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[54] FERRITIC STAINLESS STEELS WITH IMPROVED DRAWABILITY AND RESISTANCE TO RIDGING

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[51] **Int. Cl.** **C22c 39/14**

[58] **Field of Search** .....75/126, 126 B, 126 C, 126 F; 148/36, 12, 37

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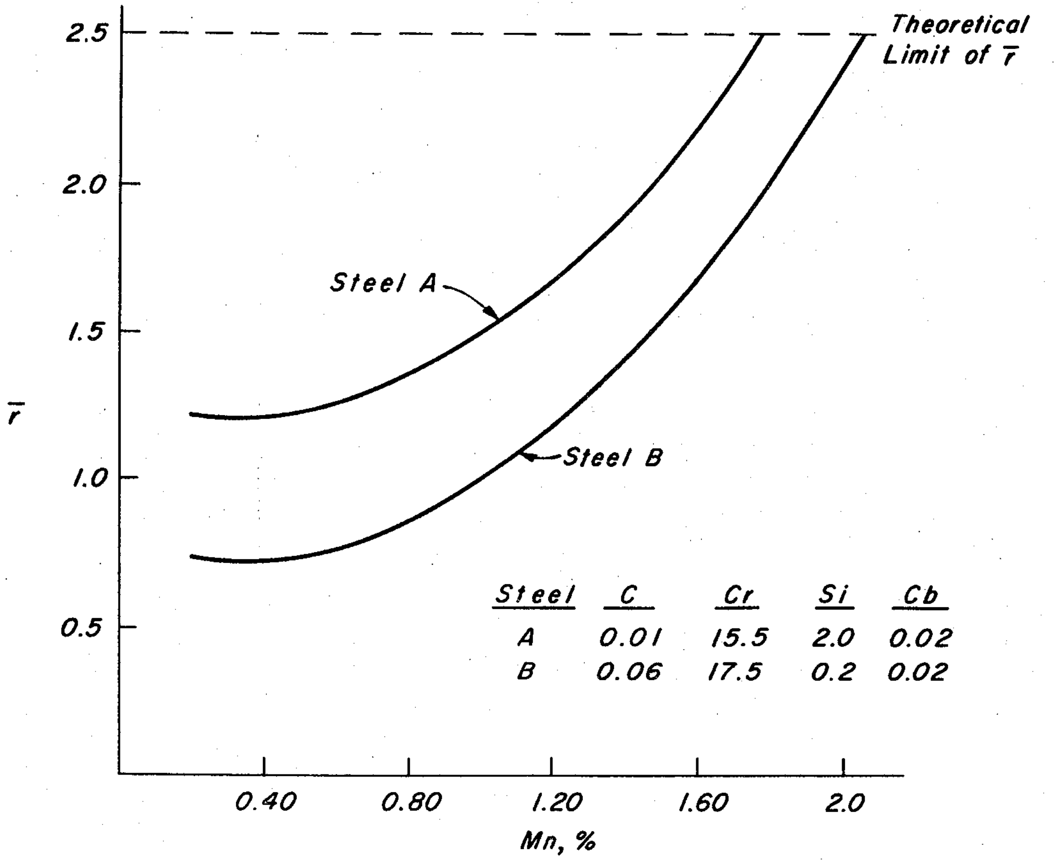
[57] ABSTRACT

A method for increasing the deep drawability, as represented by $\bar{r}$ value, of ferritic stainless steels. A complex equation shows the interrelation of the various alloying elements. Within the compositional range similar to that of type 430 steel, the $\bar{r}$ value may be increased by employing C and Cr at the lower end of the range and employing Si at the higher end of the range. Increasing the amount of Mn will increase $\bar{r}$ value for a type 430 steel, but will have just the opposite effect if Cb is present to any appreciable degree.

