martensite is decreased by annealing at 800° C, it remains over 50 kg mm^{-2} even after ageing at 650° C for 16 h, with decreasing coercive force. In the case of the mixed and the ferritic structure, the strengths are similar to those of the martensite mentioned above. In the specimens that were again transformed martensitically after cold rolling, inclusive of subsequent annealing, the yield strengths were maintained at about 50 kg mm^{-2}. For FeCo–2V alloys, it is concluded that once cold rolling is carried out, the yield strength can be maintained at about 50 kg mm^{-2}, even though such rolled specimens are subsequently annealed.

3.2. Effect of cold rolling and heat treatments upon tensile and magnetic properties in FeCo–X alloys

In Table II the mechanical and magnetic properties are shown for the alloys having different ratios of iron to cobalt and having different kinds of additive elements. For the alloys in which the ratios are varied, the decreases in yield strength due to ageing are relatively larger at 650° C than at 400° C. However, this difference in strength between the two ageings can be seen to be lessened as the ratio approaches an equiatomic one, 50/50. For the FeCo–2V alloy, for example, the difference is very small, the yield strength being about 113 kg mm^{-2} even after ageing at 650° C for 16 h; while for the $Fe_{70}Co_{30}$–2V alloy and the $Fe_{30}Co_{70}$–2V alloy, yield strength is noticeably reduced to 39 and 75 kg mm^{-2}, respectively. These values are less than half of their tensile strengths.

Carbon-bearing alloys with 0.5% carbon all are weak irrespective of heat treatments. The alloys with 2% carbon, however, show high strength – even after annealing and then ageing, the yield strengths are above 80 kg mm^{-2}, with a relatively small coercive force. From this viewpoint of strengthening, tungsten seems to be the most effective element. In an alloy with 2% tungsten, when aged at 500° C for 1 h after cold rolling to 90%, the yield strength is over 200 kg mm^{-2}, with about 9% elongation.

3.3. Magnetic properties at a low magnetic field in an FeCo–2V alloy

It is expected that yield strength can be easily

TABLE I Effect of cold rolling and heat treatment upon mechanical and magnetic properties in an FeCo–2V alloy

Heat treatments	Ageing (°C, h)	Tensile strength ($kg\,mm^{-2}$)	Yield strength ($kg\,mm^{-2}$)	Elongation (%)	Saturation magnetization (T)	Coercive force ($kA\,m^{-1}$)
1100° C 5 min IBQ*, 90% CR†	As-rolled	146	119‡	5.6	2.22	2.9
	500 0.5	154	135.7	6.7	2.25	2.0
	500 1	136	128.9	4.4	2.23	2.0
	500 2	154	130.8	8.3	2.27	1.9
	600 16	118	–	1	2.24	2.0
1100° C 5 min IBQ, 90% CR, 800° C 5 min, IBQ	As-annealed	79	61.7	9.0	2.24	0.25
	400 1	101	63.0	11.5		
	400 16	70	56.1	5.0		
	400 48	75	59.3	7.0		
	650 16	62	51.6	6.0	2.27	0.54
950° C 5 *min* IBQ, 90% CR, 800° C 5 *min*, IBQ	As-rolled	137	136‡	2.2		
	As-annealed	82	58.4	8.5	2.24	0.25
	400 1	86	56.7	10.0		
	400 16	75	48.0	5.0		
	400 48	68	53.2	5.0		
	650 16	59	44.5	3.5	2.29	0.68
800° C 5 min IBQ, 90% CR, 800° C 5 min, IBQ	As-rolled	142	141‡	2.8		
	As-annealed	90	58.0	10.0	2.24	0.24
	400 1	96	54.2	11.0	2.25	0.29
	400 16	73	50.5	6.0		
	400 48	67	50.5	5.0		
	500 1	61	49.0	5.0	2.3	0.33
	650 16	53	44.2	3.5	2.28	0.60
1100° C 5 min IBQ, 90% CR, 1050° C 5 min, IBQ	As-transformed	75	60‡	12.0		
	400 1	81	51.7	13.5		
1100° C 5 min IBQ, 90% CR, 1050° C 5 min and then 800° C 5 min IBQ	As-annealed	79	49.7	10.5		
	400 1	90	50.0	16.0		

*IBQ = iced-brine quenching.
†CR = cold rolled.
‡0.2% proof.

