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HIGH-STRENGTH NONMAGNETIC STEELS

Peter Payson, New York, N. Y., assignor to Crucible Steel Company of America, New York, N. Y., a corporation of New Jersey

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This invention pertains to age-hardenable austenitic alloy steels, and more particularly to an alloy steel of this type which can be forged and rolled, and which as annealed or solution-treated is quite soft, so that it can be cold-formed readily or machined, and which can be subsequently age-hardened to a hardness in excess of "C" 35 Rockwell, and which in the age-hardened condition is characterized in being substantially non-magnetic and in having an 0.02% yield strength of at least 85,000 and for most analyses upwards of 100,000 pounds per square inch.

A broad range of analysis of the steel in accordance with the invention is that containing about: 19 to 25% nickel; 5 to 14% chromium; 2 to 6% manganese; 3 to 5% aluminum; from an effective amount up to about 3% silicon; 0.3 to 0.8% carbon; and the balance substantially iron except for optional additions of up to about 3% in aggregate of other elements which do not substantially affect or impair the above mentioned desirable characteristics of the steel of this invention. As illustrative of optional additions within this category, mention may be made of such elements as copper, vanadium, tungsten, molybdenum and cobalt. The usual impurities, such as phosphorous, sulphur, etc., may be present in the steel of the invention within commercial tolerances.

A preferred range of analysis of steel in accordance with the invention is that containing about: 20 to 22% nickel; 8 to 11% chromium; 3.5 to 5% manganese; 3 to 4% aluminum; 0.3 to 0.6% carbon; and the balance substantially iron except for impurities within commercial tolerances, and optional minor additions of other elements as aforesaid.

The steel of the invention is of especial utility for use in retainer rings on the rotors of large electric generators and the like; also for use in periscope tubes in submarines, wherein a non-magnetic steel of high hardness combined with high yield strength is required.

In this connection there has long been a need for a high strength non-magnetic material for use as retainer rings on the rotors of large electric generators. The function of the retainer ring is to hold in place on the rotor the heavy conductors which carry the magnetic field circuit. The centrifugal force generated by the high speed at which the rotor revolves during the operation of the generator tends to throw these conductors off the rotor and it is necessary to have a strong retaining ring to keep them in place. For many machines the retaining rings are made of a low alloy steel such as SAE 4140 heat treated to have a 0.02% yield strength of at least 100,000 pounds

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per square inch (p.s.i.). These provide adequate strength for the application, but they seriously limit the efficiency of the generators in which they are used by the fact that they are magnetic. Retaining rings made of magnetic material have eddy currents induced in them because they are in close contact with conductors carrying large currents. These eddy currents not only represent wasted energy in the system, but also generate heat in the rings which causes undesirable operating conditions. If the rings are non-magnetic, the energy loss is negligible and the rings remain quite cool.

It is well known that steel can be non-magnetic if the composition is so balanced that austenite, the non-magnetic phase of iron, is retained at room temperature. The well known 18-8, type 302 Stainless, is an example of this. However, this steel and all other austenitic steels have relatively low yield strengths unless they are severely cold-worked. When some austenitic steels such as type 302 are severely cold-worked they become magnetic because the cold-working induces the phase change from austenite to ferrite. However, there are some austenitic steels which are sufficiently stable so that they remain austenitic, that is, non-magnetic even after they have been severely cold-worked. The 25 Cr-20 Ni steel, type 310 Stainless, is an example of such a steel. Another example is a steel containing

C	Mn	Si	Ni	Cr	Mo
.35	12.0	.50	3.5	4.5	.30

which has been used in the electrical industry for non-magnetic retaining rings. The shortcoming of this material however is that in the forging of the rings made from it, temperatures and amounts of forging have to be very carefully controlled so that the cold working may be of exactly the right amount to develop in the steel the very high yield strength required of these retaining rings. The electrical industry would much prefer a material in which the high yield strength could be developed by heat treatment rather than by carefully controlled cold-working.