16 Claims, 2 Drawing Figures

FIG. 1



Steel	C	Cr	Si	Cb
A	0.01	15.5	2.0	0.02
B	0.06	17.5	0.2	0.02

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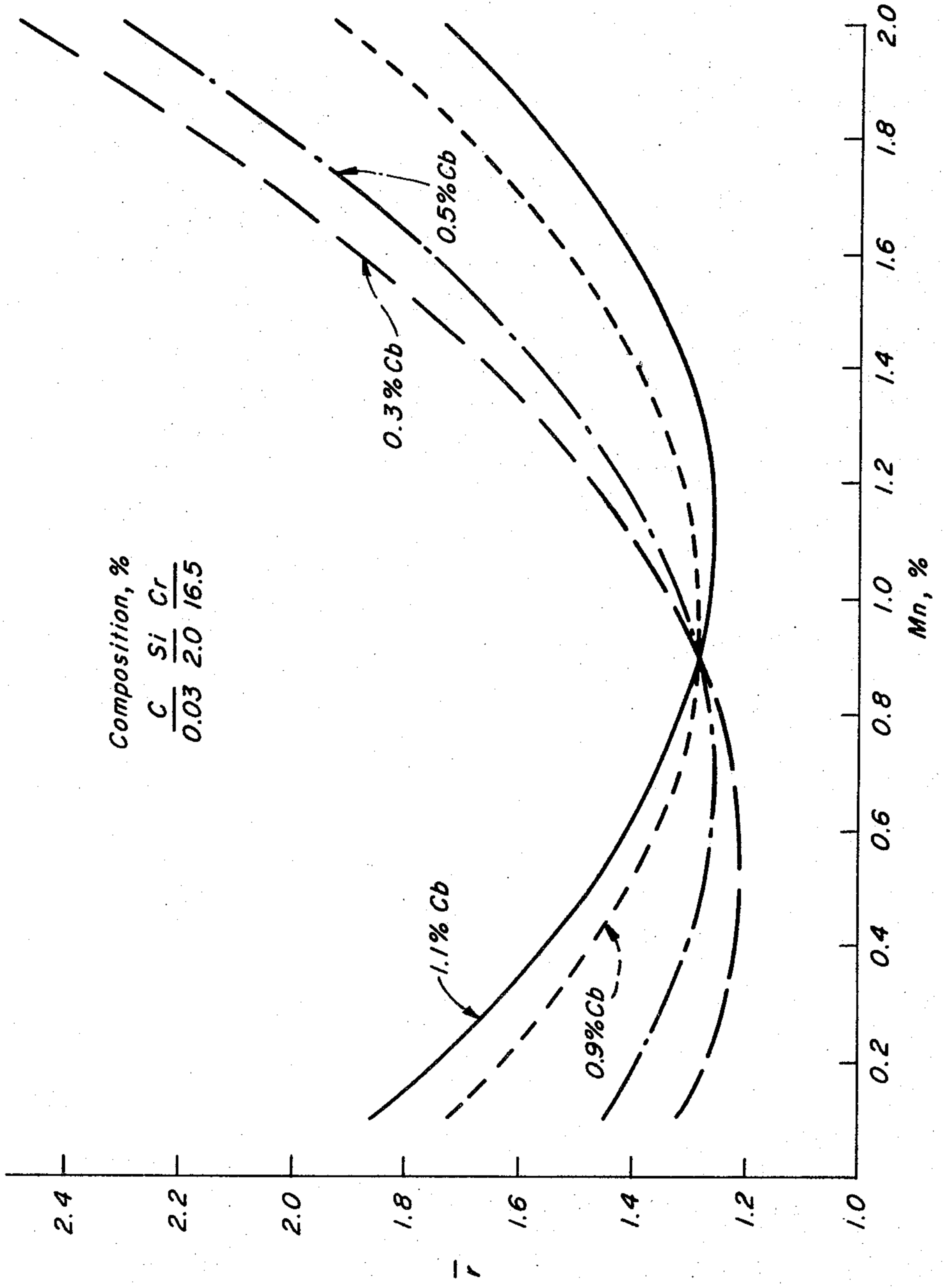
FIG. 2



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FERRITIC STAINLESS STEELS WITH IMPROVED DRAWABILITY AND RESISTANCE TO RIDGING

This invention relates in general to ferritic stainless steel sheet and strip and, more particularly, to annealed ferritic stainless steel with good drawability.

Over the years, there has been a gradual but continual growth in the use of stainless steel sheet and strip in applications requiring forming. This growth is expected to increase as consumers become more quality conscious and demand household and industrial goods made from stainless steels. For many of these applications, the ferritic stainless steels, as typified by AISI type 430 stainless steels, are used. One drawback to the use of the ferritic stainless steels in forming applications is their poorer formability, particularly their deep drawing characteristics, in comparison to aluminum-killed low-carbon (DQSK) steel, which is generally used for severe deep drawing applications.

