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Modification of Cast 25Cr-20Ni for Improved Crack Resistance

Cracking resistance is improved by formation of small amounts of ferrite in HAZ and by lowering nitrogen and oxygen in the weld deposit

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ABSTRACT. The effects of carbon, silicon, nickel, titanium, columbium, and misch metal (rare earths) on cracking of CK-20 type alloys were investigated by the shielded metal-arc process (SMAW) using E310-16 electrodes, and by the gas tungsten-arc process (GTAW) with matching composition filler metal.

The relative cracking resistance of the alloys was established by visual examination of sectioned weldments and was correlated with measured ferrite content. The effects of the variants on weld and heat-affected zone cracking and ferrite content were established by a Yates analysis of a statistically designed series. A second series in which the only variable was columbium (0-2.90%) was also investigated.

Several experimental alloys were obtained with improved cracking resistance over the standard CK-20 and based upon zero defects in weldments were equivalent to CF-8 (our target). These were of two types. In the first type the best cracking resistance in the heat-affected zones and in the gas tungsten-arc deposits having the same composition as the base metal was associated with the presence of very small amounts of delta ferrite *formed during the weld process.* Improvement in cracking resistance in the second type alloy in gas tungsten-arc deposits was correlated directly to a decrease in nitrogen and/or nitrogen plus oxygen content in the weld deposit.

Introduction

The production of CK-20 castings (25Cr-20Ni) is limited because of hot cracking that sometimes occurs during casting, heat treating, welding, grinding or cutting. In our exploratory work, cracking during simple welding tests was the most tangible evidence of poor hot ductility hence such tests were used to investigate the problem. It was thought that if the weldability of the alloy was improved other hot cracking problems might also be alleviated. Others have shown that for identical compositions hot cracks have been encountered more frequently in welds than in castings (Refs. 1-3).

Experimental Procedure

Material

The chemical analyses of the alloys investigated are given in Table 1.

Codes 1 through 16 are a ¼ × 2^6 replicate designed to enable statistical analyses of the results. The variables were: carbon-0.06% and 0.16%, silicon-0.5% and 1.70%, nickel-17% and 21%, titanium-none and 0.25% added, columbium-none and 0.25% added, misch metal-none and 0.10% added. The base consisted of 25% chromium, 1% manganese, 0.015% sulfur, 0.015% phosphorus and an iron balance.

Codes 17 through 36 were established as follows: Code 17 was an

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Table 1 — Compositions of Alloys Investigated

