

Description

This invention relates to thermal cyclic oxidation resistant and hot workable alloys. More particularly, the invention relates to iron-chromium-aluminium alloys with rare earth additions, particularly cerium and lanthanum.

It is known to provide iron-chromium-aluminium alloys having additions of yttrium for the purpose of high temperature oxidation resistance and improved oxide surfaces. U.S. Patent 3,027,252, issued May 27, 1962, discloses a 25—95% chromium, 0.5—4% aluminium and 0.5—3% yttrium alloy for high temperature oxidation resistance at greater than 2000°F (1094°C). An objective of the alloy was to provide improved workability and a thermal shock resistant and non-spalling oxide film. Another U.S. Patent, 3,298,826, issued January 17, 1967, has as its objective to improve the resistance to embrittlement and hardening of the alloys between 650—1300°F (343—704°C) while retaining the oxidation and corrosion resistance. The patent discloses that embrittlement is avoided by lowering the chromium content below 15%. U.S. Patent 4,230,489, issued October 28, 1980, relates to the addition of 1 to 2% silicon to such alloys for increasing the corrosion resistance.

Generally, such alloys have properties which are useful in high temperature environments which require oxidation resistance and it has been proposed that they may be useful as a substrate material such as for catalytic converters, as well as for resistance heating elements and radiant heating elements in gas or oil stoves. As a catalytic substrate, a metallic substrate offers many advantages over present ceramic substrates. For example, a metal substrate is substantially more shock resistant and vibration resistant, as well as having a greater thermal conductivity, than ceramic. Furthermore, a metallic substrate can be more easily fabricated into thin foil and fine honeycomb configurations to provide greater surface area and lighter weight.

Present iron-chromium-aluminium alloys containing yttrium may provide some satisfactory properties of oxidation resistance and adherence of oxide films, however, the use of yttrium has its disadvantages. Yttrium is expensive and is subject to "fade" during melting and pouring of ferrous alloys. Yttrium, because of its highly reactive nature, combines with other elements such as oxygen and is lost to the slag and furnace refractories. Generally, because of the highly reactive nature of yttrium, a more costly process of vacuum induction melting is used for producing iron-chromium-aluminium alloys containing yttrium. Furthermore, during vacuum melting and casting, recovery of yttrium in the metal may typically be less than 50% of that added to the melt composition. If there are any delays or problems which would prevent immediate pouring of the melt, recovery may be substantially lower. Moreover, even vacuum induction melting is inadequate for substantial recovery of yttrium through the remelting of the scrap of yttrium-containing alloys.

U.S. Patent 3,920,583, issued November 18, 1975, relates to a catalytic system including an aluminium-bearing ferritic steel substrate and, particularly, an iron-chromium-aluminium yttrium alloy. The alloy is disclosed to have the property of forming an adherent stable alumina layer upon the substrate surface upon heating such that the layer protects the steel and makes it oxidation resistant.

EP-A-0 034 133 discloses an electric heating element having an outer metallic casing surrounding a resistance element of a Fe-Cr-Al alloy embedded in an insulating material. The alloy of the resistance element has additions of 0.01 to 1% by weight Y, Hf, Sc or one or more lanthanoids for improved life.

To overcome some of the disadvantages of yttrium-containing iron-chromium-aluminium alloys, it has been proposed that other lower cost alloying metals be substituted for yttrium. U.S. Patent 3,782,925, issued January 1, 1974, discloses a ferritic heat resistant iron-chromium-aluminium steel having silicon, titanium and rare earth additions. The alloy contains 10—15% chromium, 1—3.5% aluminium, 0.8—3% silicon and 0.01—0.5% calcium, cerium and/or other rare earths for scale adherence. The patent also requires a total of aluminium and silicon ranging from 2—5% free titanium of at least 0.2% and a sum of oxygen and nitrogen of at least 0.05%.

An article entitled "High Temperature Oxidation Behavior of Fe-20 Cr-4 Al Alloys With Small Additions of Cerium" by Amano et al, Trans. JIM 1979, Vol. 20, pp. 431—441 discloses an iron-chromium-aluminium alloy with increasing cerium additions for good adherence of the oxide surface. The article discloses static oxidation tests at cerium amounts of 0.01%, 0.04% and 0.37%. While there was spalling of the oxide coating at the lowest cerium level of 0.01%, no spalling was reported at the higher levels of 0.04% and 0.37% cerium. The cerium existed in the latter two alloys as a Ce-Fe intermetallic compound which precipitated at the grain boundaries. The article does not address thermal cyclic oxidation resistance and hot workability of the alloys.

A further article entitled "Effect of Rare Earths on High Temperature Oxidation of Ferritic Stainless Steels" by U. Bernabai, La Metallurgia Italiana 1 (1979), pages 22—25, discloses Fe-Cr-Al alloys with additions of Mischmetal. The alloys disclosed have a relatively low aluminium content of not more than 1.4%.

Other iron-chromium-aluminium alloys containing cerium are known for electrical resistance heating elements. U.S. Patent 2,191,790 discloses up to 5% of an addition chosen from a group of cerium and other elements and further includes up to 0.5% carbon and 0.05—0.5% nitrogen. The objective of the alloy was to improve oxidation resistance, scale adherence and toughness at elevated temperatures greater than 2102°F

(1150°C). Improvements over the alloy of that patent are shown in U.S. Patents 2,635,164, issued April 14, 1953, and U.S. Patent 2,703,355, issued March 1, 1955.

Japanese Patent Application 56-65966, published on June 4, 1981, also discloses an iron-chromium-aluminium alloy having heat absorbing and radiating properties for combustion devices.

It is also known to provide a glass sealing alloy of iron, chromium and aluminium with additions of rare earths up to 2%, disclosed in U.S. Patent 3,746,536, issued July 17, 1973.

There still exists a need, however, for an alloy which is less expensive to produce because of lower cost alloying elements, which can be produced through lower cost melting processes and which is resistant to thermal cyclic oxidation from ambient temperature up to temperatures of about 1600°F (871°C), such as in internal combustion exhaust environments, and which has improved hot workability. Furthermore, the alloy should be suitable for providing an improved aluminium oxide surface which is adherent to the metallic surface under thermal cyclic conditions. It is further desired that the alloy be susceptible to further treatment to provide an improved and texturized aluminium oxide surface to provide more surface area and so as to enable more catalytic materials to be supported on the alloy by the aluminium oxide surface.

The alloy should also be capable of being stabilized or, if need be, of being stabilized with elevated temperature creep strength properties improved.

The present invention provides a hot workable ferritic stainless steel alloy as claimed in any one of claims 1 to 7 hereof.

The invention further provides an alloy according to the present invention when used for producing an oxidation resistant catalytic substrate as well as a catalytic system comprising such a substrate.

The invention also provides according to claim 10 a method of making a hot workable ferritic stainless steel resistant to thermal cyclic oxidation and having a textured aluminium oxide surface resistant to scaling at elevated temperatures.

The invention will be more particularly described with reference to the accompanying drawings, in which:—

Figures 1 and 2 are photomicrographs of alloys which do not satisfy the present invention;

Figures 3 and 4 are photomicrographs of alloys of the present invention; and

Figure 5 is a photomicrograph of an alloy of a commercial electrical resistance heating element material.

In general, there is provided an iron-chromium-aluminium alloy with rare earth additions, particularly cerium and/or lanthanum, which provides a hot workable alloy which is resistant to thermal cyclic oxidation and scaling at elevated temperatures and suitable for forming thereon an adherent textured aluminium oxide surface.

As used herein, all composition percentages are percent by weight.

The chromium level may range from 8.0—25.0%, and preferably 12.0—23.0%, in order to provide the desired properties such as corrosion and oxidation resistance. The level of chromium is limited to avoid unnecessary hardness and strength which would interfere with the formability of the alloy. Chromium levels less than 8% tend to provide inadequate thermal cyclic oxidation resistance. The chromium alloying element is primarily responsible for providing the corrosion resistance, contributes substantially to oxidation resistance and, as shown in the Tables herein, there is a correlation between the number of thermal cycles to failure and the increase in chromium content. Above 25% chromium, however, increases in the wire life become minimal on balance with the increasing difficulty in fabrication of the alloys.

The aluminium content in the alloy provides increased oxidation resistance at elevated temperatures, reduces the amount of overall chromium needed and tends to increase the resistance to scaling.

Aluminium is necessary in the alloy to provide a source for the formation of the alumina (aluminium oxide- Al_2O_3) surface. Furthermore, it has been found that there is a correlation between the increasing aluminium content and the increasing thermal cyclic oxidation resistance of the alloy. Generally, aluminium is present in the alloy ranging from 3.0—8.0%. Below 3% and at about 2.5%, the cyclic oxidation resistance tends to become unacceptably low. Furthermore, at high aluminium contents, the ability to form a uniformly texturized aluminium oxide surface, such as "whiskers", becomes erratic, such that at values above 8%, there is a marked decline in the ability to texturize the aluminium oxide surface, i.e., form alumina whiskers.

It also appears that the aluminium content at which acceptable oxidation resistance and cyclic oxidation resistance is achieved is a function of the chromium content of the alloy. Higher aluminium levels are required at lower chromium levels. The minimum aluminium content at which suitable oxidation resistance begins can be expressed as

$$\% \text{ Cr} + 6 (\% \text{ Al}) = 40$$

or as

$$\% \text{ Al} = \frac{(40 - \% \text{ Cr})}{6}$$

Preferably, aluminium ranges from a minimum calculated by the above formula up to 8%. More preferably, aluminium may range from 4 to 7%.

