ABSTRACT: Corrosion-resistant magnetic core of low hysteresis loss and low eddy-current loss and alloy containing about 9% to 20% chromium, about 0.01% to 3% silicon and/or aluminum, manganese up to about 4%, carbon up to about 0.15%, about 0.15% to 1% sulfur and/or selenium, about 0.02% to 1% titanium and/or zirconium, and remainder substantially iron.
LOW-LOSS MAGNETIC CORE OF FERRITIC STRUCTURE CONTAINING CHROMIUM

As a matter of introduction, my invention is concerned with a magnetic core for electrical apparatus, and alloy steels.

One of the objects of the invention is the provision of a magnetic core possessing a combination of good magnetic properties along with good corrosion resistance.

Another object is the provision of a magnetic core and corrosion-resisting steel of high magnetic permeability, low reluctance, low hysteresis loss and low eddy-current loss, all at minimum cost, that is, comparatively low cost in the ingot, in processing in the mill, and in use.

A further object of my invention is the provision of a corrosion-resisting alloy steel which is suited to the production of bars, rod, wire and like mill products possessing a good combination of magnetic properties and machinability, that is, readily lends itself to cutting, threading, tapping, turning, milling and the like, as in the production of a variety of magnetic parts or components for electrical machinery, apparatus or equipment.

A still further object is the provision of an alloy steel and various flat-rolled products, such as sheet, strip, and the like, suited to various machining, forming and shaping, as in the production of the cores for electrical machinery and apparatus.

Other objects of my invention in part will become apparent and in part particularly pointed to in the following description.

My invention resides in the steel and in the correlation of steel, more particularly in the combination of ingredients, making up the same, and in the relation between the ingredients, all as more particularly described herein, the scope of the application of which is set out in the claims at the end of this specification.

BACKGROUND OF THE INVENTION

In order to gain a better understanding of certain features of my invention, it may be well to note at this point that the straight chromium grades of stainless steel have long been accepted in the art, many being identified by American Iron and Steel Institute type numbers. For example, I refer to the more popular AISI Type 403 (11.5 to 13% chromium, carbon 0.15% max., manganese 1.00% max., silicon 0.05% max., phosphorus 0.045% max., sulfur 0.030% max., and remainder iron); Type 405 (like Type 403 except 11.5 to 14.5% chromium, carbon 0.08% max., manganese 1.00% max. and 0.10 to 0.30% aluminum); Type 414 (like Type 403 except 11.5 to 13.5% chromium, silicon 1.00% max., and 1.25 to 2.50% nickel); and Type 416 (like Type 403 except 12 to 14% chromium, manganese 1.25% max., phosphorus 0.060% max., sulfur at 0.15% max., and silicon 1.00% max. The steels noted, this with the exception of the Type 405, are suited to a variety of machined articles, parts and components. The steel of Type 405, as distinguished from the others, is nonhardenable. It is particularly suited for welded assemblies which are free of the air-hardening noted in the steels of Types 403 and 410.

Others of the long known and used straight chromium grades which are not generally hardenable are Type 430 (18 to 19% chromium, carbon 0.12% max., manganese 1.00% max., phosphorus 0.040% max., sulfur 0.030% max., silicon 1.00% max. and remainder iron); Type 430F (generally like Type 430 but with sulfur at least 0.15%); Type 430FSe (similar to Type 430 but with at least 0.15% selenium instead of the 0.15% sulfur); and Type 442 (generally similar to Type 430 except 18 to 23% chromium and carbon 0.20% max.). These various steels are suited to a variety of applications, where a nonhardenable corrosion-resisting steel is required; the steels containing a high sulfur and/or silicon content are employed for a variety of machined articles and components.

While the straight chromium grades of stainless steel, as noted above, are suited to a wide variety of applications, none seems peculiarly adapted to the use in electrical machinery, i.e., magnetic cores for solenoid, relay and the like. Nor, indeed, for wider applications where a controlled magnetic field of high permeance, low reluctance, and a minimum loss is desired. And while the steel of Type 430F is readily machineable and, as such, is suited to many applications, I find that in straightening bar, rod, and wire stock, high stresses are developed which adversely affect the magnetic characteristics of the metal, as well as the mechanical properties.