Heat treatment in the ordinary sense applied to steels, that is, a heating to form austenite; followed by a cooling to permit the austenite to transform to martensite or other low temperature transformation product; followed by a tempering treatment to stress relieve and toughen the steel; cannot be considered for non-magnetic steel because all transformation products of austenite such as pearlite, bainite, and martensite are

magnetic. For this application it is desirable that the steel be hardened by heat treatment without causing the austenite to transform.

In my copending application Serial No. 792,929, filed December 20, 1947, I have shown that austenitic steels can be hardened by heat treatment if the composition is such that precipitation hardening occurs, when the steel is given suitable solution and aging treatments. Such a precipitation hardening steel as described in my said copending application has the following constituents and range of analysis:

Carbon	Up to 0.4%
Manganese plus nickel	About 20 to 30%
Chromium	About 15 to 25%
Aluminum	About 2.5 to 4.5%
Molybdenum and/or tungsten	Up to about 5%
Balance	Substantially iron

The above analysis was developed to provide a hardenable corrosion and heat-resisting austenitic steel. In the steel of the present application, the corrosion and heat resistant features are of no significance, the main requirements being high yield strength, low permeability, and low cost. To keep the cost down it is desirable to use as little alloy as possible and this has been accom-

and aluminum for producing a steel which when suitably heat treated will have the desired high yield strength together with the low permeability.

It has been established by tests that steel of this type must have a hardness in excess of Rockwell "C" 35 in order to have the desired 0.02% yield strength of close to 100,000 p. s. i., i. e. at least about 85,000 p. s. i. In order to get a measure of the attainable hardness of the steels of this invention specimens were solution treated at 2300° F. for about 10 minutes, water quenched and then aged at 1100°, 1200°, and 1300° F. for 16 hours, and tested for hardness. The heat treated pieces were also tested for relative magnetism by measuring the pull in grams on a magnetic balance.

I have discovered that both manganese and chromium and also carbon in suitable amounts are very effective in raising the attainable hardness of austenitic, non-magnetic nickel-aluminum steels to over Rockwell "C" 35. This was unexpected since it had been assumed that precipitation hardening in this type of austenitic steel was dependent on a nickel-aluminum compound, and that the balance of the composition was relatively unimportant. The data showing the effects of manganese and chromium are given in Tables I and II.

TABLE I

Effect of manganese on the hardening of austenitic 21% Ni-9% Cr-3.5% Al steel

[Samples solution treated at 2300° F., water quenched and aged for 16 hours at indicated temperatures.]

Bar	Analysis, Per Cent						Rockwell C Hardness After Aging at—		
	C	Mn	Si	Ni	Cr	Al	1100° F.	1200° F.	1300° F.
5814	.35	1.24	.58	20.77	7.81	3.29	3	13	32
5880	.44	2.97	.61	21.45	8.66	3.69	21	45	40
5815	.35	3.75	.59	21.80	8.81	3.58	8	42	32
5881	.49	3.84	.68	21.26	8.68	3.45	17	43	35
5882	.46	4.70	.90	21.29	8.66	3.63	20	46	37
2001	.43	4.69	.67	21.55	8.52	3.17	18	42	33
5816	.36	6.73	.70	20.90	8.75	3.11	8	26	31
5817	.34	1.42	.73	21.50	10.52	2.95	3	18	31
5818	.34	3.52	.51	21.12	10.68	3.43	9	42	32
2007	.45	4.82	.64	21.65	11.05	3.50	22	44	39

NOTE: All steels practically non-magnetic as hardened.

plished in the present invention by limiting the nickel to about 25% maximum; limiting the chromium to about 14% maximum; keeping the carbon over about 0.30%, thus to minimize the need for expensive low-carbon ferroalloys and to permit a freer use of scrap steel; omitting molybdenum and tungsten; and depending on the balance of carbon, manganese, nickel, chromium,