In recent years, the good drawing performance of DQSK steel sheet and strip has been shown to be related to its high average plastic-strain ratio. The plastic-strain ratio, r, is defined as the ratio of the width-strain to the thickness-strain determined during the tension testing of sheet specimens. It is a measure of the normal anisotropy of sheet material and is a measure of the resistance of a material to thinning. The average plastic-strain ratio, $\bar{r}$, is defined as follows:

$$r = (r_0 + 2r45 + r90)/4$$

where 0, 45, and 90 are degrees from the rolling direction of sheet or strip. Generally, DQSK steel exhibits $\bar{r}$ values between 1.4 and 1.8 with an $\bar{r}$ value of 1.6 being typical for this steel.

In addition to their enhanced corrosion resistance, the ferritic stainless steels polish to a very high luster and are therefore used in applications where appearance is important. Type 430 steel is used in applications that require some degree of forming such as kitchen sinks, automotive trim, and luggage trim. For applications requiring somewhat better corrosion resistance than type 430, such as automobile trim and hubcaps which are subject to chloride-containing environments, molybdenum modified types 430 Mo (434) or 430 Mo—Cb (436) are employed. For applications involving severe stretch forming in addition to deep drawing and in which ridging would be detrimental to appearance, columbium modified type 430 (435) is often used because of the enhanced resistance to ridging supplied by columbium (U.S. Pat. No. 2,965,479). Ridging is an undesirable surface condition that occurs during forming of sheet or strip. The defect occurs parallel to the direction of rolling and appears as narrow, raised areas, similar to corrugations on the surface of the sheet. All of the above ferritic stainless steels, however, are generally deficient in formability, particularly their deep drawing characteristics. The $\bar{r}$ values of some typical ferritic stainless steels, when tested as 0.040 inch thick annealed sheet are provided below.

Type	$\bar{r}$	Composition							
		C	Mn	P	S	Si	Cr	Mo	Cb
430	1.01	0.096	0.54	0.018	0.012	0.54	16.9	0.11	0.03
434	0.93	0.094	0.050	0.017	0.011	0.56	16.9	1.06	0.024
435	0.76	0.096	0.55	0.017	0.013	0.49	17.1	0.12	0.50
436	0.88	0.10	0.52	0.017	0.012	0.61	17.2	1.02	0.47

These $\bar{r}$ values, which generally do not exceed 1.2, do not compare favorably with the hereinabove mentioned average of 1.6 exhibited by DQSK steel.

It is, therefore, an object of this invention to provide annealed, ferritic stainless steels with particularly enhanced deep drawability, and with improved resistance to corrosion and ridging.

It is another object of this invention to provide a method for tailoring ferritic stainless steels for particular properties such as corrosion resistance, resistance to ridging and deep drawability.

It is a further object of this invention to provide a ferritic stainless steel with a plastic-strain ratio, $\bar{r}$, of at least about 1.6 when it is produced as annealed sheet and strip.

These and other objects of the invention will become more apparent when read in reference with the claims and with the following description, in which:

FIG. 1 depicts the effect of manganese on $\bar{r}$ value; and

FIG. 2 is a graph showing the interaction of columbium with manganese and the effect of this interaction on $\bar{r}$ value.

Shown in table I are the compositions of the **34** steels that were prepared as induction furnace heats during the development of this invention. These steels can also be made by conventional practice in an electric furnace. All heats were melted under an argon cover and cast into 3 inch thick by 8 inch wide by 14 inch high slab-type molds for this study. The surfaces of each slab-type ingot were conditioned by machining. The slabs were hot-rolled at 2,150°F to 0.160 inch thick strip. The strip-finishing temperature was about 1,500°F. Hot-rolled strip from each heat was given a simulated box anneal at 1,450°F for 6 hours and furnace cooled. The annealed strip was shot-blasted to remove scale and then cold-rolled to 0.080 inch thick strip. The cold-rolled strip was then annealed in salt for 15 seconds at 1,450°F and air cooled. The salt-annealed 0.080 inch thick strip was cleaned with a detergent and cold-rolled to 0.040 inch thick strip, which was annealed in salt for 2 minutes at 1,450°F, and air cooled. These latter annealing treatments simulated commercial continuous annealing. The processing cycle from ingot to cold-rolled and annealed strip simulated closely that which is given commercially produced ferritic stainless steel.