Rare earth metal additions are essential to the adherence of the aluminium oxide surface. Rare earth metals suitable for the present invention may be those from the lanthanon series of 14 rare earth elements. A common source of the rare earths may be as mischmetal which is a mixture primarily of cerium, lanthanum, neodymium, praseodymium and samarium with trace amounts of 10 other rare earth metals. Preferably, the alloy contains at least additions of cerium or lanthanum, or a combination of them, to assure adherence of the alumina scale and to provide a scale which is characterized by its ability to be texturized and subjected to a growth of alumina whiskers. The rare earth addition can be made in the form of pure cerium metal, pure lanthanum metal, or a combination of those metals. As rare earth metals are difficult to separate from one another, mischmetal, the relatively inexpensive mixture of rare earth elements, may be utilized as an alloying addition.

Preferably, the alloy of the present invention contains a rare earth metal addition in metal form of at least 0.002% of cerium, lanthanum, neodymium and/or praseodymium. More preferably, the alloy contains an addition of at least 0.002% of cerium and/or lanthanum and a total content of the rare earth metals cerium and lanthanum not to exceed 0.05%. When rare earth metals other than cerium, lanthanum, neodymium and praseodymium are present, the total of all rare earth metals should not exceed 0.06% and preferably, not exceed 0.05%. It appears that greater levels of rare earth metals have little tendency to improve the resistance to oxidation and scaling or the adherence of oxide scale, while it does tend to make the alloys unworkable at normal steel hot working temperatures of about 1900—2350°F (1038—1288°C).

Even more preferably, the cerium and/or lanthanum content should range from a lower limit which is proportional to the chromium content of the steel. It has been found that the cerium and/or lanthanum content may range from a lower limit expressed as

% Cr

2200

An optimum total amount of rare earths in the alloy appears to be about 0.02%.

It is desirable to keep normal steelmaking impurities at relatively low levels. The alloy of the present invention, however, does not require special raw material selection or melting processes such as vacuum induction melting to maintain such impurities at extremely low levels. The alloy of the present invention can be satisfactorily made by using electric arc furnaces or AOD (argon-oxygen-decarburization) processes. The rare earth metals show a strong affinity for combination with nitrogen, oxygen and sulfur which are normal impurities in the steelmaking processes. That portion of the rare earth additions which combine with such elements is effectively removed from the metallic alloy and become unavailable for contributing to adherence of the aluminium oxide surface and any textured or whisker growth thereon. For that reason, it is desirable to have the content of these elements in the molten alloy bath as low as possible before making the rare earth additions.

Methods for reducing carbon and nitrogen contents are well known and such conventional methods are applicable to the present invention. Carbon levels may range from up to 0.05% and, preferably, up to 0.03% with a practical lower limit being 0.001%. Nitrogen levels may range up to 0.05% and, preferably, up to 0.03% with a practical lower limit being 0.001%.

Methods for reducing oxygen and sulfur content are also well known and such conventional methods are applicable to the present invention. Oxygen content may range up to 0.020% and, preferably, up to 0.01% with a practical lower limit being 0.001%. Sulfur levels may range up to 0.03%. Preferably sulfur may range up to 0.02% with a practical lower limit being 0.0005%.

Conventional processes for reduction of oxygen and sulfur content will sometimes involve the use of additions of calcium or magnesium and may leave residual quantities of these elements in the alloy. Calcium and magnesium are strong deoxidizing and desulfurizing elements and it is desirable to keep them low. The sum of calcium and magnesium may range up to 0.005% and, preferably, up to 0.003%. It has been found that such deoxidizing additions, whether residual content of calcium or magnesium remain in the analysis or not, do not adversely affect the thermal cyclic oxidation resistance or aluminium oxide adherence or texturizing and whisker growth of the oxide surface.

Another normal steelmaking impurity is phosphorus which may be present up to 0.04% and, preferably, up to 0.03% with a practical lower limit being about 0.001%.

Copper and nickel are two other normal steelmaking impurities. Nickel should be less than 1.0% and, preferably, less than 0.4% with a typical lower limit being 0.001%. Copper also should be maintained at a level of less than 0.5% and, preferably, less than 0.4% with a practical lower limit being about 0.005%. To provide for copper and nickel contents of less than the lower limit would have no effect on the ordered properties, but would be difficult to achieve without special melting techniques and specific raw material selection.

Silicon may be present in amounts up to 4.0% and, preferably, up to 3.0%. The presence of silicon generally tends to improve the general oxidation resistance and improves the fluidity of the molten alloy and, thus, improves the ability to cast the alloy into thin sections. Silicon is an element commonly used for deoxidation in the production of steel and appears to have a neutral or only slightly beneficial effect upon oxide adherence and can be tolerated up to about 4% without interfering with texturizing of the aluminium

oxide surface and the formation of alumina whiskers. Preferably, the silicon content is kept below 3% for the production of wrought products, because silicon contributes to the brittleness of the alloy during cold working. The embrittlement effect is most noticeable when the chromium content is below 14%. Such amounts of silicon can be included in the alloy without adversely affecting the hot workability of the alloy.

5 Manganese levels may range up to 1% and, preferably, up to 0.5% with a lower limit being 0.06% and preferably 0.10%. Such manganese levels provide for efficient fabrication and avoid unnecessary hardness and strength which could interfere with the formability and hot workability of the alloy. Manganese levels greater than 1% do not appear to contribute to the desired properties of the alloy. Manganese below 0.06% tends to contribute to nonuniform texturizing or whisker growth of the oxide surface.

10 Anticipated use of the alloy of the present invention is in cyclic high temperature environments such as may be found in catalytic converters and electrical resistance heating elements. As a result of heating and cooling slowly through a temperature range such as 900—1300°F (482—704°C), grain boundary sensitization can take place. Such sensitization can reduce the corrosion and oxidation resistance of ferritic stainless steel substrate materials. The addition of stabilizing elements which are strongly attracted to
15 carbon to prevent sensitization are also well known. However, stabilizing elements, particularly in percentages far above those necessary for theoretical stabilization as those elements are normally added to stainless steels, will adversely affect thermal cyclic oxidation resistance of the alloy. It has been found that the more common stabilization elements, such as titanium, zirconium, niobium and vanadium, have different effects on thermal cyclic oxidation resistance. Titanium appears to have the most adverse effect,
20 while zirconium, at low percentages, has a neutral or slightly beneficial effect. It is generally preferred to have only one stabilizing element in the alloy. Combinations of stabilizing elements are generally not desirable, as the effect of the combined additions is approximately that of an equivalent addition of the element having the more adverse effect on thermal cyclic oxidation resistance. In the present alloy for stabilization, the preferred element is zirconium which may be added in amounts up to

$$25 \quad 91 \left[\left(\frac{\%C}{12} \right) + \left(\frac{\%N}{14} \right) + 0.004 \right] \%$$

30 Preferably, zirconium may range up to

$$91 \left[\left(\frac{\%C}{12} \right) + \left(\frac{\%N}{14} \right) + 0.003 \right] \%$$

35 When zirconium is added to the alloy as a stabilizing element in amounts greater than that required for the above formula, the thermal cyclic oxidation resistance is adversely affected. Similarly, such excessive amounts of zirconium do not improve the elevated temperature creep strength after high temperature annealing.

40 Of the most common stabilization elements used for providing improved elevated temperature creep strength after high temperature annealing, the preferred element is niobium, for it appears to have the least adverse effect on thermal cyclic oxidation resistance. When stabilization and improved elevated temperature creep resistance are required, the alloy may contain niobium in amounts up to

$$45 \quad 93 \left[\left(\frac{\%C}{12} \right) + \left(\frac{\%N}{14} \right) + 0.013 \right] \%$$

or preferably up to

$$50 \quad 93 \left[\left(\frac{\%C}{12} \right) + \left(\frac{\%N}{14} \right) + 0.0075 \right] \%$$

55 Amounts of niobium in excess of the amounts required for the above formula will not sufficiently improve the elevated temperature creep resistance without having a great adverse effect on the thermal cyclic oxidation resistance.

60 In making the alloy of the present invention, a melt of the alloy is prepared in a conventional manner. Preferably, the normal steelmaking impurities of oxygen, nitrogen and sulfur are reduced prior to additions of rare earths of the melt. No particular process is required for the alloy of the present invention and, thus, any conventional process, including electric arc furnaces, AOD and vacuum induction melting processes, are acceptable.

65 The melt can then be cast into ingots, bars, strips or sheets. The steel can be subsequently hot and/or cold rolled and subjected to conventional processes such as descaling and heating prior to fabrication into the desired shape.

The ferritic stainless steel of the present invention can then be heat treated to form an aluminium oxide surface, which is adherent and provides for thermal cyclic oxidation resistance. Preferably, the oxide surface is a textured surface which increases the surface area and facilitates support for catalytic materials. A suitable process for texturizing the aluminium oxide surface may be one for growing dense aluminium oxide "whiskers" substantially generally perpendicular to the metal surface. The "whiskers" provide a brush-like surface to effectively support catalytic materials.

Two processes are known for producing alumina whiskers on iron-chromium-aluminium alloys to further increase the surface area and provide more effective catalyst retention on the surface for improving catalyst efficiency, and the processes include basically either:

1. Producing a thin strip with a heavily cold worked surface by removing the strip from a solid log through a machining process called "peeling" and subjecting said strip to 870°C to 930°C in air, as disclosed in United Kingdom Patent Application GB 2063723A; or

2. Using a thin strip produced by conventional hot and cold rolling, preconditioning the surface by heating for a short time to temperatures of about 900°C in an essentially oxygen-free inert atmosphere (<0.1% O₂) and after cooling to room temperature following which a whisker growing heat treatment in air for longer periods of time at about 925°C.