It is an object of my invention, therefore, to provide a steel which enjoys a combination of corrosion resistance, good mechanical properties and good magnetic properties, namely, high permeance, low hysteresis loss, and low eddy-current loss, all at minimum cost.

SUMMARY OF THE INVENTION

Referring now more particularly to the practice of my invention, I provide a magnetic core and an alloy steel essentially consisting of about 9 to about 20% chromium (particularly about 12 to about 18% chromium), about 0.01 to about 3% silicon and/or aluminum (especially about 0.50 to about 2% silicon), about 0.15 to about 1% sulfur and/or selenium (especially about 0.15% to about 0.50% sulfur), about 0.02 to about 1% titanium and/or zirconium (particularly about 0.1 to about 0.6% titanium), and remainders substantially all iron.

Carbon, of course, is present in my steel, this in amounts up to about 0.15%, more particularly about 0.01% or even 0.001%, to just under 0.065%, say to about 0.05%; for best results about 0.01% to about 0.04%. Manganese, too, is present in my steel, this in amounts up to about 4%, more particularly about 0.01 to about 1%. The remainder of the steel, of course, is substantially all iron. The metal is not hardenable by heat-treatment; it is wholly ferritic with an absence of austenite. And, of course, there is an absence of a martensitic constituent.

I find that with controlled carbon content and the essential presence of sulfur and titanium in the amounts indicated, the steel not only is possessed of good mechanical properties with minimum adverse effect resulting from straightening, bending, or the like, but that it is possessed of good magnetic properties. More particularly, the steel is of high magnetic permeance and of low loss, i.e., low hysteresis loss and low eddy-current loss. I attribute the superior magnetic characteristics to a virtual freedom of the steel from intermetallic compounds involving the iron present. In the prior corrosion-resisting steels, I feel that certain compounds of iron, chromium, and carbon, and even iron, chromium and nitrogen, are present which adversely affect the magnetic properties in that while readily magnetized, they are not readily demagnetized. And, in a way, serving as permanent magnets as they do, substantial loss is encountered with rapid reversal of the magnetic field as in alternating current electrical machinery, apparatus and equipment.

In the steel of my invention, I am inclined to the view that the carbon present in the metal appears in the form of titanium carbides, and the nitrogen as titanium nitrides, or perhaps other compounds involving titanium, carbon, nitrogen, and one or more of the alloying ingredients present, this excluding the iron, however. These compounds introduce no magnetic effects, this because of the absence of iron in the compound.

Moreover, in my steel I feel that the eddy-current loss is effectively minimized as a result of the increase in the electrical resistance of the metal by reason of the chromium content, and, to some extent, the silicon and aluminum contents. In consequence, the eddy-currents which develop in the use of the metal as magnetic core for alternating current electrical applications are minimized by reason of the increased electrical resistance of the metal. Thus, there is enjoyed more efficient operation with less heating in use.

In the steel of my invention, I feel that the desired magnetic permeability with low hysteresis loss may be had with the use of one or more of columbium, vanadium and molybdenum instead of the titanium and/or zirconium addition. In general, however, I prefer the titanium addition for reasons of economy and for the further reason that it combines with both the carbon and nitrogen contents of the steel, effectively eliminating the adverse effects of both.
In my steel the particular composition is considered to be in every sense critical. Although a rather wide latitude of chromium content is contemplated, that is, from about 9 to about 20 percent, a steel with less than about 9 percent chromium is not acceptable because of a sharp loss in corrosion resistance and, conversely, a steel having a chromium content exceeding about 20 percent is not desired because of a sacrifice in magnetic permeability. While the electrical resistivity of the metal increases with the chromium addition, the permeability decreases. For best results a chromium content of about 12 to about 18 percent is desired.

The ingredients silicon or aluminum generally are employed in small amounts, this not exceeding about 3 percent for the two together. These ingredients assure clean metal essentially free of contaminating oxide inclusions. A best steel employs silicon, this in the amount of about 0.05 to about 2 percent, preferably about 1 to about 2 percent for maximum cleanliness and an ease of furnacing, pouring and teeming. An excessive silicon content, however, indeed an excessive aluminum content, is not desired as it works adversely to the high magnetic permeability which is sought. The same may be said with respect to the manganese content of the steel, since I view silicon, aluminum and manganese as additives which are beneficial to the melting of the steel, that is, in assuring an ease of furnacing and teeming with assured cleanliness, but not beneficial to the desired magnetic properties.