From the cold-rolled and annealed 0.040 inch thick strip from each of the 34 heats, six tension-test specimen blanks were sheared. Two blanks were sheared parallel to the rolling direction (longitudinal), two blanks were sheared transverse to the rolling direction, and two blanks were sheared at 45° from the rolling direction (diagonal). These blanks were then machined into formability test specimens, which were tension-tested at room temperature and their r values determined. The $\bar{r}$ values of each steel were then calculated.

The $\bar{r}$ values in the longitudinal, diagonal, and transverse directions for the steels investigated are shown in table II. Also shown in this table are the r values for these steels.

TABLE I

Compositions of Ferritic Stainless Steels Investigated, in Percent

Heat No.	C	Mn	Si	Cr	Mo	Cb
V9156-3	0.10	0.52	0.61	17.2	1.02	0.47
V9157-2	0.099	0.53	0.56	18.9	0.59	0.50
V9158-2	0.054	0.74	0.36	17.9	0.35	0.26
V9159-1	0.053	0.34	0.66	17.8	0.35	0.26
V9160-1	0.096	0.16	0.51	17.0	0.59	0.50
V9161-1	0.095	0.51	0.55	17.0	0.60	0.50
V9162-2	0.15	0.33	0.38	16.4	0.80	0.25
V9163-1	0.10	0.51	0.53	16.9	0.60	0.96
V9164-1	0.11	0.53	0.52	17.1	0.59	0.51
V9165-1	0.060	0.70	0.41	16.0	0.33	0.72
V9166-1	0.15	0.70	0.65	16.0	0.83	0.28
V9167-1	0.059	0.35	0.70	17.9	0.83	0.75
V9168-1	0.11	0.52	0.50	17.1	0.60	0.50
V9169-1	0.096	0.55	0.54	17.1	0.58	0.028
V9170-1	0.051	0.72	0.41	17.8	0.83	0.71
V9171-1	0.096	0.55	0.49	17.1	0.12	0.50
V9172-1	0.096	0.98	0.50	17.1	0.58	0.50
V9173-1	0.049	0.70	0.40	15.9	0.79	0.26
V9174-1	0.098	0.55	0.55	17.1	0.60	0.52
V9175-1	0.014	0.47	0.54	17.3	0.60	0.52
V9176-1	0.15	0.72	0.72	18.6	0.82	0.78
V9177-1	0.14	0.36	0.42	16.2	0.35	0.76
V9178-1	0.10	0.53	0.94	17.1	0.60	0.53
V9179-3	0.16	0.54	0.40	17.0	0.59	0.48
V9180-1	0.14	0.73	0.79	18.0	0.32	0.25
V9181-1	0.096	0.56	0.55	17.0	0.57	0.48
V9182-1	0.13	0.36	0.37	18.0	0.32	0.24
V9183-1	0.096	0.52	0.52	15.2	0.57	0.48
V9184-1	0.14	0.71	0.77	16.2	0.32	0.73
V9185-1	0.050	0.36	0.80	16.2	0.33	0.75
V9186-1	0.14	0.35	0.36	17.9	0.80	0.70
V9187-1	0.049	0.34	0.74	16.2	0.82	0.26
V9188-1	0.093	0.55	0.23	17.0	0.57	0.48
V9189-1	0.094	0.54	0.55	17.2	0.58	0.49