In order to more completely understand the present invention, the following examples are presented.

Examples

The alloys of the present invention and comparative examples shown in the following Tables I through IV are made by alloying the elements in a molten state. Most of the alloys shown in the four Tables were melted by vacuum induction processes into 17 or 50- pound heats. Generally, the ingots were heated to about 225°F (1232°C) for pressing or hot rolling to bars four to five inches wide (10.16 to 12.70 centimeters) and one to two inches (2.54 to 5.08 centimeters) thick. The bars were then either cooled to room temperature for conditioning or were directly reheated to the temperature range 2100 to 2350°F (1147 to 1232°C) for hot rolling to strip material approximately 0.11 inch (0.28 centimeters) thick. The strip was descaled, conditioned as necessary and cold rolled to 0.004 inch or 0.020 inch (0.010 or 0.051 centimeters) thick. Some of the strip was preheated to 300—500°F (149 to 260°C) before cold rolling if such preheating was necessary. The strip was then annealed at about 1550°F (843°C), descaled and again cold rolled to foil of about 0.002 inch (.005 centimeters) thick.

The clean and cold-rolled samples of foil strip were then treated in accordance with the above-described Process 2 for the purpose of growing dense alumina whiskers on the foil surface. The samples were then examined for whisker growth, uniformity and adherence under a scanning electron microscope (SEM) to 100 to 10,000 magnifications.

In the Tables, the ability of the heats to grow whiskers is indicated in the column headed "Whiskers". An "OK" symbol indicates the ability to grow dense adherent whiskers uniformly distributed over the whole surface. Negative exponents or minus signs following the term "OK" indicate a degree of non-uniformity of the whiskers at lower magnifications ranging from 100 to 1000. The column may also include comments about the shape or configuration of the whiskers, such as "Fine", "Coarse", "Short", "Medium", "Long", "Short Rosettes", "Very Short Rosettes", "Flaked" and "Slight Flake". If a sample was not workable, an indication is made in the "Whiskers" column. Under the column entitled "Wire Life", the results of more than one test may be indicated and are reported as the number of cycles to failure.

The wire life tests were conducted in an ASTM wire life tester generally in accordance with the procedure outlined in Specification B78—59.T. The tester essentially consists of a controlled power supply for resistance heating of the sample by an electrical current, a temperature measuring device and a counter to record the number of heating and cooling cycles which the sample undergoes before failing by rupture. Samples of the heats were prepared by cutting about 3/16-inch wide and 6-inches long (0.476 centimeters and 15.24 centimeters) from the 0.002-inch thick foil. The samples were attached to the wire life tester and subjected to thermal cyclic conditions. The cycle imposed on all samples or specimens was heating to 2300°F (1260°C), holding for two minutes at that temperature, cooling to ambient temperature, holding for two minutes at ambient temperature, and repeating the cycle until failure of the specimen by rupture. The testing procedure departed from the standard ASTM procedure by the use of a rectangular foil section to replace round wire and the use of 2300°F (1260°C) instead of 2200°F (1204°C) as the heating temperature in order to decrease the time for testing.

It is accepted that the wire life test is directly related to performance in electrical resistance heating element applications. The test is also expected to show a relationship to catalyst substrate uses as a method of evaluating resistance to oxidation at high temperatures and retention of adherent oxides under thermal cyclic conditions. Normally, flaking of oxide at the point of failure preceded actual failure in the test. Alumina whiskers were not developed during the wire life testing. As part of the analysis of the data, heats having a wire life below 80 cycles were considered to be undesirable.

0 091 526

TABLE I—16% Cr Heats

	Heat No.	Cr	Al	Ce	La	Nd	Pr
5	RV7458	15.98	5.12				
	RV7517	15.85	5.21				
	RV8523	15.93	5.41				
10	RV8536	16.19	5.18		0.020		
	RV8537	16.19	5.25		0.016		
15	RV8540	16.05	5.30		0.020		
	RV8608	16.12	5.18	0.004	0.029		
	RV8765	16.30	4.80		0.001		
20	RV8766	16.26	5.63	0.051	0.020	0.017	0.004
	RV8769	16.28	4.97	0.058	0.030	0.024	0.008
25	RV8770	16.16	5.85	0.009	0.006	0.004	0.001
	RV8773	16.42	4.85	0.030	0.012	0.011	0.004
	RV8774	16.20	5.71	0.026	0.012	0.014	0.004
30	RV8792	16.21	4.96	0.003	0.003	0.0005	Nil
	RV8793	16.05	5.66	0.017	0.008	0.004	0.002
35	RV8797	16.00	5.66	0.013	0.005	0.004	0.0005
	RV8901	15.97	6.50	0.007	0.003		
	RV8902	16.05	6.45	0.009	0.005		
40	RV8903	15.95	6.47	0.009	0.004		
	RV8904	16.08	6.48	0.008	0.005		
45	RV9027A	15.21	5.06	0.013	0.0042	0.0059	0.0068
	RV9027B	15.06	5.85	0.013	0.0072	0.0072	0.0062
	RV9027C	14.89	6.55	0.011	0.0033	0.0054	0.0044

0 091 526

TABLE I—16% Cr Heats Continued...

	C	Mn	P	S	Si	Y	Total Re
5	0.0054	0.21		0.002	0.30	0.41	
	0.0036	0.006	0.009	0.001	0.33	0.34	
	0.020	0.18	0.001	0.003	0.32	<0.001	
10	0.022	0.22	0.001	0.002	0.40		0.020 +
	0.020	0.23	0.001	0.001	0.25		0.016 +
15	0.028	0.23	0.001	0.001	0.27		0.020 +
	0.022	0.23	0.005	0.005	0.28		0.033 +
	0.016	0.15	0.003	0.001	0.23		0.001 +
20	0.018	0.14	0.002	0.0007	0.27		0.092
	0.018	0.15	0.005	0.0008	0.27		0.120
25	0.018	0.15	0.003	0.0016	0.27		0.020
	0.015	0.15	0.005	0.0009	0.26		0.057
	0.013	0.15	0.006	0.0004	0.25		0.056
30	0.0011	0.15	0.002	0.001	0.24		0.0065
	0.0069	0.15	0.003	0.0008	0.24		0.031
35	0.013	0.15	0.003	0.0015	0.24		0.023
	0.018	0.32	0.023	0.001	0.40		0.010 +
	0.012	0.34	0.024	0.002	0.40		0.014 +
40	0.027	0.31	0.023	0.001	0.41		0.013 +
	0.024	0.47	0.023	0.001	0.41		0.013 +
45	0.022	0.43	0.034	0.002	0.41		0.0299
	0.022	0.43	0.034	0.002	0.41		0.0309
50	0.022	0.42	0.035	0.002	0.40		0.0241

55

60

65

0 091 526

TABLE I—16% Cr Heats Continued...

Heat No.	Stabilizer	Other
RV7458	0.001 Ca	0.18 Ni
RV7517	0.0044 Ca	
RV8523		
RV8536		
RV8537		
RV8540	0.13 Ti	
RV8608	0.041 Zr	
RV8765		
RV8766		
RV8769	0.07 Zr	
RV8770	0.10 Zr	
RV8773	0.18 Zr	
RV8774	0.03 Zr	
RV8792	0.003 Zr	
RV8793	0.0002 Ca	
RV8797	0.34 Zr	
RV8901	0.07 Zr; Nil Ca	0.14 Ni; 0.04 Cu
RV8902	0.07 Zr; Nil Ca	0.26 Ni; 0.17 Cu
RV8903	0.06 Zr; Nil Ca	0.50 Ni; 0.17 Cu
RV8904	0.06 Zr; Nil Ca	0.50 Ni; 0.17 Cu
RV9027A		0.19 Ni; 0.15 Cu; 0.048 Mo
RV9027B		0.19 Ni; 0.15 Cu; 0.049 Mo
RV9027C		0.19 Ni; 0.15 Cu; 0.050 Mo

0 091 526

TABLE I—16% Cr Heats Continued...

	Whiskers	Wire life
5	OK	173/203
	OK	137/155
	OK— — Mixed fine and coarse—flaked	82/170
10	OK— — Blades	146/204
	OK— — Blades	96/158
15	OK— — Blades	161/178
	OK— — Blades	180/214
	Flaked	51/60
20	Not workable	
	Not workable	
25	OK—	
	Not workable	195
	Not workable	
30	OK	74/74
	OK	193/236
35	OK	241/284
	OK—	216/246
	OK—	272
40	OK—	333/374
	OK—	226/280
45	OK Coarse	120/117
	OK— Coarse	161/143
50	OK— Coarse	193/165

The heats of Table I are nominally 16% chromium and 5% aluminium alloys. Heats RV7458 and RV7517 are comparative examples and are typical of iron-chromium-aluminium-yttrium alloys that have been considered for catalytic substrates. Heats RV8523 and RV8765 without significant yttrium or rare earth additions are further comparative examples and showed flaking of the oxide whisker surface and reduced wire life. Figure 1 is a photomicrograph at 500× magnification of a sample at Heat RV8765 which shows that the surface oxide had poor adherence and easily flaked off. Figure 2 is a photomicrograph at 5000× magnification of the same sample which shows that a whiskered oxide surface was formed, although it was not adherent.

Heats RV8536, RV8537, RV8540 and RV8608 were melted with additions of lanthanum metal and show that this element, by itself, is effective in providing the desired oxide adherence.