Code	C	Si	Ni	Cb	Ti	Ce	Cr	Mn	S	P	H, ppm	N, ppm	O_2 ppm	Other
1	.072	.52	17.2	NA	NA	NA	25.2	.86	.014	.017	3.4	490	395	—
2	.16	.55	17.0	.24	NA	NA	25.5	.88	.015	.017	2.3	445	235	—
3	.057	1.56	17.3	.26	NA	.014	25.4	.96	.015	.020	5.8	450	280	.005Ca
4	.16	1.55	17.0	NA	NA	.014	25.7	.94	.015	.018	3.2	565	135	.052Ca
5	.066	.52	19.8	.21	NA	.011	25.5	.92	.015	.017	3.2	415	385	.041Ca
6	.16	.51	19.9	NA	NA	.010	25.3	.94	.015	.020	3.0	445	355	.041Ca
7	.068	1.34	19.8	NA	NA	NA	25.7	.98	.015	.019	2.4	380	320	—
8	.15	1.54	20.1	.23	NA	NA	25.7	.94	.014	.016	3.5	495	295	—
9	.058	.65	17.1	NA	.01	.009	25.5	.98	.014	.018	2.1	510	425	.032Ca
10	.15	.62	17.3	.24	.03	.009	25.7	.99	.014	.017	2.1	485	340	.033Ca
11	.067	1.67	17.0	.25	.03	NA	25.7	1.02	.014	.015	2.1	475	175	—
12	.15	1.72	17.1	NA	.04	NA	25.8	.99	.014	.016	2.9	410	140	—
13	.056	.65	20.1	.23	.01	NA	25.6	.96	.014	.018	1.8	475	350	—
14	.15	.62	20.0	NA	.01	NA	25.6	.97	.014	.018	2.0	555	320	—
15	.066	1.64	20.0	NA	.03	.009	25.4	1.06	.012	.018	1.4	505	215	.040Ca
16	.16	1.64	20.0	.24	.02	.013	25.4	1.08	.014	.017	1.8	420	205	.034Ca
17	.12	1.06	18.8	.11	.02	.013	25.3	1.05	.015	.018	1.3	485	275	.033Ca
18	.065	1.36	17.2	NA	NA	.012	26.6	.91	.015	.019	2.0	435	175	.44Ca
19	.15	.57	20.1	NA	NA	NA	25.1	96	.014	.021	1.1	515	400	—
20	.15	.57	20.1	1.38	NA	NA	25.3	.98	.013	.017	1.1	475	465	—
21	.15	.55	20.0	2.90	NA	NA	25.4	.96	.014	.014	1.6	445	515	—
22	.067	1.75	19.9	NA	.25	NA	25.8	1.14	.014	.014	2.1	415	72	.12Al
23	.053	1.70	11.0	NA	NA	NA	21.2	.86	.015	.017	2.6	340	145	—
24	.053	1.60	8.5	NA	NA	NA	18.8	.84	.016	.014	3.1	395	155	—
25	.15	1.60	21.5	NA	NA	NA	27.6	1.02	.013	.019	3.3	445	220	—
26	.14	1.65	18.4	NA	NA	NA	24.0	.91	.014	.018	2.4	435	210	—
27	.040	1.65	19.8	NA	NA	NA	26.8	1.02	.013	.019	4.3	390	180	—
28	.047	1.55	18.6	NA	NA	NA	24.0	.95	.014	.018	2.5	520	175	—
29	.063	1.81	10.6	NA	NA	NA	20.0	1.01	.010	.023	6.0	375	145	—
30	.060	1.80	8.3	NA	NA	NA	18.1	.97	.014	.012	3.9	385	145	—
31	.16	1.69	21.0	NA	NA	NA	26.9	1.00	.011	.020	3.3	515	190	—
32	.16	1.59	18.4	NA	NA	NA	23.5	.88	.010	.012	3.9	400	150	—
33	.058	1.64	20.6	NA	NA	NA	26.4	.98	.011	.018	3.5	370	210	—
34	.064	1.61	18.8	NA	NA	NA	23.7	.95	.012	.013	3.2	425	185	—
35	.13	.47	20.8	NA	—	.014	25.3	1.76	.006	.009	11.0	510	860	—
36	.14	.61	21.5	NA	NA	NA	25.9	1.67	.010	.024	5.4	440	255	—

NA — not added

Table 2 — Welding Parameters

Process	SMAW	GTAW
Volts (dc)	24	16
Amperage	120-130	200
Polarity	RP	SP
Travel speed	Manual	Manual
Interpass temp.	200 F max.	200 F max.
Shield	—	35 cfh argon
Electrode	5/32 in. diam	1/8 in. diam
No. of passes	9	13-16
Tungsten	—	1/8 in.
Type groove	U	U

alloy made to the average composition of the replicate series. Code 18 was the same as Alloy 3 but without columbium. Codes 19 through 21 were conventional CK-20 type alloys with columbium varied to 2.90%. Code 22 was an alloy made with a 0.25% aluminum and 0.25% titanium addition which was reported to improve the hot working characteristics of 25Cr-20Ni alloy. Codes 23 and 24 were CF-8 type alloys and 25 through 34 were CK-20 alloys used for standards. Code 35 is the deposited chemistry obtained from the E310-16 electrode and Code 36 was an alloy made to duplicate the deposit chemistry.

All heats were 40 kilogram air melts. Armco iron and ferro-alloys were used. Additions of sulfur and phosphorus were made to obtain values of about 0.015% in order to more closely approximate values obtained industrially. The composition of the misch metal was reported to be 50%Ce, 27%La, 16%Nd, 5%Pr, 2% ore; 99% combined rare earths.

Eight dry sand cast blocks approximately 1 × 3 × 6 in. and several 1/4 in. diam × 36 in. long vacuum extractions were obtained from each heat. The extractions were swaged to 1/8 in. diam and used for filler metals with the GTAW process.