TABLE II

Plastic-Strain Ratios of Ferritic Stainless Steels Investigated

Heat No.	r_0	r_{45}	r_{90}	$\bar{r}$
V9156-3	0.68	0.93	0.98	0.88
V9157-2	0.88	0.78	1.12	0.88
V9158-2	0.74	0.89	0.96	0.87
V9159-1	0.98	0.80	1.19	0.94
V9160-1	0.79	0.87	1.12	0.91
V9161-1	0.75	0.85	1.06	0.89
V9162-2	0.59	1.05	0.91	0.90
V9163-1	1.05	0.73	1.35	0.96
V9164-1	0.82	0.96	1.17	0.97
V9165-1	1.13	0.91	1.30	1.07
V9166-1	0.56	0.88	0.90	0.80
V9167-1	1.10	1.12	1.49	1.21
V9168-1	0.70	0.78	1.23	0.87
V9169-1	0.60	0.91	1.01	0.84
V9170-1	0.71	0.74	0.61	0.70
V9171-1	0.85	0.51	1.18	0.76
V9172-1	0.76	0.92	1.38	0.99
V9173-1	0.86	0.94	1.14	0.97
V9174-1	0.75	0.99	0.97	0.93
V9175-1	0.88	0.92	1.21	0.98
V9176-1	0.69	0.87	0.92	0.84
V9177-1	0.76	0.83	1.13	0.89
V9178-1	0.85	0.84	1.15	0.92
V9179-3	0.60	0.87	0.85	0.80
V9180-1	0.66	1.04	1.03	0.94
V9181-1	0.71	0.98	1.02	0.92
V9182-1	0.73	0.99	1.06	0.93
V9183-1	0.70	0.84	1.13	0.88
V9184-1	0.68	0.83	0.96	0.83
V9185-1	1.22	1.00	1.66	1.22
V9186-1	0.79	0.91	1.02	0.90
V9187-1	0.88	0.98	1.21	1.01
V9188-1	0.72	0.99	1.00	0.92
V 9189-1	0.71	0.98	1.08	0.94

Analysis of the $\bar{r}$ values in table II indicated that a relation exists between $\bar{r}$ and the composition of the steels investigated. It was found that the relation could be expressed by the following equation:

$$\bar{r} = 1.22 - 1.10\,(\%C) - 0.174\,(\%Mn) = 0.169\,(\%Si) - 0.015\,(\%Cr) + 0.083\,(\%Cb) + 1.15\,(\%C - 0.097)(\%Cr - 17.05) - 3.41\,(\%C - 0.097)(\%Cb - 0.50) + 0.602\,(\%Mn - 0.53)^2 - 0.861\,(\%Mn - 0.53)(\%Cb - 0.50)$$

Inspection of this equation indicates the complexity of the problem of attempting to tailor the drawability of the hereinbefore mentioned ferritic stainless steels. Note, for example, the strong quadratic effect of manganese and the interactions between carbon and chromium, carbon and columbium, and manganese and columbium. These effects complicate the relation between these elements and $\bar{r}$. However, with the aid of this equation, it is possible to modify type 430, 434, 435, and 436 steels so as to critically and unexpectedly enhance the $\bar{r}$ values of these compositions.

The applicability of these equations to a number of ferritic stainless steels (e.g., types 430, 434, 435 and 436) will be demonstrated individually.

Type 430—The AISI range for this steel is (all percentages by weight):

C max.	Mn max.	Si max.	P max.	S max.	Cr
0.12	1.0	1.0	0.040	0.030	14.0–18.0

In such a steel, columbium is not added as a purposeful alloy addition and is present only as a residual element (trace to 0.05 percent), generally in amounts of about 0.02 weight percent.

From the standpoint of $\bar{r}$ value, silicon is a beneficial alloying element. Therefore, increasing Si to above that of the AISI specification will provide a deeper drawing steel. However, silicon is known to be detrimental to both hot workability and weldability and should generally be limited to less than 2.0 percent. In applications in which severe bending will be encountered in addition to deep drawing, it is desirable to even further limit the silicon content, to eliminate the detrimental effect that silicate inclusions have on bending performance.

In compositions similar to that of type 430, the especially critical effect of manganese may be seen by reference to FIG. **1**. This figure depicts two different steels, one in which C, Cr, and Si are favorable for high $\bar{r}$ values (i.e., Steel A, with low C, low Cr and high Si) and the other, Steel B, in which C, Cr and Si are unfavorable. In both steels, as Mn is increased above about 1.1%, its effect on $\bar{r}$ values increases more rapidly. However, since about 2.25% Mn will provide the theoretical $\bar{r}$ value limit of 2.5, Mn over this amount will not be required for the purposes of this invention.

A perusal of the above equation will show that low carbon contents are generally beneficial with respect to $\bar{r}$ values. Low carbon contents, i.e., below 0.06 percent are also desirable for minimizing bend failures. Because drawn parts are often subject to severe bending, such as crimping of flanges, the ability to make such bends is also important. Thus, based on the analysis of **28** commercial heats in the cold-rolled and annealed condition, the percentage of failures in a standard "handkershief" bend test was found to increase from zero for a C content of 0.053% to 20 percent for a C content of 0.087%. Analysis of the above bend test data also showed that sulfur should be kept below about 0.025 percent and preferably below 0.015 percent to minimize failures.