Heats RV8766, RV8769, RV8773 and RV8774 are further comparative examples and all have rare earth content above 0.05% and all were found to break up during hot working. Heat RV8770 with near optimum cerium and lanthanum content and partial stabilization with zirconium can be hot and cold worked to

produce foil exhibiting acceptable properties. Heat RV8792 with lower cerium and lanthanum and insignificant zirconium stabilization content shows acceptable whisker growth but marginal wire life.

Heats RV8793 and RV8797 were melted using a cerium-nickel alloy for the rare earth addition. Acceptable whisker growth and wire life were obtained both with and without zirconium stabilization.

5 Heats RV8901 through RV8904 with relatively high aluminium content and residual element (Ni, Cu, Si, Mn, P, S) contents typical of those obtained in electric furnace or AOD processing had an addition of calcium-aluminium made prior to the addition of rare earths in the form of mischmetal. These heats all show acceptable whisker growth and adherence and excellent wire life.

10 The rare earth additions to Heats RV9027A through C were made in the form of mischmetal. In this series of heats, it can be seen that although acceptable, the uniformity of whisker growth decreases and the wire life increases as aluminium content is increased.

15

20

25

30

35

40

45

50

55

60

65

0 091 526

TABLE II—21% Cr Heats

	Heat No.	Cr	Al	Ce	La	Nd
5	RV8442	21.30	5.82	0.0165	0.0092	0.0069
	RV8767	21.05	4.90	0.063	0.063	0.025
	RV8768	21.90	5.77	0.005	0.003	0.002
10	RV8771	21.08	4.45	0.002	0.0005	0.0005
	RV8772	20.80	6.01	0.046	0.018	0.018
15	RV8775	20.97	5.03	0.016	0.005	0.006
	RV8776	21.18	5.63	0.030	0.013	0.014
	RV8794	20.90	4.94	0.018	0.008	0.005
20	RV8795	21.23	5.66	0.008	0.004	0.002
	RV8798	21.08	4.98	0.009	0.003	0.003
25	RV8825A	21.90	5.04	0.016	0.0091	
	RV8825B	21.50	5.00	0.011	0.0054	
	RV8825C	21.35	5.00	0.007	0.0038	
30	RV8849A	21.89	3.20	0.018	0.007	
	RV8849B	21.53	3.16	0.010	0.002	
35	RV8849C	21.42	3.15	0.006	0.001	
	RV8867	21.18	5.46	0.010	0.003	0.003
	RV8869	21.10	5.69	0.018	0.005	0.007
40	RV8871	21.20	5.50	0.011	0.003	0.004
	RV8873	21.22	5.67	0.023	0.008	0.009
45	RV8898	21.81	5.77	0.007	0.002	
	RV8899	21.82	5.76	0.009	0.005	
	RV8900	22.03	5.70	0.009	0.004	
50	RV8910	21.52	5.82	0.003	0.005	
	RV8911	21.58	5.76	0.011	0.003	
55	RV8912	21.60	5.78	0.009	0.002	
	RV8913	21.80	5.76	0.0091	0.0039	0.004
	RV8945	20.80	6.45	0.038	0.001	
60	RV8946	20.86	6.62	0.024	0.001	
	RV8947	20.83	6.59	0.021	0.001	
65	RV8948	20.82	6.53	0.003	0.039	

TABLE II—21% Cr Heats Continued...

	Pr	C	Mn	P	S	Si	Total Re
5	0.0017	0.015	0.13	0.002	0.002	0.23	0.036
	0.006	0.014	0.14	0.004	0.0012	0.26	0.126
	0.001	0.017	0.15	0.005	0.0016	0.26	0.011
10	Nil	0.008	0.15	0.006	0.0001	0.26	0.003
	0.004	0.014	0.16	0.005	0.0001	0.28	0.088
15	0.002	0.013	0.14	0.006	0.0006	0.27	0.029
	0.003	0.010	0.14	0.005	0.0007	0.27	0.060
	0.002	0.0086	0.15	0.003	0.0011	0.25	0.032
20	Nil	0.017	0.15	0.002	0.002	0.23	0.014
	Nil	0.011	0.16	0.004	0.0011	0.24	0.15
25		0.019	0.38	0.028	0.002	2.00	0.0251 +
		0.025	0.37	0.029	0.003	3.03	0.0164 +
		0.066	0.38	0.028	0.002	3.91	0.0108 +
30		0.021	0.41	0.036	0.001	1.98	0.025 +
		0.021	0.40	0.036	0.001	3.09	0.012 +
35		0.023	0.40	0.036	0.001	3.08	0.007 +
	0.0006	0.0039	0.16	0.005	0.0001	0.27	0.017
	0.002	0.0021	0.15	0.006	0.0001	0.27	0.032
40	0.001	0.008	0.15	0.006	0.0001	0.26	0.019
	0.003	0.003	0.15	0.006	0.0001	0.26	0.043
45		0.012	0.35	0.027	0.002	0.32	0.009 +
		0.024	0.33	0.024	0.002	0.32	0.014 +
		0.016	0.49	0.026	0.001	0.33	0.013 +
50		0.022	0.17	0.004	0.002	0.39	0.008 +
		0.031	0.18	0.007	0.002	0.36	0.014 +
55		0.033	0.18	0.004	0.002	0.31	0.011 +
	0.001	0.030	0.17	0.004	0.001	0.33	0.018
		0.030	<0.005	0.003	0.001	0.30	0.039 +
60		0.017	<0.005	0.003	0.003	0.30	0.25 +
		0.030	<0.005	0.003	0.003	0.30	0.022 +
65		0.019	<0.005	0.003	0.003	0.31	0.041 +

0 091 526

TABLE II—21% Cr Heats Continued...

Heat No.	Cr	Al	Ce	La	Nd
RV8949	20.80	6.56	0.002	0.027	
RV8950	20.82	6.58	0.0005	0.013	
RV8955	20.69	5.79	0.023	0.007	0.007
RV8956	20.62	5.85	0.048	0.001	0.0011
RV8957	20.68	5.82	0.0023	0.028	0.0005
RV8958	20.59	5.77	0.0021	0.033	0.0006
RV8959	20.84	5.83	0.0095	0.0052	0.0038
RV8960	20.62	5.88	0.0071	0.0040	0.0029
RV8961	20.68	5.73	0.0090	0.0053	0.0035
RV8962	20.59	5.87	0.0045	0.0029	0.0022
XW33	20.89	5.32	0.003	0.001	
011563E	19.80	5.55	0.022	0.009	0.008

TABLE II—21% Cr Heats Continued...

Pr	C	Mn	P	S	Si	Total Re
	0.030	<0.005	0.003	0.004	0.25	0.029 +
	0.020	<0.005	0.003	0.003	0.31	0.0135 +
0.0025	0.008	0.065	0.003	0.002	0.31	0.0395
0.0013	0.027	0.056	0.003	0.002	0.32	0.0514
0.0008	0.025	0.061	0.003	0.002	0.32	0.0316
0.0009	0.028	0.057	0.003	0.003	0.31	0.0366
0.0016	0.023	0.061	0.005	0.003	0.32	0.0201
0.0010	0.023	0.057	0.002	0.002	0.31	0.0150
0.0005	0.026	0.063	0.002	0.003	0.32	0.0183
0.0003	0.022	0.063	0.002	0.003	0.32	0.0097
	0.030	0.18	0.003	0.003	0.53	0.004 +
0.0035	0.015	0.40	0.012	0.002	0.31	0.0425

0 091 526

TABLE II—21% Cr Heats Continued...

	Heat No.	Stabilizer	Other
5	RV8442	0.049 Zr	
	RV8767		
	RV8768		
10	RV8771	0.08 Zr	
	RV8772	0.12 Zr	
15	RV8775	0.022 Zr	
	RV8776	0.11 Zr	
	RV8794		0.0002 Ca
20	RV8795	0.003 Zr	
	RV8798	0.37 Zr	
25	RV8825A		0.03 Ni; 0.015 Cu
	RV8825B		0.027 Ni; 0.015 Cu
	RV8825C		0.031 Ni; 0.016 Cu
30	RV8849A		0.024 Ni; 0.017 Cu
	RV8849B		0.026 Ni; 0.018 Cu
35	RV8849C	0.61 Nb	0.027 Ni; 0.019 Cu
	RV8867		
	RV8869		
40	RV8871		
	RV8873		
45	RV8898	0.07 Zr	0.26 Ni; 0.04 Cu
	RV8899	0.06 Zr	0.50 Ni; 0.17 Cu
	RV8900	0.06 Zr	0.50 Ni; 0.16 Cu
50	RV8910	0.07 Zr	
	RV8911	0.06 Zr	
55	RV8912	0.07 Zr	
	RV8913	0.06 Zr	
	RV8945		0.0015 Ca
60	RV8946		0.0035 Ca
	RV8947		0.0032 Ca
65	RV8948		0.0031 Ca

0 091 526

TABLE II—21% Cr Heats Continued...

	Whiskers	Wire life
5	OK	
	Not workable	322/408/481/535
10	OK	181/240
	OK	217/255
	Not workable	
15	OK—	236/274
	Not workable	
20	OK—	270
	OK	112/113
	OK—	147/181
25	OK	265/211
	OK	180/156
	OK	133/91
30	OK	121/119
	OK	164/111
35	OK	174/98
	OK	241/147
	OK	248/309
40	OK—	254/263
	OK—	276/239
45	OK—	255/306
	OK—	277/375
	OK—	289/337
50	OK—	498/437
	OK—	464/397
55	OK—	455/601
	OK—	451/492
	OK Short rosettes	195/226
60	OK— Short rosettes	183/185
	OK Very short rosettes	295/212
65	OK— Very short rosettes	216/216

0 091 526

TABLE II—21% Cr Heats Continued...