The carbon content, the sulfur content, and the titanium content of my steel, too, are viewed as critical, for with a carbon content exceeding about 0.15 percent, the workability as by straightening, bending, and the like, is inclined to suffer even though the machinability is improved. A best combination of results is had where the carbon content amounts to about 0.01 to about 0.04 percent, this assuring good bending properties, and a balance between an increase in the electrical resistivity resulting from the carbon addition and a decrease in the magnetic permeability. For some applications the carbon may range from about 0.01 percent to just short of 0.06 percent. For application where the metal is to be machined, the carbon content very well may approach the 0.15 percent figure. On the other hand, where the metal is employed in the form of sheet, strip, or the like, and a deep-drawing operation is contemplated, the carbon content should be near the minimum figure, that is, about 0.02 percent or even about 0.01 percent.

Sulfur and/or selenium in the amount of at least about 0.05 percent is found necessary to achieve good machinability in my steel, while more than 0.50 percent seems unnecessary. A sulfur and/or selenium content exceeding about 1 percent is not acceptable, for I find with such a high content the workability in the hot-mill immediately suffers, with objectionable tearing and splitting of the metal.

The importance of the titanium and/or zirconium addition, along with the sulfur and/or selenium and the chromium contents of the steel, is particularly pointed to above. The amount of titanium and zirconium must be at least about 0.02 percent in order to enjoy a beneficial effect, but an amount exceeding about 1 percent not only produces no beneficial effect, but represents an unnecessary cost. Moreover, the excessive titanium and/or zirconium in a measure detracts from the desired magnetic qualities of the metal. For best results it is titanium that is employed, and this in the amount of about 0.1 to about 0.5 percent.

I conveniently melt my steel in the electric arc furnace. Where desired, of course, it may be melted in the vacuum furnace. Or a combination of arc-furnace melting and vacuum-furnace refining may be employed to advantage. But however melted, the steel handles well in the furnace, it teems well, and the mold strip from the ingots with ease.

The ingots in turn work well in the hot-mill at temperatures commonly employed. And so, too, the resulting blooms, billets, and the like, as in the production of plate, sheet, strip, bars, rods, wire, and special shapes. Additionally, the metal works well in the cold-mill as in the production of cold-rolled sheet and strip, and cold-drawn bars, rods, and wire. In this latter operation, as in the production of sheet and strip, bar, rod, and wire stock of high finish, I find a direct saving in mill cost, this through elimination of the common practice of annealing the finished metal in the presence of hydrogen to preserve the highly finished surface.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

While, as noted above, in broad aspect the magnetic core and alloy steel of my invention essentially consists of about 9 to about 20% chromium, about 0.01 to about 3% silicon and/or aluminum, manganese up to about 4%, carbon up to about 0.15% (especially about 0.01% to just under 0.06%) with about 0.15 to 1% sulfur and/or selenium (preferably about 0.15 to about 0.50% sulfur), about 0.02% to about 1% titanium and/or zirconium, and remainder substantially all iron, there are several particular steels in which a best combination of properties is had. One such magnetic core and steel essentially consists of about 12 to about 18% chromium about 0.5 to about 2% silicon, about 0.01% to less than 0.06% carbon (particularly about 0.01 to about 0.04% carbon), about 0.15 to about 0.50% sulfur (particularly about 0.20 to about 0.40% sulfur about 0.1 to about 0.5% titanium, and remainder substantially all iron. Such a core and steel enjoys an excellent combination or magnetic permeability with low hysteresis loss, good electrical resistance and consequent low eddy-current losses, ready machinability, formability, and corrosion-resistance.

A further core and steel essentially consists of about 14 to about 16% chromium, about 0.5 to about 2% silicon, about 0.01 to less than 0.06% carbon (particularly about 0.01 to about 0.04% carbon), about 0.20 to about 0.40% sulfur about 0.1% to about 0.6% titanium, and remainder substantially all iron. In this core and steel there is had a somewhat higher electrical resistance with consequently reduced eddy-current losses in use of the metal as a magnetic core component in electrical machinery, apparatus, and the like. The mechanical properties are good, and so, too, the magnetic permeability. And, too, the corrosion resistance is somewhat improved, suitit to some applications in which the somewhat higher corrosion resistance is deemed desirable.