Welding

Weld repair tests using a U-groove specimen (Fig. 1) were made on each alloy. With the SMAW process E310-16 electrodes were used for the CK-20 type alloys and E308-16 electrodes for the CF-8 alloys (Ref. 4). For the GTAW process, filler metals matching the base metal composition were used. The latter results are of particular interest since published data on weld and heat-affected zone cracking of stainless steel weldments over 1/2 in. thick made by inert gas processes appear limited (Ref. 7,12-14).

Welding parameters are given in Table 2. Recommended procedures for welding stainless steels were followed (Refs 15, 20).

Measurement of Ferrite Content

Since the presence of ferrite is known to affect weld cracking, ferrite contents were measured with a Magne Gage. This instrument has been used extensively for measuring the ferrite content of weld metal (Refs. 5-8). Gunia (Ref. 9) lists seventeen other references in which the Magne Gage was used for ferrite determinations. Excellent reproducibility can be obtained but quantitative accuracy is dependent upon the standards used to calibrate the instrument (Ref. 9,10). In the present study, bakelite-iron powder (-320 mesh) standards were made and the instrument calibrated as described by Simpkinson and Lavigne (Ref. 11). The results are plotted in Fig. 2 and compared to published curves (Ref. 9).

A recent publication (Ref. 46) described a procedure approved by the WRC for calibrating Magne Gages using NBS Standards. Our instrument, P5858, was then recalibrated in this manner. The calibration curves obtained with the NBS standards, published values (Ref. 46), and the bakelite-iron powder compacts using number 2 and 3 magnets are given in Fig. 3. The ferrite contents (numbers) reported in this paper were obtained by converting the values obtained previously from the compact-magnet number 3 curve to the appropriate curve obtained with the NBS standards; i.e., the number 3 magnet for weld metal and heat-affected zone and the number 2 magnet for the castings and the vacuum extractions. Higher ferrite values would be obtained in the heat-affected zone with the number 2 magnet curve. It is interesting to note that the curve obtained with the compacts and the number 2 magnet coincides with the curve obtained with the NBS standards up to a ferrite number of 16. Apparently, the ferrite particle size represented by the -320 mesh size iron powder-bakelite compacts relates more closely to the NBS standards with the number 2 magnet than with the number 3 magnet.

The measurements for ferrite content were made both on cross sections of the weldments midway along the length of the welds and on the top surface. A minimum of five readings were taken for each area of the specimen, that is, weld metal, heat-affected zone and base metal. The average ferrite contents reported in Table 3 for heat-affected zone and weld metal do not include the measurements obtained on the top surface; these values are reported separately.

Results and Discussion

Standard Alloys — CF-8 and CK-20

A considerable difference in crack sensitivity, related to both composition and weld process, was obtained (Table 4). Weldments made with the CF-8 alloy, Codes 23 and 24, were defect-free when welded by either process; that is, SMAW or GTAW. CK-20