TABLE II Effect of heat treatment on mechanical and magnetic properties in different alloys

Alloys	Heat treatments	Ageing (° C, h)	Tensile strength (kg mm^{-2})	Yield strength (kg mm^{-2})	Elongation (%)	Saturation magnetization (T)	Coercive force (kA m^{-1})
$Fe_{70}Co_{30}-2V$	1100° C 10 min IBQ, 90% CR	400 1	127	92.6*	3.5	2.35	1.83
		650 16	58	38.7	11.3	2.34	0.76
$Fe_{60}Co_{40}-2V$		400 1	140	127.1*	5	2.31	2.3
		650 16	119	113.0	4	2.31	1.3
$Fe_{40}Co_{60}-2V$		400 1	167	165*	4	2.15	2.1
		650 16	128	104.2*	8.5	2.21	1.8
$Fe_{30}Co_{70}-2V$		400 1	154	134*	1	2.04	1.7
		650 16	82	74.8*	3.8	1.94	2.0
$Fe_{30}Co_{70}$		400 1	107	102.6*	4	2.14	1.0
		650 16	59	39.1*	15	2.12	0.49
FeCo–0.5C	800° C 10 min IBQ, 90% CR, DeC,† 800° C 10 min IBQ	As-annealed	33	32.5	0.5	2.33	0.56
	800° C 10 min IBQ, 90% CR, DeC, 800° C 5 min IBQ	400 1	35	28.2	5.5	2.34	0.48
		600 1	23	13.6	3	2.37	1.0
	800° C 10 min IBQ, 90% CR, 800° C 5 min IBQ	400 1	89	46.7	15	2.36	1.0
		650 1	40	36.9	1.2	2.37	0.82
FeCo2C	800° C 10 min IBQ, 90% CR	400 1	119	107.2	9	2.37	2.5
		600 1	139	110.3	9	2.37	1.5
		650 16	94	56.7	12	2.36	0.92
	800° C 10 min IBQ, 90% CR, 800° C 5 min IBQ	400 1	90	83.8*	15.5	2.34	1.0
		650 16	66	40.7	9	2.37	0.66
FeCo–0.5Cr	1200° C 5 min IBQ, 90% CR	500 0.5	143	132.1*	6	2.35	2.8
Mo		500 0.5	170	152.0	8.7	2.33	2.0
W		500 0.5	174	156.8	7	2.33	2.3
Ta		500 0.5	167	157.1*	1	2.33	2.1
Nb		500 0.5	154	142*	5.8	2.33	2.2
FeCo–2CR	1100° C 10 min IBQ, 90% CR	500 0.5	131	114*	1.7	2.29	2.4
W		500 0.5	195	194.7	1.7	2.21	2.0
Ta		500 0.5	214	200*	0.6	2.24	2.8
Nb		500 0.5	182	180*	0	2.16	3.3
Ni		500 0.5	167	160.9	3.3	2.34	2.4
FeCo–2W		as-rolled	151	127.6*	5.6	2.16	2.5
		500 0.5	195	194.7	1.7	2.21	2.0
		500 1	227	213.3	8.9	2.24	2.2

*0.2% proof.

†DeC = decarburized at 1050° C over 10 h.

TABLE III Effect of cold rolling and heat treatments upon magnetization behaviour at low magnetic fields in an FeCo–2V alloy

Sample number	Thickness of sample (mm)	Heat treatments		Coercive force ($kA\,m^{-1}$)	Magnetization (T) at different magnetic fields ($kA\,m^{-1}$)						Saturation magnetization (T)
		Intial conditions	Final conditions		1.2	2.4	4.8	7.2	9.6	12.0	
1	0.5	1100° C IBQ, 90% CR	As-rolled	2.6	0.12	0.26	0.59	0.81	0.98	1.12	2.15
2	0.5	1100° C IBQ, 90% CR	800° C 5 min WQ*	0.37	1.40	1.48	1.60	1.66	1.70	1.72	2.24
3	0.5	950° C IBQ, 90% CR	As-rolled	1.8	0.09	0.23	0.54	0.81	1.03	1.18	2.27
4	0.5	950° C IBQ, 90% CR	800° C 2 min WQ	0.27	1.78	1.90	2.05	2.13	2.17	2.20	2.29
5	0.5	950° C IBQ, 90% CR	800° C 5 min WQ	0.29	1.62	1.69	2.07	2.16	2.20	2.24	2.28
6	0.5	950° C IBQ, 90% CR	800° C 5 min WQ and 500° C 1 h	0.28	1.64	1.91	2.07	2.14	2.18	2.22	2.31
7	1.0	1100° C WQ	As-quenched	1.3	0.98	1.06	1.22	1.37	1.46	1.54	2.21
8	1.0	1100° C WQ	500° C 1 h	1.7	1.00	1.12	1.28	1.42	1.52	1.60	2.23
9	1.0	950° C WQ	As-quenched	0.92	0.76	1.04	1.32	1.48	1.60	1.69	2.12
10	1.0	950° C WQ	500° C 1 h	1.5	0.84	1.04	1.30	1.50	1.63	1.72	2.28
11	1.0	800° C WQ	As-quenched	0.6	1.36	1.54	1.74	1.83	1.90	1.96	2.23
12	1.0	800° C WQ	500° C 1 h	0.76	1.57	1.75	1.98	2.09	2.15	2.21	2.22

*WQ = water quenched.

raised sufficiently either by combining cold rolling and heat treatments, and/or by adding the effective elements mentioned above. In addition to the strength, however, the magnetization at a low magnetic field will come into question in applications to motors or rotors. Such magnetic properties of an FeCo–2V alloy have been measured with ring-like specimens made of cold-rolled plates of 0.5 mm thickness and hot-rolled plates of 1 mm thickness, using a d.c. hysteresis loop tracer. The results are shown in Table III.