Heat No.	Stabilizer	Other
RV8949		0.0031 Ca
RV8950		0.0021 Ca
RV8955		0.0012 Ca
RV8956		0.0025 Ca
RV8957		0.0019 Ca
RV8958		0.0021 Ca
RV8959		0.01 Co
RV8960		0.20 Co
RV8961		0.43 Co
RV8962		0.90 Co
XW33	0.10 Zr	
011563E		0.24 Ni; 0.10 Cu; 0.02 Mo; 0.02 Co; 0.001 Ca

TABLE II—21% Cr Heats Continued...

Whiskers	Wire life
OK— Very short rosettes	320/264
OK— Very short rosettes	351/365
OK Very short rosettes	418/375
Not workable	
OK— Very short	296/243
OK— — Very short	414/323
OK— — Very short rosettes	428/475
OK— — Short	264/189
OK Very short rosettes	236/292
OK— Very short rosettes	290/247
OK	195/209
OK— —	162/163/169/152/215/222

The heats of Table II nominally contain about 21% chromium and 3% to 6% aluminium. Heat RV8442 illustrates the superior whisker growth and wire life of a high chromium alloy of the present invention. Figure 3 is a photomicrograph of that heat at magnification of 5000x which clearly illustrates the developed adherent whiskered aluminium oxide surface on the alloy.

Heats RV8767, RV8772, RV8776 and RV8956 were comparative examples and were found to break up during hot working at normal steel hot working temperatures and, thus, were considered not workable. All

four of these heats have a total content of the rare earth cerium lanthanum, neodymium and praseodymium greater than 0.060%.

Heats RV8768, RV8771, RV8775 and RV8794 illustrate various alloys of the invention, all showing good whisker growth adherence and wire life as do the low carbon content heats RV8867, RV8869, RV8871 and RV8873 which are also alloys of the invention.

Heats RV8795 and RV8798 are alloys of the invention melted without (RV8795) and with (RV8798) a deliberate zirconium stabilizing addition. Both show good whisker growth, adherence and acceptable wire life and wire life is not decreased as a result of the zirconium addition.

Heats RV8898 through RV8962 were melted using a calcium-aluminum deoxidizing addition before the rare earth addition was made to the melt.

Heats RV8898, RV8899 and RV8900 are alloys of the invention with nickel and copper additions made to approximate high residual contents which are frequently found in conventional melting practice. Acceptable whisker growth, adherence and wire life were found.

Heats RV8910, RV8911, RV8912 and RV8913 are alloys of the invention which, aside from the use of calcium-aluminum deoxidation in these heats, duplicate the alloy of Heat RV8442, both in analysis and in the properties of interest.

Heats RV8945, RV8946, RV8947, RV8955 and RV8956 were melted using cerium metal as the rare earth addition. All of these, with the exception of Heat RV8956, which is a comparative example, are alloys of the invention and show acceptable whisker growth, adherence and wire life.

Heats RV8948, RV8949, RV8950, RV8957 and RV8958 were melted using lanthanum metal for the rare earth addition. All are alloys of the invention and show acceptable whisker growth, adherence and wire life.

Heats RV8959, RV8960, RV8961 and RV8962 are alloys of the invention using mischmetal for the rare earth addition. Cobalt additions made to Heats RV8960, RV8961 and RV8962 showed no regular effect on whisker growth, adherence or on wire life.

Heats RV8825A, RV8825B, RV8825C, RV8849A, RV8849B and RV8849C are alloys of the invention melted with high silicon content to improve fluidity of the melt and facilitate the casting of thin sections. All show acceptable whisker growth, adherence and wire life. Heat RV8849C illustrates that acceptable properties can be obtained when niobium overstabilization is utilized. The Heats RV8945 through RV8962 all have low manganese content. All of these heats show either the growth of short whiskers or the onset of nonuniform whisker growth as evidenced by formation of rosettes of whiskers.

Heat XW33 is a laboratory induction air melted heat of an alloy of the invention showing acceptable properties.

Heat 011563E is a commercial production size AOD (argon-oxygen-decarburization) heat of an alloy of the invention showing acceptable properties.

0 091 526

TABLE III—13% Cr Heats

	Heat No.	Cr	Al	Ce	La	Nd	Pr
5	RV7772	13.05	4.18				
	RV8885A	13.13	4.21	0.008			
	RV8885B	13.03	4.13	Nil			
10	RV8885C	12.97	4.15	0.023			
	RV8964A	12.74	5.03	0.001	0.0001	0.003	Nil
15	RV8964B	12.72	5.11	0.019	0.009	0.010	0.0033
	RV8964C	12.61	5.00	0.013	0.0034	0.0079	0.0022
	RV8965A	12.99	4.03	Nil	0.0002	0.0002	0.0016
20	RV8965B	12.96	4.15	0.019	0.0094	0.0069	0.0032
	RV8965C	12.95	4.10	0.013	0.0062	0.0049	0.0028
25	RV8966A	12.82	5.07	0.0001	0.0003	0.0003	0.0016
	RV8966B	12.81	5.13	0.021	0.011	0.0076	0.0026
	RV8966C	12.68	5.08	0.013	0.0054	0.0074	0.0027
30	RV8986A	12.77	5.32	0.0058	0.0025	0.0025	0.0016
	RV8986B	12.77	5.22	0.0051	0.0028	0.0022	0.0012
35	RV8986C	12.77	5.22	0.0054	0.0029	0.0025	0.0041
	RV8987A	12.98	5.37	0.0050	0.0024	0.0028	0.0017
	RV8987B	12.94	5.21	0.0064	0.0037	0.0042	0.0025
40	RV8987C	12.91	5.16	0.0069	0.0024	0.0051	0.0019
	RV9000A	13.90	4.99	Nil			
45	RV9000B	13.60	4.91	Nil			
	RV9000C	13.53	4.82	0.012			
	RV9023A	13.01	6.00	0.011	0.0026	0.0049	0.0065
50	RV9023B	12.94	5.93	0.010	0.0024	0.0050	0.0055
	RV9023C	12.95	5.90	0.010	0.0022	0.0048	0.0059
55	RV9025A	12.85	4.76	0.016	0.0077	0.0090	0.0070
	RV9025B	12.73	5.52	0.013	0.0059	0.0071	0.0051
60	RV9025C	12.62	6.28	0.0094	0.0041	0.0052	0.0063

0 091 526

TABLE III—13% Cr Heats Continued. . .

	C	Mn	P	S	Si	N	Total Re
5	0.029	0.24	0.014	0.012	0.30		
	0.020	0.44	0.027	0.001	0.34	0.014	0.008 +
	0.020	0.40	0.032	0.001	0.34	0.014	
10	0.022	0.40	0.031	0.001	0.33	0.015	0.023 +
	0.019	0.37	0.033	0.004	0.33	0.013	0.0041
15	0.019	0.37	0.035	0.002	0.34	0.011	0.041
	0.018	0.36	0.033	0.002	0.33	0.013	0.0265
	0.019	0.40	0.032	0.006	0.37	0.013	0.0020
20	0.019	0.39	0.032	0.004	0.38	0.014	0.0385
	0.019	0.40	0.034	0.003	0.38	0.013	0.0269
25	0.020	0.41	0.031	0.006	0.35	0.013	0.0023
	0.018	0.39	0.033	0.004	0.37	0.014	0.0422
	0.020	0.42	0.034	0.002	0.37	0.012	0.0285
30	0.021	0.43	0.030	0.004	0.35	0.012	0.0124
	0.022	0.42	0.028	0.004	0.35	0.0098	0.0113
35	0.021	0.41	0.030	0.003	0.36	0.0113	0.0149
	0.020	0.43	0.026	0.004	0.36	0.0111	0.0119
	0.020	0.43	0.029	0.003	0.37	0.0111	0.0168
40	0.024	0.42	0.028	0.002	0.36	0.0106	0.0163
	0.020	0.41	0.025	0.004	1.90	0.013	
45	0.021	0.41	0.025	0.004	2.62	0.013	
	0.021	0.41	0.025	0.004	2.61	0.012	0.012 +
	0.019	0.43	0.028	0.002	0.32	0.012	0.025
50	0.019	0.43	0.031	0.002	0.32	0.010	0.0229
	0.021	0.44	0.030	0.002	0.32	0.012	0.0229
55	0.026	0.39	0.034	0.002	0.37	0.012	0.0397
	0.025	0.38	0.035	0.002	0.36	0.013	0.0311
60	0.026	0.38	P.033	0.002	0.36	0.013	0.0250

TABLE III—13% Cr Heats Continued...