Therefore, a modified type 430 steel with good formability and particularly good deep drawability may be obtained in a composition comprising:

C	Mn	S	Si	Cr	
trace 0.06	1.10 2.25	0.025 max.	trace 2.00	14.00 18.00	balance Fe, and incidental residual impurities

wherein the $\bar{r}$ value may be increased by:

a. employing C at the lower end of the range;
b. employing Cr at the lower end of the range;
c. employing Si at the higher end of the range;
d. employing Mn at the higher end of the range; or a combination of the above.

To demonstrate the predictability of the equation as applicable to above compositional range, a laboratory induction furnace heat was melted to the following composition:

C	Mn	S	Si	Cr
0.032	1.46	0.015	1.07	16.0

The $\bar{r}$ value when processed to annealed sheet was:

	$\bar{r}$
predicted	1.80
measured	1.71, 1.87

Type 430-Mo (434)—These steels, likewise, do not contain Cb as a purposeful addition. Since Mo plays no part in the $\bar{r}$ equation, the desirable range of alloy additions will be similar to that of the modified type 430 steel, with one exception. Since these steels are primarily employed for their corrosion resistance (especially to pitting), it is preferred to employ at least about 15.5% Cr, even though lower Cr contents are more favorable to improved drawability.

Type 430-Cb (435)—These steels contain up to about 1.0% Cb as a purposeful alloy addition. In these steels, i.e. those containing more than about 0.3% Cb, the effect of Mn is more complex as shown by FIG. 2. Here, for values of Mn below 0.88%, its effect is opposite to that of the basic type 430 composition (in which Cb is present in residual amounts less than 0.05%). Thus $\bar{r}$ values greater than about 1.6 can be achieved by either decreasing the Mn to values substantially below 0.88 percent (preferably below 0.35%) or to values substantially above 0.88% (preferably above 1.4%). It may also be seen from this figure that for low Mn values, increasing the amount of Cb is beneficial to the attainment of high $\bar{r}$ values.

The effect of Cr is also more crucial in these steels. Thus, in a steel containing 0.9% Cb, 2.0% Si, 0.02% C and 0.30% Mn, the effect of decreasing Cr on $\bar{r}$ value may be seen below:

Cr	$\bar{r}$
17.5	1.43
17.0	1.50
16.5	1.56
16.0	1.63
15.0	1.69

Therefore, while it is possible to attain $\bar{r}$ values greater than 1.6 (e.g. by further decreasing C and Mn and increasing Cb) with a steel containing as much as 17.5% Cr, it is preferred to maintain an upper limit of about 16.5% Cr, so that a practical and commercially acceptable melt can be made without the need for especially tight controls on the amount of other elements.

A modified type 435 steel with good formability and particularly good deep drawability may be obtained in a composition comprising:

C	S	Si	Cr	Cb	Mn
trace 0.03	0.025 max.	trace 2.00	14.0 16.5	0.70 1.10	trace, 1.4 0.35 2.25

balance Fe and normal residual impurities, wherein the $\bar{r}$ value may be increased by either:

a. employing Cr at the lower end of the range;
b. employing C at the lower end of the range;
c. employing Mn within either of the above two ranges;
d. employing Si at the higher end of the range;
e. employing Cb at the higher end of the range; or a combination of the above.

A laboratory induction furnace heat was made having the following composition:

C	Mn	S	Si	Cr	Cb
0.025	0.12	0.015	1.05	16.4	1.05

The $\bar{r}$ value, when processed to annealed sheet, was:

	$\bar{r}$
predicted	1.71
measured	1.63 and 1.79

Type 430-Mo-Cb (436)—On the basis of the foregoing analysis (for type 435), it was seen that when Cb is present as a purposeful alloy addition, i.e., generally at levels greater than about 0.3%, it is desirable to employ less than about 16.5% Cr to ensure high $\bar{r}$ values. However, since Mo is employed to provide corrosion resistance, it would be defeating to the purpose to employ less than about 15.5% Cr. Therefore, for steels suitable for chloride environments and yet exhibiting high $\bar{r}$ values, the Cr range is quite limited, e.g., 15.5 to 16.5%.