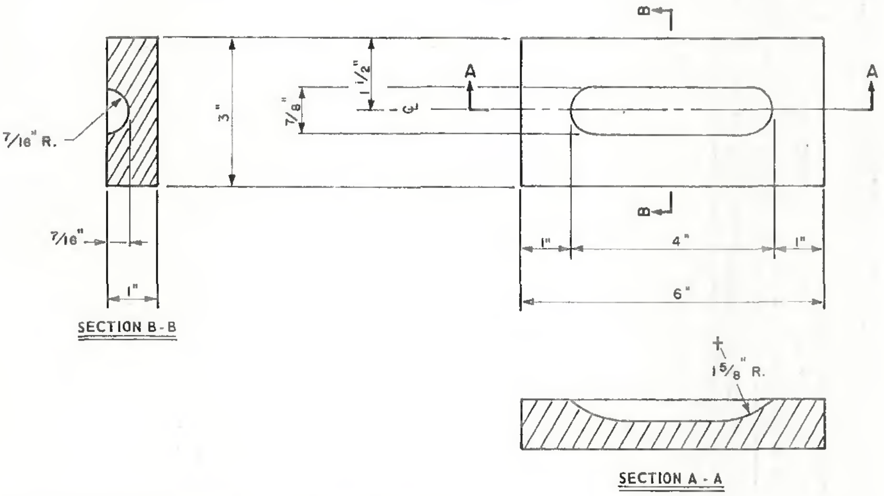
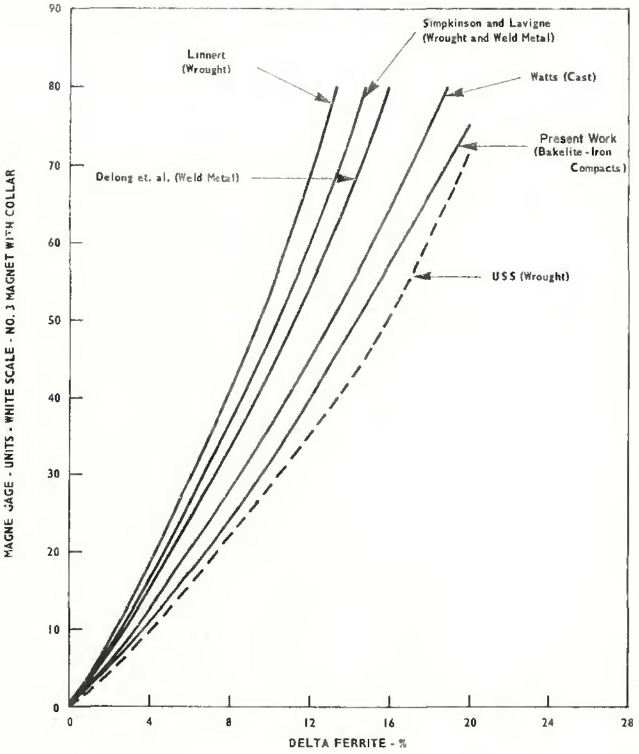


Fig. 1 — Crack sensitivity test weld specimen



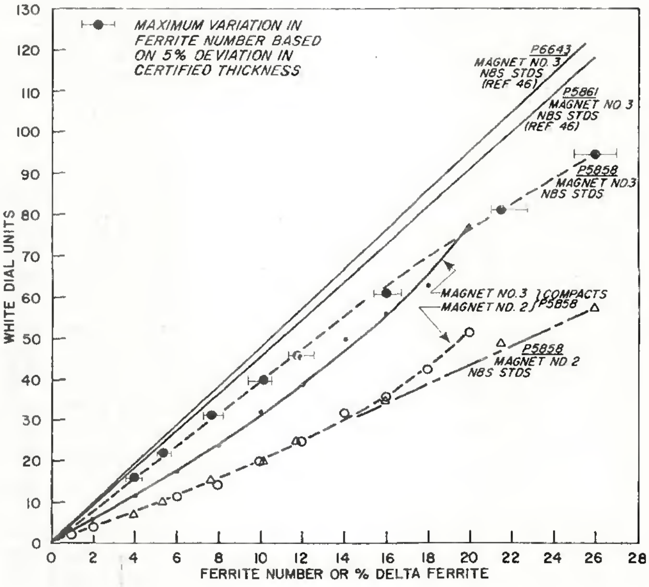


Fig. 3 — Comparison of calibration curves obtained with NBS standards and compacts

Fig. 2 — Calibration curve compared to published curves for other Magne Gage instruments