5

10

15

20

25

30

35

40

45

50

55

60

65

Heat No.	Stabilizer	Other
RV7772		0.20 Ni
RV8885A		0.23 Ni; 0.03 Cu; 0.055 Mo
RV8885B	0.78 Nb	0.22 Ni; 0.021 Cu; 0.045 Mo
RV8885C	0.79 Nb	0.22 Ni; 0.021 Cu; 0.045 Mo
RV8964A	0.27 Zr; 0.002 Nb	0.23 Ni; 0.018 Cu; 0.067 Mo
RV8964B	0.28 Zr; 0.002 Nb	0.23 Ni; 0.019 Cu; 0.067 Mo
RV8964C	0.28 Zr; 0.30 Nb	0.23 Ni; 0.019 Cu; 0.066 Mo
RV8965A	0.22 Ti; 0.005 Nb	0.18 Ni; 0.017 Cu; 0.058 Mo
RV8965B	0.21 Ti; 0.005 Nb	0.19 Ni; 0.014 Cu; 0.060 Mo
RV8965C	0.21 Ti; 0.28 Nb	0.18 Ni; 0.014 Cu; 0.059 Mo
RV8966A	0.44 Ti; 0.012 Zr; 0.005 Nb	0.17 Ni; 0.016 Cu; 0.060 Mo
RV8966B	0.44 Ti; 0.015 Zr; 0.005 Nb	0.18 Ni; 0.017 Cu; 0.061 Mo
RV8966C	0.43 Ti; 0.29 Zr; 0.005 Nb	0.18 Ni; 0.017 Cu; 0.072 Mo
RB8986A	0.056 V	0.23 Ni; 0.031 Cu; 0.057 Mo
RV8986B	0.11 V	0.23 Ni; 0.024 Cu; 0.058 Mo
RV8986C	0.21 V	0.22 Ni; 0.029 Cu; 0.057 Mo
RV8987A		0.23 Ni; 0.029 Cu; 0.062 Mo
RV8987B	0.11 Zr	0.23 Ni; 0.029 Cu; 0.060 Mo
RV8987C	0.22 Zr	0.23 Ni; 0.029 Cu; 0.062 Mo
RV9000A		0.47 Ni; 0.031 Cu; 0.22 Mo
RV9000B		0.46 Ni; 0.031 Cu; 0.22 Mo
RV9000C		0.49 Ni; 0.031 Cu; 0.22 Mo
RV9023A		0.024 Ni; 0.16 Cu
RV9023B		0.55 Ni; 0.17 Cu
RV9023C		0.80 Ni; 0.17 Cu
RV9025A		0.21 Ni; 0.16 Cu
RV9025B		0.20 Ni; 0.16 Cu
RV9025C		0.21 Ni; 0.16 Cu

0 091 526

TABLE III—13% Cr Heats Continued...

	Whiskers	Wire life
5	OK Flaked	8/9
	OK Slight flake	75/76
10	OK Flaked	37/24
	OK	42/34
	OK— Slight flake	157/137
15	OK	226/163
	OK	174/113
	OK— Slight flake	73/84
20	OK—	86/119
	OK—	57/63
25	OK— Slight flake	141/89
	OK—	118/93
	OK	32/32
30	OK	87/90
	OK	85/81
35	OK	81/83
	OK	74/80
	OK	176/236
40	OK	165/227
	Not workable	
45	Not workable	
	OK—	420/327*
	OK—	173/129
50	OK—	137/106
	OK	158/161
55	OK— Short	82/87
	OK— Medium	127/89
60	OK— Long	148/133

*0.003 inch sample —stiff cold rolling

The heats of Table III are nominally 13% chromium and 4% to 6% aluminium. Heat RV7772 a comparative example was made without rare earth addition and exhibited whisker growth but oxide flaking

and low wire life. Heat RV8885A is an alloy of the invention made with a mischmetal addition and low rare earth recovery. Here the flaking was reduced and wire life became marginal. Figure 4 is a photomicrograph of Heat 8885A at 5000X magnification illustrating the whisker growth. Heat 8885B is a second fraction of the same melt which does not represent an alloy of this invention. Here the rare earth addition was allowed to "fade" until the cerium content became undetectable and a stabilizing addition of niobium was made. Again, the oxide whiskers exhibited poor adherence (flaking) and low wire life. A second rare earth addition in Heat RV8885C restored the whisker adherence but still exhibited low wire life in the presence of niobium overstabilization.

Heats RV8964A, RV8964B and RV8964C have higher aluminium content and zirconium stabilization. Heat RV8964A, melted without intentional rare earth addition, exhibited questionable whisker adherence and acceptable wire life. The unexpectedly high neodymium content may be a contributing factor to whisker adherence. An intentional mischmetal addition was made to Heat RV8964B with a resulting improvement in whisker adherence and wire life. Additional stabilization with niobium in Heat RV8964C produced acceptable whisker adherence and acceptable but reduced wire life test values.

Heats RV8965A, RV8965B and RV8965C were comparative examples and were melted with lower aluminium content and titanium stabilization. Heat RV8965A was melted without intentional rare earth addition and exhibited questionable whisker adherence and marginal wire life. Addition of mischmetal to Heat RV8965B resulted in improved whisker adherence and wire life while an additional stabilization addition of niobium to Heat RV8965C resulted in unacceptable wire life without affecting whisker adherence.

Heats RV8966A, RV8966B and RV8966C, were again comparative examples and were melted with higher aluminium content and a higher degree of titanium stabilization. Heat RV8966A, melted without intentional rare earth addition, exhibited questionable whisker adherence and acceptable wire life. A mischmetal addition to Heat RV8966B improved whisker adherence to an acceptable level while maintaining acceptable wire life. Additional niobium stabilization added to Heat RV8966C maintained whisker adherence but produced unacceptable wire life.

Heats RV8986A, RV8986B and RV8986C were comparative examples and were used to examine vanadium as a stabilizing element. In each case, although whisker adherence was satisfactory, the wire life values were marginal.

Heats RV8987A, RV8987B and RV8987C were used to examine the effects of zirconium as a stabilizing element. Heat RV8987A melted without zirconium addition shows acceptable whisker adherence and marginal wire life. Zirconium stabilizing additions to Heats RV8987B and RV8987C improved the wire life to acceptable levels without destroying whisker growth or adherence.

Heats RV9023A, RV9023B and RV9023C were used to examine the effect of nickel content in alloys of the invention on whisker growth, adherence and wire life. No significant effect was found, all heats showing acceptable whisker adherence and wire life.

Heats RV9025A, RV9025B and RV9025C were used to examine the effect of aluminium content in 13% chromium alloys of the invention on whisker growth, adherence and wire life. Whisker growth and adherence were acceptable in all three heats, while wire life increased as aluminium content increased.

Heats RV9000A, RV9000B and RV9000C were used to examine the effect of silicon additions which are desirable to improve fluidity when casting thin sections. Heats RV9000A and RV9000B which are not alloys of the invention had no rare earth additions and were found to crack in cold rolling. A mischmetal rare earth addition to Heat RV9000C improved the workability so that cold rolling was possible. The material, however, was stiff and resisted deformation so that the minimum thickness obtained was 0.003" (in contrast to 0.002" for all other specimens). Whisker growth and adherence of this heat were acceptable, but wire life could not be evaluated comparatively because of the greater foil thickness.

TABLE IV—Low Cr heats

Heat No.	Cr	Al	Ce	La	Nd	Pr
RV8983	6.99	5.26	0.0041	0.0016	0.0014	0.0018
RV8984	9.04	5.86	0.0077	0.0039	0.0037	0.0019
RV8985	10.91	5.16	0.0050	0.0021	0.0023	0.0031

TABLE IV—Low Cr heats Continued...

C	Mn	P	S	Si	N	Total Re
0.017	0.41	0.029	0.010	0.31	0.0091	0.0089
0.017	0.43	0.026	0.003	0.035	0.0083	0.0172
0.028	0.43	0.029	0.003	0.029	0.0115	0.0125

TABLE IV—Low Cr heats Continued...

Heat No.	Stabilizer	Other	Whiskers	Wire life
RV8983	0.20 Ti	0.23 Ni; 0.029 Cu; 0.055 Mo	OK	9/5
RV8984	0.21 Ti	0.23 Ni; 0.029 Cu; 0.056 Mo	OK—	89/33
RV8985	0.20 Ti	0.23 Ni; 0.029 Cu; 0.056 Mo	OK—	71/76

The experimental heats shown in Table IV illustrate a marked decrease in the thermal cyclic oxidation resistance of the comparative example alloys when the chromium content is lowered to below 8%.

Figure 5 is a photomicrograph of a commercial electrical resistance heating element material identified as Kanthal A alloy. The material did not develop a whiskered surface oxide, as illustrated in the figure. Nominally, Kanthal A is an alloy having a composition of 0.06% carbon, 23.4% chromium, 6.2% aluminium, 1.9% cobalt and the balance iron.

The alloy of the present invention satisfies its objectives. A hot workable ferritic stainless steel alloy is provided, having good thermal cyclic oxidation resistance. The alloy retains an adherent aluminium oxide surface which is suitable to be texturized to increase the surface area for facilitating support of catalytic materials. Such an alloy is a good candidate for end uses which include electrical resisting heating elements and catalytic substrates, such as may be used in catalytic systems and converters for automobiles. The alloy is less expensive to produce than present alloys because of the lower cost of alloying elements and because it can be produced by lower cost melting processes.

Claims

1. A hot workable ferritic stainless steel alloy resistant to thermal cyclic oxidation and scaling at elevated temperatures and suitable for forming thereon an adherent textured aluminium oxide surface, characterized in that the alloy consists of, by weight, 8.0—25.0% chromium, 3.0—8.0% aluminium, and an addition of at least 0.002% and up to 0.05% cerium, lanthanum neodymium and/or praseodymium, a total of all rare earths up to 0.060%, up to 4.0% silicon, 0.06% to 1.0% manganese and normal steelmaking impurities of less than 0.050% carbon, less than 0.050% nitrogen, less than 0.020% oxygen, less than 0.040% phosphorus, less than 0.030% sulfur, less than 0.50% copper, less than 1.0% nickel, the sum of calcium and magnesium less than 0.005%, up to

$$91\left[\left(\frac{\%C}{12}\right) + \left(\frac{\%N}{14}\right) + 0.004\right]\%$$

zirconium to stabilize the alloy, and/or up to

$$93\left[\left(\frac{\%C}{12}\right) + \left(\frac{\%N}{14}\right) + 0.013\right]\%$$

niobium for stabilization and elevated creep strength, and the remainder being iron.