In as-rolled specimens, indicated by Nos. 1 and 3 in Table III, the early magnetization is small and the coercive force is large compared with that of other samples. In the case of specimens annealed after rolling, including subsequent ageing (samples Nos. 4, 5 and 6), relatively rapid risings at low magnetization are observed, leading, even in the field of $12\,\mathrm{kA\,m^{-1}}$, to magnetization values of 2.2 T, which are close to the saturation magnetization. On the other hand, the changes in the early rising of the magnetization can be seen to depend on quenching temperature; the rising in the mixed structure (No. 5) is superior to that in the martensitic structure (No. 2), when the rolled specimens were annealed. Interestingly, a relatively shorter annealing brings about a more favourable rising to the early magnetization, although both structures are identical: the annealing for 2 min is superior to that for 5 min. For the same annealing condition, it can be seen that cold rolled specimens, if aged, make the early magnetization better.

In the case of as-hot-rolled specimens of 1 mm in thickness, the best magnetic properties are seen for ferritic specimens (No. 11), and further improvement is produced by ageing (No. 12). On the other hand, since the mechanical properties of the as-hot-rolled plates are relatively inferior to those of cold-rolled plates as previously mentioned [8], cold rolling must be essential to satisfy the need for the high strength materials with high soft magnetic properties.

4. Discussion

Many investigations have, since Elmen's patent [11], been reported with regard to the magnetic properties of FeCo and FeCo–V alloys [10–32]. Recently, with the aim of lessening the weight of generators or motors, high yield strength is imposed on the alloys in addition to excellent soft magnetic properties [27, 28, 32]. Nevertheless, as shown previously [8], it is difficult to improve the strength of the alloys without reducing the magnetic properties. According to Fiedler [27] the yield strength required for application to motors is more than $50\,\mathrm{kg\,mm^{-2}}$, and he has been successful in obtaining such strengths by controlling the grain size by a combination of cold rolling and recrystallization. In such a procedure, however, it is not easy to obtain the desired grain size, particularly in thick plates.

From the present experiment, the possibility that a high yield strength can be obtained without lowering the soft magnetic properties is suggested. Firstly, other than vanadium, the addition of certain elements is effective, e.g., carbon, chromium, molybdenum, tungsten, tantalum, niobium, and nickel, although the strength will depend on the amount of the elements and on whether they are added singly or together. Secondly, since the strength can easily be increased by cold rolling, it is suggested that the desired yield strength should be obtained by combining the rolling with annealing and/or ageing. As an example, in an alloy with 2% tungsten, which was cold rolled and then aged, the resulting yield was greater than $200\,\mathrm{kg\,mm^{-2}}$. Since annealing is occasionally required for developing the desired magnetic properties at low magnetic field, the strength will be decreased. But, as shown for the $Fe_{60}Co_{40}$–2V alloy in Table II, the strength scarcely decreases even after ageing at 650° C, remaining at about $100\,\mathrm{kg\,mm^{-2}}$. Therefore, the strength, even after annealing or ageing, may be expected to be maintained, depending on the extent of such heat treatments.

Increase in strength can be accomplished either by imposing cold rolling or by increasing the amount of additional elements. However, the effective factors for strengthening are sometimes responsible for lowering the magnetic properties. The coercive force of FeCo alloys has been said to be raised by the existence of the strains in the samples [10, 21, 29], by decrease in grain size [10], by occurrence of precipitation [10], by increased degree of ordering [5, 21], by the presence of carbon [15], as well as to be sensitive to changes in structure [10, 21, 23, 29, 30]. The mechanism of increasing the coercive force has not been clarified, but the presence of strains is certainly considered to greatly affect the force. However, cold rolling, as can be seen in Table III, is not necessarily a hindrance in accomplishing the desired properties, because the strain resulting from the rolling can be removed by subsequent annealing.

In conclusion, without reducing the desired soft magnetic properties, high-strength FeCo alloys can be developed by combining cold rolling with heat treatments, or/and by adding, singly or complexly, elements such as carbon, chromium, molybdenum, tungsten, tantalum, niobium, nickel and vanadium.

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