It is clear in both these groups that steels with manganese under 1.5% do not harden as well as those with manganese from about 2% up to about 5%. It also appears from the tests on Bar 5816 that manganese over 6% is detrimental. Accordingly I set the limits on manganese in the steel of this invention at approximately from 2.0 to 6.0%, with the preferred range at 4.0 to 5.0%

TABLE II

Effect of chromium on the hardening of austenitic 5% Mn-22% Ni-3.5% Al steel

[Samples solution treated at 2300° F., water quenched and aged for 16 hours at indicated temperatures.]

Bar	Analysis, Per Cent						Rockwell C Hardness After Aging at—		
	C	Mn	Si	Ni	Cr	Al	1100° F.	1200° F.	1300° F.
2004	.44	4.79	.62	21.56	0.19	3.55	18	22	9
2005	.43	4.56	.65	21.60	2.65	3.51	21	22	12
2006	.45	4.72	.61	21.52	5.51	3.54	17	38	33
5882	.46	4.70	.90	21.29	8.66	3.63	20	46	37
2007	.45	4.82	.64	21.65	11.05	3.50	22	44	39
2008	.46	4.71	.56	21.58	13.96	3.47	22	42	41

NOTE: All steels practically non-magnetic as hardened.

The data of Table II show that a minimum of about 5% chromium is necessary for adequate hardening of this steel, and that the hardness tends to become constant or to decrease somewhat as the chromium is increased beyond about 8%. Accordingly I set the limits on chromium in the steel of this invention at from 5 to 14% with the preferred range at 8 to 11%, the latter for optimum hardening.

It was indicated to a slight degree in Table I that the steels of higher carbon have higher hardness. This is confirmed by the following data of Table III.

TABLE III

*Effect of carbon on the hardening of austenitic
5% Mn-21% Ni-8.5% Cr-3% Al steel*

[Samples solution treated at 2300° F., water quenched and aged for 16 hours at indicated temperatures.]

Bar	Analysis, Per Cent						Rockwell C Hardness After Aging At—		
	C	Mn	Si	Ni	Cr	Al	1100° F.	1200° F.	1300° F.
2000	.27	4.61	.56	21.24	8.78	3.05	16	16	28
2001	.43	4.69	.67	21.55	8.52	3.17	18	42	38
2002	.58	4.76	.69	21.55	8.31	3.54	27	46	37

NOTE: All steels practically non-magnetic as hardened.

This shows that a minimum of about 0.30% carbon is needed in this steel for adequate hardening and that hardness increases with increasing carbon. However, since carbon beyond about 0.80% would make the steel very difficult to forge

ing and that hardening improves rapidly with increasing aluminum. However, the steel becomes difficult to forge as the aluminum is increased beyond about 5%. Furthermore, because of its strong ferrite forming tendencies, aluminum in increasing amount tends to make the steel magnetic. I therefore set the limits for aluminum in the steel of this invention at about 3.0 to 5.0% with a preferred range of 3.0 to 4.0%.

It is desirable from the standpoint of economy to hold the nickel content of the steel to a minimum. However, as shown in Table V, it is necessary to have a minimum of about 19%

nickel in the steel of this invention in order to assure adequate hardening and also to assure stability of the austenite so that it does not transform to a magnetic constituent during the aging treatment.

TABLE V

*Effect of nickel on the hardening of austenitic
4% Mn-9% Cr-3.5% Al steel*

[Samples solution treated at 2300° F., water quenched and aged for 16 hours at indicated temperatures.]

Bar	Analysis, Per Cent						Rockwell C Hardness After Aging At—		
	C	Mn	Si	Ni	Cr	Al	1100° F.	1200° F.	1300° F.
5885	.45	3.97	.85	17.45	8.54	3.69	21	33	39
5886	.45	3.86	.89	19.36	8.54	3.64	21	43	37
5881	.49	3.84	.68	21.26	8.68	3.45	17	43	36

NOTE: The 17.5% Ni steel was slightly magnetic as aged at 1200° F. and strongly magnetic after the 1300° F. aging. The 19.4% Ni steel was slightly magnetic after the 1300° F. aging. All other samples were practically non-magnetic.