2. An alloy according to claim 1, characterized in that the rare earth addition consists of cerium and/or lanthanum.

3. An alloy according to claim 1 or 2, characterized in that the minimum total cerium and/or lanthanum amounts in the alloy are proportional to the chromium content as expressed by

$$\frac{\% Cr}{2200}$$



0 091 526

TABLE IV—Low Cr heats Continued...

C	Mn	P	S	Si	N	Total Re
0.017	0.41	0.029	0.010	0.31	0.0091	0.0089
0.017	0.43	0.026	0.003	0.035	0.0083	0.0172
0.028	0.43	0.029	0.003	0.029	0.0115	0.0125

TABLE IV—Low Cr heats Continued...

Heat No.	Stabilizer	Other	Whiskers	Wire life
RV8983	0.20 Ti	0.23 Ni; 0.029 Cu; 0.055 Mo	OK	9/5
RV8984	0.21 Ti	0.23 Ni; 0.029 Cu; 0.056 Mo	OK—	89/33
RV8985	0.20 Ti	0.23 Ni; 0.029 Cu; 0.056 Mo	OK—	71/76

The experimental heats shown in Table IV illustrate a marked decrease in the thermal cyclic oxidation resistance of the comparative example alloys when the chromium content is lowered to below 8%.

Figure 5 is a photomicrograph of a commercial electrical resistance heating element material identified as Kanthal A alloy. The material did not develop a whiskered surface oxide, as illustrated in the figure. Nominally, Kanthal A is an alloy having a composition of 0.06% carbon, 23.4% chromium, 6.2% aluminium, 1.9% cobalt and the balance iron.

The alloy of the present invention satisfies its objectives. A hot workable ferritic stainless steel alloy is provided, having good thermal cyclic oxidation resistance. The alloy retains an adherent aluminium oxide surface which is suitable to be texturized to increase the surface area for facilitating support of catalytic materials. Such an alloy is a good candidate for end uses which include electrical resisting heating elements and catalytic substrates, such as may be used in catalytic systems and converters for automobiles. The alloy is less expensive to produce than present alloys because of the lower cost of alloying elements and because it can be produced by lower cost melting processes.

Claims

1. A hot workable ferritic stainless steel alloy resistant to thermal cyclic oxidation and scaling at elevated temperatures and suitable for forming thereon an adherent textured aluminium oxide surface, characterized in that the alloy consists of, by weight, 8.0—25.0% chromium, 3.0—8.0% aluminium, and an addition of at least 0.002% and up to 0.05% cerium, lanthanum neodymium and/or praseodymium, a total of all rare earths up to 0.060%, up to 4.0% silicon, 0.06% to 1.0% manganese and normal steelmaking impurities of less than 0.050% carbon, less than 0.050% nitrogen, less than 0.020% oxygen, less than 0.040% phosphorus, less than 0.030% sulfur, less than 0.50% copper, less than 1.0% nickel, the sum of calcium and magnesium less than 0.005%, up to

$$91\left[\left(\frac{\%C}{12}\right) + \left(\frac{\%N}{14}\right) + 0.004\right]\%$$

zirconium to stabilize the alloy, and/or up to

$$93\left[\left(\frac{\%C}{12}\right) + \left(\frac{\%N}{14}\right) + 0.013\right]\%$$

niobium for stabilization and elevated creep strength, and the remainder being iron.

2. An alloy according to claim 1, characterized in that the rare earth addition consists of cerium and/or lanthanum.

3. An alloy according to claim 1 or 2, characterized in that the minimum total cerium and/or lanthanum amounts in the alloy are proportional to the chromium content as expressed by

$$\frac{\% Cr}{2200}$$



4. An alloy according to claim 1, 2 or 3, characterized in that the minimum amounts of aluminium in the alloy are based on the chromium content as expressed by

$$5 \quad \frac{(40-\%Cr)}{6}] \%$$

5. An alloy according to any one of the preceding claims, characterized in having up to 3% silicon.

6. An alloy according to any one of the preceding claims, characterized in having 0.10 to 0.50% manganese.

7. A hot workable ferritic stainless steel alloy resistant to thermal cyclic oxidation and scaling at elevated temperatures and suitable for forming thereon an adherent textured aluminium oxide surface, characterized in that the alloy consists of, by weight, 12.0—23.0% chromium, from

$$15 \quad \frac{(40-\%Cr)}{6}] \%$$

up to 8.0% aluminium, at least $[\%Cr/2200]\%$ of an addition of cerium and/or lanthanum, a total of all rare earths up to 0.050%, up to 3.0% silicon, 0.10 to 0.50% manganese, and normal steelmaking impurities of less than 0.030% carbon, less than 0.030% nitrogen, less than 0.010% oxygen, less than 0.030% phosphorus, less than 0.020% sulfur, less than 0.4% copper, less than 0.4% nickel, the sum of calcium and magnesium being less than 0.003%, up to

$$25 \quad 91 \left[\frac{\%C}{12} + \frac{\%N}{14} + 0.003 \right] \%$$

zirconium to stabilize the alloy, and/or up to

$$30 \quad 93 \left[\frac{\%C}{12} + \frac{\%N}{14} + 0.0075 \right] \%$$

niobium for stabilization and elevated temperature creep strength, and the remainder being iron.

8. Use of an alloy according to any one of the preceding claims for producing an oxidation resistant catalytic substrate.

9. A catalytic system characterized in comprising an oxidation resistant catalytic substrate according to claim 8.

10. A method of making a hot workable ferritic stainless steel resistant to thermal cyclic oxidation and having a textured aluminium oxide surface resistant to scaling at elevated temperatures, characterized in that the method comprises the steps of

preparing a melt consisting of, by weight, 8.0—25.0% chromium 3.0—8% aluminium, an addition of at least 0.002% and up to 0.05% of cerium, lanthanum, neodymium and/or praseodymium, a total of all rare earths up to 0.060%, up to 4.0% silicon, 0.06 to 1.0% manganese and normal steelmaking impurities of less than 0.050% carbon, less than 0.050% nitrogen less than 0.020% oxygen, less than 0.040% phosphorus, less than 0.030% sulfur, less than 0.50% copper, less than 1.0% nickel, the sum of calcium and magnesium less than 0.005%, up to

$$50 \quad 91 \left[\frac{\%C}{12} + \frac{\%N}{14} + 0.004 \right] \%$$

zirconium to stabilise the alloy, and/or up to

$$55 \quad 91 \left[\frac{\%C}{12} + \frac{\%N}{14} + 0.013 \right] \%$$

niobium for stabilisation and elevated creep strength, the remainder being iron,

producing a ferritic stainless steel article from the melt; and

treating the steel article to form an adherent textured aluminium oxide surface thereon.

Patentansprüche

1. Warmverformbare, ferritische, nicht-rostende Stahllegierung, die gegenüber thermischer zyklischer



0 091 526

Oxidation und Verzunderung bei erhöhten Temperaturen beständig und zur Ausbildung einer festhaftenden, texturierten Aluminiumoxidoberfläche darauf geeignet ist, dadurch gekennzeichnet, daß die Legierung, bezogen auf Gewicht, besteht aus 8,0—25,0% Chrom, 3,0—8,0% Aluminium und einem Zusatz von wenigstens 0,002% und bis zu 0,05% Cer, Lanthan, Neodym und/oder Praseodym, wobei die Gesamtmenge aller Seltene Erden bis zu 0,060% beträgt, bis zu 4,0% Silicium, 0,06% bis 1,0% Mangan und normalen Stahlherstellungs-Verunreinigungen mit weniger als 0,050% Kohlenstoff, weniger als 0,050% Stickstoff, weniger als 0,020% Sauerstoff, weniger als 0,040% Phosphor, weniger als 0,030% Schwefel, weniger als 0,50% Kupfer, weniger als 1,0% Nickel, der Summe von Calcium und Magnesium von weniger als 0,005%, bis zu

10

$$91\left[\frac{\%C}{12} + \frac{\%N}{14} + 0,004\right]\%$$

Zirkon, um die Legierung zu stabilisieren, und/oder bis zu

15

$$93\left[\frac{\%C}{12} + \frac{\%N}{14} + 0,013\right]\%$$

20 Niob zur Stabilisierung und erhöhten Dauerstandfestigkeit, und der Rest Eisen ist.

2. Legierung nach Anspruch 1, dadurch gekennzeichnet, daß der Seltene Erden-Zusatz aus Cer und/oder Lanthan besteht.

3. Legierung nach Anspruch 1 oder 2, dadurch gekennzeichnet, daß die minimalen Cer- und/oder Lanthan-Gesamtmenen in der Legierung proportional zum Chromgehalt sind, wie ausgedrückt durch

25

$$\frac{\% Cr}{2200}$$

30 4. Legierung nach Anspruch 1, 2 oder 3, dadurch gekennzeichnet, daß die Mindestmengen an Aluminium in der Legierung auf den Chromgehalt basieren, wie ausgedrückt durch

$$\left[\frac{(40-\%Cr)}{6}\right]\%$$

35

5. Legierung nach mindestens einem der vorangehenden Ansprüche, dadurch gekennzeichnet, daß sie bis zu 3% Silicium enthält.

6. Legierung nach mindestens einem der vorangehenden Ansprüche, dadurch gekennzeichnet, daß sie 0,10 bis 0,50% Mangan enthält.