It should be recognized that as predicted by the equation, ferritic stainless steels could be produced to provide $\bar{r}$ values greater than 1.6 and nevertheless be somewhat outside of the prescribed compositional ranges. These ranges were provided as guidelines for the attainment of desirable $\bar{r}$ values under normal commercial melting practices and are therefore governed to a large extent by practical considerations. Thus, for example, if in the production of a type 435 steel with 0.7% Cb, the carbon and manganese were reduced by special melting procedures to particularly low levels (e.g., 0.005 and 0.1 percent respectively), then the desired drawability could be achieved in a steel with considerably higher Cr than that prescribed.

I claim:

1. A method for enhancing the deep drawability of ferritic stainless steels within the range,

C	trace to 0.15%
Mn	trace to 2.25%
Si	trace to 2.0%
Cr	14.0 to 21.0%
Mo	trace to 1.1%
Cb	trace to 1.1%
balance Fe and incidental residual impurities	

which comprises, combining the above elements in proportions in which the desired $\bar{r}$ value is represented by the equation:

$$\bar{r} = 1.22 - 1.10\,(\%C) - 0.174\,(\%Mn) + 0.169\,(\%Si) - 0.015\,(\%Cr) + 0.083\,(\%Cb) + 1.15\,(\%C - 0.097)\,(\%Cr - 17.05) - 3.41\,(\%C - 0.097)\,(\%Cb - 0.50) + 0.602\,(\%Mn - 0.53)^2 - 0.861\,(\%Mn - 0.53)\,(\%Cb - 0.50)$$

so as to achieve an $\bar{r}$ value equal to or greater than 1.6.

2. The method of claim 1, wherein columbium is only present as an incidental residual impurity, and which further includes employing more than 1.1% Mn and less than 17.0% Cr and 0.06% C.

3. The method of claim 2, wherein greater than 1.0% Si is employed to further enhance the $\bar{r}$ value.

4. The method of claim 1, wherein when columbium is present as a purposeful alloy addition, Mn is employed in an amount no greater than 0.35%.

5. The method of claim 4, wherein 0.7 to 1.1% columbium is added to further increase the $\bar{r}$ value.

6. The method of claim 5, which includes employing more than 1.0% Si and less than 0.03% C and 16.5% Cr.

7. An annealed, ferritic stainless steel within the range,

C	trace to 0.15%
Mn	trace to 2.25%
Si	trace to 2.0%
Cr	14.0 to 21.0%
Mo	trace to 1.1%
Cb	trace to 1.1%
balance Fe and incidental residual impurities	

having an enhanced deep drawability, as represented by an $\bar{r}$ value greater than 1.6, and consisting essentially of those combinations of the above elements which satisfy the equation:

$$-0.38 \leq -1.10\,(\%C) - 0.174\,(\%Mn) + 0.169\,(\%Si) - 0.015\,(\%Cr) + 0.083\,(\%Cb) + 1.15\,(\%C - 0.097)\,(\%Cr - 17.05) - 3.41\,(\%C - 0.097)\,(\%Cb - 0.50) + 0.602\,(\%Mn - 0.53)^2 - 0.861\,(\%Mn - 0.53)\,(\%Cb - 0.50).$$

8. The steel of claim 7 consisting essentially of,

C	trace to 0.06%
Mn	1.1–2.25%
Si	trace to 2.0%
Cr	14.0–17.0%
balance Fe and incidental residual impurities.	

9. The steel of claim 8, containing more than 1.0% Si.

10. The steel of claim 8, additionally containing from 0.5 to 0.9% Mo and greater than about 15.5% Cr.

11. The steel of claim 7, consisting essentially of,

C	trace to 0.03%
Mn	trace to 0.35%
Si	trace to 2.0%
Cr	14.0–16.5%
Cb	0.7–1.1%
balance Fe and incidental residual impurities.	

12. The steel of claim 11, containing more than 1.0% Si.

13. The steel of claim 11, additionally containing from 0.5 to 0.9% Mo and greater than about 15.5% Cr.

14. The steel of claim 7, consisting essentially of,

C	trace to 0.03%
Mn	greater than 1.4%
Si	trace to 2.0%
Cr	14–16.5%
Cb	0.7–1.1%
balance Fe and incidental residual impurities.	

15. The steel of claim 14, containing more than 1.0% Si.

16. The steel of claim 14, additionally containing from 0.5 to 0.9% Mo, and greater than 15.5% Cr.

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