Table 3 — Delta Ferrite Content — Average Values

				Measured — Magne Gage						
Code	Ni_E	Cr_E	Calculated	B	W_{CE}	H_{CE}	H_{GTA}	W_{GTA}	GTA_T	V
1	19.79	25.98	2	1.2	0.2	1.6	2.0	1.1	0.7	2.2
2	22.27	27.90	1	0	0	0	0.2	0.2	0.4	7.7
3	19.49	27.77	6	0.2	0.2	2.0	1.4	1.4	2.4	6.0
4	22.26	28.00	1	0	0.2	0.2	0.2	0.2	0.5	0.2
5	22.24	26.39	0	0	0	0.2	0	0	0	0
6	25.17	26.06	0	0	0	0	0	0	0	0
7	22.33	27.71	0	0	0	0	0	0	0	0
8	25.07	28.13	0	0	0	0	0	0	0	0
9	19.33	26.47	3	1.0	0	2.0	3.4	3.7	3.8	5.3
10	22.28	26.75	0	0	0	0.2	0.4	1.0	1.9	2.3
11	19.80	28.32	7	0	0.2	2.2	3.0	6.6	9.2	11.4
12	22.09	28.38	2	0.2	0	0.4	1.0	2.1	4.2	4.8
13	22.26	26.68	0	0	0	0	0	0	0	0.2
14	24.98	26.53	0	0	0	0	0	0	0	0.2
15	22.51	27.86	0	0	0	0	0	0	ND	0
16	25.34	27.98	0	0	0	0	0	0	0	0.2
17	22.92	26.94	0	0	0	0	0	0	0	0.2
18	19.60	27.30	5	0.2	0	2.9	3.9	6.2	8.5	8.0
19	25.07	25.96	0	0	0	0	0	0	0	0
20	25.08	26.84	0	0	0	0	0	0.2	ND	0.2
21	24.97	27.67	0	0.4	0	0	0.2	0.6	0.5	1.8
22	22.47	28.42	1	0	0	0	0.3	1.1	2.2	2.1
23	12.92	23.75	12	6.6	7.3	5.2	7.8	—	—	8.6
29	12.99	22.70	10					10.7	11.8	14.3
24	10.56	21.20	14	7.2	7.6	5.6	6.6	—	—	9.0
30	10.58	20.80	12					10.4	10.3	14.4
25	26.29	30.00	0	0	0	0	0	—	—	0.1
31	26.30	29.48	0					0	0.2	0.2
26	23.14	26.47	0	0	0	0	0	—	0	0
32	23.64	25.89	0					0	0	0.1
27	21.57	29.27	5	0	0	0	0	—	—	0.2
33	22.83	28.86	2					0	0	0
28	21.36	26.32	0	0.2	0	0	0	—	—	0.1
34	21.19	26.10	0					0	0	0.1
36	26.53	26.81	0	0	0	0	0	0	0	0

Legend: B — Base
W_{CE} — Covered electrode weld
H_{CE} — Covered electrode heat-affected zone
H_{GTA} — GTA heat-affected zone
W_{GTA} — GTA weld
GTA_T — Top of GTA weld
V — Vacuum extraction
Ni_E — Ni equivalent = %Ni + 30 (%C) + 0.5 (%Mn)
Cr_E — Cr equivalent = %Cr + %Mo + 1.5 (%Si) + 0.5 (%Cb)
Note: Code 29 wire used for GTA filler of Code 23 base,
Code 30 filler for Code 24, etc. through Code 34.

alloy represented by Codes 19 and 25 through 28 was more crack sensitive and the degree of cracking varied with the process used. With the SMAW process, heat-affected zone cracking varied from 4 to 15 cracks in six faces examined at 30X whereas weld cracking was moderate (none to two in five weldments). However, with the GTAW process and matching composition filler, weld cracking was very severe, varying from 20 to 25 cracks, and heat-affected zone cracking from 3 to 10.

Code 36 (Table 4) shows the effect of the welding process on cracking in an alloy made to duplicate the undiluted deposit composition of the E310-16 electrode (Code 35). In this manner the composition difference between base and weld metal was essentially removed and the difference in cracking can be attributed to the weld process, GTAW or SMAW. As shown the GTAW process resulted in more total cracking, 15 versus 9. The largest difference in crack sensitivity was in the weld metal, 14 versus 6, and may have been related in part to the higher phosphorus content of the GTAW weld metal, as will be discussed later.

Experimental Compositions

The alloys with improved cracking resistance, particularly in the heat-affected zones, are given in Table 5. The crack resistance of these alloys was influenced both by the welding process and the composition as described below.

Gas Tungsten-Arc Process. Defect-free weldments were obtained in the alloys coded 9, 11, 18 and 21. Alloys 9, 11 and 18 were in the composition range of .058-.067% carbon, 0.65-1.67% silicon, 17.0-17.2% nickel, 25.5-26.6% chromium, 0.91-1.02% manganese and had .25% titanium and/or .10% misch metal or .25% titanium and .25% columbium added to the melt. Raising carbon to .15%, Alloy 12, resulted in a very slight cracking tendency, one crack each in both the weld and heat-affected zone.