A still further preferred core and steel enjoying a best combination of corrosion resistance, electrical resistance with minimum eddy-current loss, along with good magnetic permeability, machinability, and mechanical properties, essentially consists of about 16 to about 18% chromium, about 0.5 to about 1% silicon, 0.01 to about 0.05% carbon (particularly about 0.02 to about 0.04%), about 0.20 to about 0.40% sulfur, about 0.1 to about 0.5% titanium, and remainder substantially all iron. Here, the lower maximum carbon content permits the lower maximum titanium content, with consequent savings and, yet, with a good combination of magnetic permeability, low eddy-current losses, and good corrosion resistance in magnetic core applications.

Another preferred core and steel essentially consists of about 12 to about 18% chromium (more particularly about 14 to about 16% chromium), about 0.50 to about 3% silicon (especially about 1 to about 3% silicon), carbon less than 0.10% and preferably not exceeding 0.04%, about 0.15 to about 0.50% selenium, about 0.1 to about 0.6% titanium, and remainder substantially all iron.

In specific illustration of the steels of my invention, I give below in table I two groups of chromium-silicon-sulfur-titanium magnetic core steels, each of three different chromium contents, namely, about 13%, about 15% and about 17%, with differing titanium contents for each of the three. Of the two groups of magnetic core steels, one has a silicon level of about 0.30% and the other of about 0.65%. For all steels there are given the maximum permeability (μ), the value as compared to air the permeability (1) in the hot-forged condition.
A review of the data presented above rather clearly indicates that the maximum permeability of the magnetic core steels of my invention progressively increases with an increase in the chrominum content and with an increase in the tin content. Note, for example, that for the three steels RS633-2, RS634-2 and RS635-2, having a tin content of about 0.2%, the permeability for the steel of about 13% chromium amounts to 352, for that of the 15% chromium steel to come to 546, and for that of the 17% chromium steel amounts to 915. In these steel the silicon content is about 0.30% and the carbon, manganese, phosphorus and nickel contents diminish but little from one steel to the other.

For the three steels RS633-1, RS633-2 and RS633-3, with respective tin contents of 0.01%, 0.21% and 0.37%, the maximum permeability is seen to be 237, 352 and 404, the permeability thus directly increasing with the increase in tin content.

To like extent, the permeability increases with respect to the silicon content, for it will be seen that the steel of about 13% chromium content, 0.2% tin content, with about 0.25% silicon, namely RS633-2, has a permeability of 352, while the steel RS636-2, with like chromium and tin contents but with a silicon content of 0.60%, has a permeability of 473. As the tin content approaches 0.5%, however, and the chromium content is on the order of 17%, little change in permeability results from an increase in the silicon content, at this chromium level the permeability actually decreasing with an increase in silicon. Compare, for example, the 17% chromium, 0.46% tin steel RS635-3, having a silicon content of 0.30% and a permeability of 1076, with the steel RS636-2 of about 17% chromium, 0.47% tin and 0.71% silicon, having a permeability of only 908.

It is in the electrical resistivity, rather than the permeability, that greatest change is had with silicon content as seen from the data present in table II below. In that table there are given the electrical resistivities and the permeabilities in the annealed condition of two groups of steels (and in the hot-forged condition for one group), one group of steel containing about 16% chromium and 0.2% tin with the further ingredient selenium in the amount of about 0.15%, all of differing silicon contents, and the other containing about 14% chromium with a sulfur content of about 0.3% and titanium content of about 0.15%, also of differing silicon contents. The electrical resistivity is expressed in microhms per circular mill.

For the one group of magnetic core steels given in table II, this for a chromium content of about 16%, about 2% tin and about 0.15% selenium, it will be immediately seen that the electrical resistivity, as well as the permeability, increases with an increase in silicon content. Notably, with the increasing silicon contents of 0.45%, 0.92%, 1.89% and 2.97% for the respective steels RS650, RS651, RS652 and RS653, the electrical resistivities amount to 58.3, 72.5, 88.0 and 99.3 microhms per circular mill. And for the group of steels of about 14% chromium, 0.15% titanium, with sulfur rather than selenium, this in the amount of about 0.3%, the electrical resistivities amount to 67.5, 94.2 and 103.1 microhms per circular mill for the three respective steels RS610, RS6101 and RS6102, having silicon contents of 1.15%, 2.32% and 3.18%. The permeability of the steels of both groups increases with the increase in silicon content, going from 2194 in the annealed condition for the 16% chromium steel of 0.48% silicon content for the steel RS650 up to 3015 for the steel RS653, with silicon content of 2.97%. The steels of the lower chromium content of 14% are possessed of significantly lower permeability but, here again, there is an increase in permeability with an increase in silicon content, the permeability increasing from steel RS6100 having a silicon content of 1.15% and permeability of 1217, up to 2628 for steel RS6102 with silicon content of 3.18%.