I set the carbon limits of the steel of this invention at 0.30 to 0.80% with a preferred range of 0.40 to 0.60%.

Aluminum has an appreciable effect on the hardening of the austenitic steel as may be seen from Table IV.

TABLE IV

Effect of aluminum on the hardening of austenitic 4% Mn-21% Ni-9% Cr steel

[Samples solution treated at 2300° F., water quenched and aged for 16 hours at indicated temperatures.]

Bar	Analysis, Per Cent						Rockwell C Hardness After Aging At—		
	C	Mn	Si	Ni	Cr	Al	1100° F.	1200° F.	1300° F.
5883	.46	3.92	.90	21.36	8.57	2.61	8	26	27
5881	.49	3.84	.68	21.26	8.68	3.45	17	45	35
5884	.48	3.91	.88	21.38	8.57	3.83	34	51	46

NOTE: The 3.8% aluminum steel was very slightly magnetic when aged at 1200° F. All other samples were practically non-magnetic.

Thus it may be seen that a minimum of about 3% aluminum is required for adequate harden-

ing and that hardening improves rapidly with increasing aluminum. However, the steel becomes difficult to forge as the aluminum is increased beyond about 5%. Furthermore, because of its strong ferrite forming tendencies, aluminum in increasing amount tends to make the steel magnetic. I therefore set the limits for aluminum in the steel of this invention at about 3.0 to 5.0% with a preferred range of 3.0 to 4.0%.

On the basis of these data the limits of nickel in the steel of this invention are set at 19 to 25% with a preferred range at 20 to 22%.

The silicon content of the steel within the limits ordinarily found in forgeable steels seems

to have only a minor effect on the hardening of the steel as shown in Table VI.

TABLE VI

*Effect of silicon on the hardening of austenitic
5% Mn-21% Ni-8% Cr-3% Al steel*

[Samples solution treated at 2300° F., water quenched and aged for 16 hours at indicated temperatures.]

Bar	Analysis, Per Cent						Rockwell C Hardness After Aging At—		
	C	Mn	Si	Ni	Cr	Al	1100° F.	1200° F.	1300° F.
2001-----	.43	4.69	.67	21.55	8.52	3.17	18	42	38
5882-----	.46	4.70	.90	21.29	8.66	3.63	20	46	37
2003-----	.47	4.88	1.62	21.39	8.23	3.54	29	47	40

NOTE: All steels practically non-magnetic as hardened.

The limits for silicon in the steel of this invention are therefore set at from an effective amount to about 3.0%.

Aside from those elements already specified above, the balance of the steel consists of iron alone, or with up to about 3% in aggregate of elements that might be introduced with scrap and ferro alloys such as phosphorus, sulfur, copper, vanadium, tungsten, molybdenum, and cobalt, and which do not affect the hardening and the magnetic properties of the steel.

Although maximum hardness and yield strength are attainable in the steel of this invention with a solution treatment of about 2300° F. and an aging at about 1200° F., a good value of yield strength can be obtained together with a low value of permeability with a solution treatment at 2200° F., and even at 2100° F. as shown in Table VII. Furthermore, better values of ductility are obtainable by use of the lower solution temperature.

TABLE VII

Tensile and permeability values of age hardened austenitic Mn-Ni-Cr-Al steel

[Samples solution treated as indicated, and aged for 16 hours at 1200° F., then tested for room temperature mechanical and magnetic properties.]