40

7. Warmverformbare, ferritische, nicht-rostende Stahllegierung, die gegenüber thermischer zyklischer Oxidation und Verzunderung bei erhöhten Temperaturen beständig und zur Ausbildung einer festhaftenden, texturierten Aluminiumoxidoberfläche darauf geeignet ist, dadurch gekennzeichnet, daß die Legierung, bezogen auf Gewicht, besteht aus 12,0—23,0% Chrom,

45

$$\left[\frac{(40-\%Cr)}{6}\right]\%$$

bis zu 8,0% Aluminium, wenigstens [% Cr/2200]% eines Zusatzes an Cer und/oder Lanthan, wobei die Gesamtmenge aller Seltene Erden bis zu 0,050% beträgt, bis zu 3,0% Silicium, 0,10 bis 0,50% Mangan, und normalen Stahlherstellungs-Verunreinigungen mit weniger als 0,030% Kohlenstoff, weniger als 0,030% Stickstoff, weniger als 0,010% Sauerstoff, weniger als 0,030% Phosphor, weniger als 0,020% Schwefel, weniger als 0,4% Kupfer, weniger als 0,4% Nickel, der Summe von Calcium und Magnesium von weniger als 0,003%, bis zu

55

$$91\left[\frac{\%C}{12} + \frac{\%N}{14} + 0,003\right]\%$$

Zirkon, um die Legierung zu stabilisieren und/oder bis zu

60

$$93\left[\frac{\%C}{12} + \frac{\%N}{14} + 0,0075\right]\%$$

65 Niob zur Stabilisierung und erhöhten Temperatur-Dauerstandfestigkeit, und der Rest Eisen ist.



8. Verwendung einer Legierung nach mindestens einem der vorangehenden Ansprüche zur Herstellung eines oxidationsbeständigen, katalytischen Substrats.

9. Katalytisches System, dadurch gekennzeichnet, daß es ein oxidationsbeständiges, katalytisches Substrat gemäß Anspruch 8 umfaßt.

10. Verfahren zur Herstellung eines warmverformbaren, ferritischen, nicht-rostenden Stahls, der gegenüber thermischer zyklischer Oxidation beständig ist und eine texturierte Aluminiumoxidoberfläche, die gegenüber Verzunderung bei erhöhten Temperaturen beständig ist, besitzt, dadurch gekennzeichnet, daß das Verfahren die Stufen umfaßt.

Herstellen einer Schmelze, bestehend aus, bezogen auf Gewicht, 8,0—25,0% Chrom, 3,0—8,0% Aluminium, einem Zusatz von wenigstens 0,002% und bis zu 0,05% Cer, Lanthan, Neodym und/oder Praseodym, wobei die Gesamtmenge aller Seltene Erden bis zu 0,060% beträgt, bis zu 4,0% Silicium, 0,06% bis 1,0% Mangan und normalen Stahlherstellungs-Verunreinigungen mit weniger als 0,050% Kohlenstoff, weniger als 0,050% Stickstoff, weniger als 0,020% Sauerstoff, weniger als 0,040% Phosphor, weniger als 0,030% Schwefel, weniger als 0,50% Kupfer, weniger als 1,0% Nickel, der Summe von Calcium und Magnesium von weniger als 0,005% bis zu

$$91\left[\frac{\%C}{12} + \frac{\%N}{14} + 0,004\right]\%$$

Zirkon, um die Legierung zu stabilisieren, und/oder bis zu

$$91\left[\frac{\%C}{12} + \frac{\%N}{14} + 0,013\right]\%$$

Niob zur Stabilisierung und erhöhten Dauerstandfestigkeit, wobei der Rest Eisen ist, Herstellen eines ferritischen, nicht-rostenden Stahlgegenstandes aus der Schmelze; und Behandeln des Stahlgegenstandes zur Ausbildung einer festhaftenden, texturierten Aluminiumoxidoberfläche darauf.

Revendications

1. Un alliage d'acier inoxyidable ferritique ouvrable à chaud résistant à l'oxydation cyclique thermique et à l'écaillage aux températures élevées et sur lequel peut être formée une surface d'oxyde d'aluminium texturisée adhérente, caractérisé en ce que l'alliage consiste en poids, en 8,0—25,0% de chrome, 3,0—8,0% d'aluminium et une addition d'au moins 0,002% et jusqu'à 0,05% de cérium, de lanthane, de néodyme et/ou de praséodyme, un total de toutes les terres rares pouvant atteindre 0,060%, jusqu'à 4% de silicium, 0,06% à 1,0% de manganèse et comme impuretés normales de la fabrication de l'acier, moins de 0,050% de carbone, moins de 0,050% d'azote, moins de 0,020% d'oxygène, moins de 0,040% de phosphore, moins de 0,030% de soufre, moins de 0,5% de cuivre, moins de 1,0% de nickel, la somme du calcium et du magnésium étant inférieure à 0,005%, jusqu'à

$$91\left[\frac{\%C}{12} + \frac{\%N}{14} + 0,004\right]\%$$

de zirconium pour stabiliser l'alliage et/ou jusqu'à

$$93\left[\frac{\%C}{12} + \frac{\%N}{14} + 0,013\right]\%$$

de niobium pour la stabilisation et la résistance au fluage aux températures élevées, le restant étant du fer.

2. Un alliage selon la revendication 1, caractérisé en ce que l'additif des terres rares consiste en cérium et/ou en lanthane.

3. Un alliage selon la revendication 1 ou 2, caractérisé en ce que le total minimum des quantités de cérium et/ou de lanthane dans l'alliage est proportionnel à la teneur en chrome, comme exprimé par:

$$\frac{\% CR}{2200}$$

4. Un alliage selon la revendication 1, 2 ou 3, caractérisé en ce que les quantités minimales d'aluminium dans l'alliage sont basées sur la teneur en chrome comme exprimé par



0 091 526

$$\left[\frac{(40 - \%Cr)}{6} \right] \%$$

5 5. Un alliage selon l'une quelconque des revendications précédentes, caractérisé en ce qu'il contient jusqu'à 3% de silicium.

6. Un alliage selon l'une quelconque des revendications précédentes, caractérisé en ce qu'il contient 0,10 à 0,50% de manganèse.

10 7. Un alliage d'acier inoxydable ferritique ouvrable à chaud résistant à l'oxydation cyclique thermique et à l'écaillage aux températures élevées et sur lequel peut être formée une surface d'oxyde d'aluminium texturée adhérente, caractérisé en ce que l'alliage consiste en poids en 12,0—23,0% de chrome, de

$$\left[\frac{(40 - \%Cr)}{6} \right] \%$$

15

jusqu'à 8% d'aluminium, au moins [%Cr/2200]% d'une addition de cérium et/ou de lanthane, un total de toutes les terres rares pouvant atteindre, 0,050%, jusqu'à 3,0% de silicium, 0,10 à 0,50% de manganèse et comme impuretés normales de la fabrication de l'acier moins de 0,030% de carbone, moins de 0,30% d'azote, moins de 0,010% d'oxygène, moins de 0,030% de phosphore, moins de 0,020% de soufre, moins de 0,4% de cuivre, moins de 0,4% de nickel, la somme du calcium et du magnésium étant inférieure à 0,003%, jusqu'à

20

$$91 \left[\left(\frac{\%C}{12} \right) + \left(\frac{\%N}{14} \right) + 0,003 \right] \%$$

25

de zirconium pour stabiliser l'alliage et/ou jusqu'à

30

$$93 \left[\left(\frac{\%C}{12} \right) + \left(\frac{\%N}{14} \right) + 0,0075 \right] \%$$

de niobium pour la stabilisation et la résistance au fluage aux températures élevées, le restant étant du fer.

35

8. Utilisation d'un alliage conformément à l'une quelconque des revendications précédentes pour la production d'un substrat catalytique résistant à l'oxydation.

9. Un système catalytique caractérisé en ce qu'il comprend un substrat catalytique résistant à l'oxydation conformément à la revendication 8.

40

10. Un procédé pour fabriquer un acier inoxydable ferritique ouvrable à chaud résistant à l'oxydation cyclique thermique et ayant une surface d'oxyde d'aluminium texturisée résistant à l'écaillage aux températures élevées, caractérisé en ce que ledit procédé comporte les étapes suivantes:

45

La préparation d'une masse fondue constituée en poids de 8,0—25,0% de chrome, 3,0—8% d'aluminium, une addition d'au moins 0,002% et jusqu'à 0,05% de cérium, de lanthane, de néodyme et/ou de praséodyme, un total de toutes les terres rares pouvant atteindre 0,060%, jusqu'à 4,0% de silicium, 0,06 à 1,0% de manganèse et comme impuretés normales de fabrication d'acier moins de 0,050% de carbone, moins de 0,050% d'azote, moins de 0,020% d'oxygène, moins de 0,040% de phosphore, moins de 0,030% de soufre, moins de 0,50% de cuivre, moins de 1,0% de nickel, la somme de calcium et de magnésium étant inférieure à 0,005%, jusqu'à

50

$$91 \left[\left(\frac{\%C}{12} \right) + \left(\frac{\%N}{14} \right) + 0,004 \right] \%$$

de zirconium pour stabiliser l'alliage et/ou jusqu'à

55

$$91 \left[\left(\frac{\%C}{12} \right) + \left(\frac{\%N}{14} \right) + 0,013 \right] \%$$

60

de niobium pour la stabilisation et la résistance au fluage aux températures élevées, le restant étant du fer,

La production d'un article en acier inoxydable ferritique à partir de la masse fondue; et

Le traitement de l'article en acier pour former dessus une surface d'oxyde d'aluminium texturisée adhérente.

65