In conclusion, it will be seen that I provide in my invention a magnetic core and alloy steel in which the various objects hereinbefore set forth are successfully achieved. The core and steel are characterized by desired magnetic permeability, particularly in the annealed condition, together with desired electrical resistivity. The steel, moreover, is corrosion-resistant and well lends itself to a variety of machinery operations, such as cutting, threading, tapping, turning, and the like, as in the production of magnetic cores for solenoid, relay and other electrical machinery, apparatus and equipment.

Inasmuch as many embodiments may be made of the core and steel of my invention, and since many variations in the embodiments herein disclosed may occur to those skilled in the art to which the invention relates, it will be understood that all matter described herein is to be considered illustrative and not by way of limitation.

I claim:
1. Magnetic core of ferritic structure and desired resistivity and permeability for solenoid, relay or other electrical machinery, apparatus and equipment, said core essentially consisting of about 9 to about 20% chromium, about 0.01 to about 3% silicon up to about 0.15% carbon, about 0.15 to about 0.5% ingredient of the group sulfur and selenium, about 0.02 to about 1% titanium, and remainder substantially all iron.
2. Magnetic core of ferritic structure and desired resistivity and permeability for solenoid, relay or other electrical machinery apparatus and equipment, said core essentially consisting of about 12 to about 18% chromium, about 0.5 to about 2% silicon, up to about 4% manganese, carbon less than 0.06%, about 0.15 to about 0.5% sulfur about 0.1 to about 0.6% titanium, and remainder substantially all iron.
3. Magnetic core of ferritic structure and desired resistivity and permeability for solenoid, relay or other electrical machinery apparatus and equipment, said core essentially consisting of about 12 to about 18% chromium, about 0.5 to about 2% silicon, up to about 4% manganese, carbon less than 0.06%, about 0.15 to about 0.5% sulfur about 0.1 to about 0.6% titanium, and remainder substantially all iron.

<table>
<thead>
<tr>
<th>Heat No.</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>Si</th>
<th>Cr</th>
<th>Ni</th>
<th>Ti</th>
<th>15%</th>
<th>40%</th>
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<tr>
<td>RS633-1</td>
<td>0.05</td>
<td>0.15</td>
<td>0.015</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>16</td>
<td>272</td>
</tr>
<tr>
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<td>0.02</td>
<td>0.015</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>16</td>
<td>272</td>
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<tr>
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<td>0.03</td>
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<td>272</td>
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<tr>
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<td>0.015</td>
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<td>16</td>
<td>272</td>
</tr>
<tr>
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<tr>
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<tr>
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<tr>
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<tr>
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The electrical resistivity is expressed in microhms per circular mill.
machinery, apparatus and equipment, said core essentially consisting of about 12 to about 18% chromium, about 0.5 to about 2% silicon, about 0.01 to about 0.04% carbon, about 0.15 to about 0.50% sulfur about 0.1 to about 0.6% titanium, and remainder substantially all iron.

4. Alloy steel core of ferritic structure and desired resistivity and permeability for solenoid relay or other electrical machinery, apparatus and equipment, said core essentially consisting of about 12 to about 18% chromium, about 0.50 to about 3% silicon, carbon less than 0.06%, about 0.15 to about 0.50% selenium, about 0.1 to about 0.6% titanium, and remainder substantially all iron.

5. Alloy steel core of ferritic structure and desired resistivity and permeability for solenoid, relay or other electrical machinery, apparatus and equipment, said core essentially consisting of about 14 to about 16% chromium, about 1 to about 3% silicon, carbon not exceeding 0.04%, about 0.15 to about 0.50% selenium, about 0.1 to about 0.6% titanium, and remainder substantially all iron.