Bar	C	Mn	Ni	Cr	Al	Sol. Temp. ° F.	Rock. C	Tens. Strength, p. s. i.	.02% Yld. Strength, p. s. i.	El. in 2 in., Per Cent	R. A., Per Cent	Permeability at H=1000
5880-----	.44	3.0	21.5	8.7	3.7	2,200	41	161,000	95,000	15.0	35.4	1.033
5880-----	.44	3.0	21.5	8.7	3.7	2,300	45	173,000	121,000	6.0	15.2	-----
5815-----	.35	3.8	21.8	8.8	3.6	2,300	43	221,000	104,000	6.4	19.1	1.008
5881-----	.49	3.8	21.3	8.7	3.5	2,200	37	160,000	85,000	21.2	33.1	-----
5881-----	.49	3.8	21.3	8.7	3.5	2,300	39	179,000	119,000	4.0	13.6	-----
5882-----	.46	4.7	21.3	8.7	3.6	2,100	37	178,000	97,000	19.2	25.5	1.015
5882-----	.46	4.7	21.3	8.7	3.6	2,200	38	176,000	102,000	13.3	21.0	1.010
5882-----	.46	4.7	21.3	8.7	3.6	2,300	44	177,000	125,000	10.4	2.4	-----
5818-----	.34	3.8	21.1	10.7	3.4	2,300	38	181,000	105,000	6.7	14.0	1.006

It will thus be seen that the steel of the invention is characterized in possessing in the age- or precipitation-hardened condition, high hardness combined with high tensile and yield strength and is, moreover substantially non-magnetic.

I claim:

1. A forgeable and machineable, age-hardenable, austenitic alloy steel which, on solution-treating at about 2100° to 2300° F., followed by aging at about 1200° to 1300° F., is characterized in being substantially non-magnetic and in having a hardness in excess of Rockwell "C" 35 and an 0.02% yield strength of at least 85,000 pounds per square inch, said steel containing: about 19 to 25% nickel; about 2 to 6% manganese; about 5 to 14% chromium; about 3 to 5% aluminum; from an effective amount up to about 3% silicon; from about 0.3 to 0.8% car-

bon; up to about 3% in aggregate of other elements which do not substantially impair the age-hardening and non-magnetic properties of the steel; and the balance substantially all iron.

2. A forgeable and machineable, age-hardenable, austenitic alloy steel which, on solution-treating at about 2100° to 2300° F., followed by aging at about 1200° to 1300° F., is characterized in being substantially non-magnetic and in having a hardness in excess of Rockwell "C" 35 and an 0.02% yield strength of at least 85,000 pounds per square inch, said steel containing: about 20 to 22% nickel; about 8 to 11% chromium; about 3.5 to 5% manganese; about 3 to 4% aluminum; about 0.3 to 0.6% carbon; up to about 3% in aggregate of other elements which do not substantially impair the age-hardening and non-magnetic properties of the steel; and the balance substantially all iron.

3. An age-hardened, austenitic alloy steel which is characterized in being substantially

non-magnetic and in having a hardness in excess of about Rockwell "C" 35 and an 0.02% yield strength of at least 85,000 pounds per square inch, said steel containing: about 19 to 25% nickel; about 2 to 6% manganese; about 5 to 14% chromium; about 3 to 5% aluminum; from an effective amount up to about 3% silicon; from about 0.3 to 0.8% carbon; up to about 3% in aggregate of other elements which do not substantially impair the age-hardening and non-magnetic properties of the steel; and the balance substantially all iron.

4. An age-hardened, austenitic alloy steel which is characterized in being substantially non-magnetic and in having a hardness in excess of about Rockwell "C" 35 and an 0.02% yield strength of at least 85,000 pounds per square inch, said steel containing: about 20 to 22% nickel; about 8 to 11% chromium; about

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3 to 5% manganese; about 3 to 4% aluminum; about 0.3 to 0.6% carbon; up to about 3% in aggregate of other elements which do not substantially impair the age-hardening and non-magnetic properties of the steel; and the balance substantially all iron.

PETER PAYSON.

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