Alloy 21 was a standard CK-20 alloy with a high columbium addition. This alloy contained 0.15% carbon, 0.55% silicon, 20.0% nickel, 25.4% chromium, 0.96% manganese and 2.90% columbium and the weldment was crack-free when welded with matching composition filler metal.

Shielded Metal-Arc Process. Alloys 9, 11, 12 and 18 were defect-free in

Table 4 — Delta Ferrite vs. Cracking

			Shielded metal-arc (a)					Gas tungsten-arc (b)			
Code	Calculated	Actual base	% Ferrite HAZ	HAZ cracks	% Ferrite weld	Weld cracks	Code	% Ferrite HAZ	HAZ cracks	% Ferrite weld	Weld cracks
18	5	0.2	2.9	0	0	2	18	3.9	0	6.2	0
11	7	0	2.2	0	0.2	35	9	3.4	0	3.7	0
9	3	0.4	2.0	0	0	2	11	3.0	0	6.6	0
3	6	0.2	2.0	3	0	2	1	2.0	3	1.1	3
1	2	1.2	1.6	0	0.2	5	3	1.4	0	1.4	91
12	2	0.2	0.4	0	0	1	12	1.0	1	2.1	1
10	0	0.2	0.4	5	0	11	10	0.4	4	1.0	51
4	1	0	0.2	7	0.2	16	4	0.2	6	0.2	41
5	0	0	0.2	5	0	23	2	0.2	6	0.2	56
15	0	0	0	2	0	1	14	0	2	0	21
2	1	0	0	4	0	16	7	0	4	0	51
7	0	0	0	7	0.2	10	15	0	9	0	56
6	0	0	0	8	0	17	6	0	10	0	41
14	0	0	0	9	0	0	5	0	11	0	70
13	0	0	0	16	0	2	16	0	15	0	64
16	0	0	0	20	0	2	13	0	17	0	88
17	0	0	0	27	0	0	17	0	18	0	101
8	0	0	0	28	0	31	8	0	19	0	74
					Cb SERIES						
19	0	0	0	4	0	0	19	0	3	0	20
20	0	0	0	1	0	17	20	0	0	0.2	5
21	0	0.4	0	1	0	36	21	0.2	0	0.6	0
					(Al & Ti)						
22	1	0	0	6	0	1	22	0.3	7	1.1	34
					STANDARDS - CF-8						
23	12	6.6	5.2	0	7.3	0	23	7.8	0	10.7	0
24	14	7.2	5.6	0	7.6	0	24	6.6	0	10.4	0
					STANDARDS - CK-20						
25	0	0	0	5	0	1	25	0	10	0	43
26	0	0	0	15	0	0	26	0	8	0	47
27	5	0	0	5	0	1	27	0	3	0	35
28	0	0.2	0	6	0	2	28	0	5	0	31
					COVERED ELECTRODE COMPOSITION						
36	0	0	0	3	0	6	36	0	1	0	14

(a) E310-16 filler
(b) Matching filler

Table 5 — Compositions with Improved Crack Resistance in the Heat-Affected Zone

									Cracks in six faces		
Code	C	Si	Ni	Cr	Cb	Ti	Ce	SMA weld	SMA HAZ	GTA weld	GTA HAZ
1	.072	.52	17.2	25.2	—	—	—	5	0	3	3
3	.057	1.56	17.3	25.2	.26	—	.014	2	3	91	0
9	.058	.65	17.1	25.5	—	.01	.009	2	0	0	0
11	.067	1.67	17.3	25.7	.24	.03	—	35	0	0	0
12	.15	1.72	17.1	25.8	—	.04	—	1	0	1	1
15	.066	1.64	20.0	25.4	—	.03	.009	1	2	56	9
18	.065	1.36	17.2	26.6	—	—	.012	2	0	0	0
20	.15	.57	20.0	25.3	1.38	—	—	17	1	5	0
21	.15	.55	20.0	25.4	2.90	—	—	36	1	0	0
CK-20[a]	.04–.15	.55-1.60	18.4-21.5	24.0-27.6	—	—	—	0-2	4-15	20-51	3-10

(a) Range of 5 heats

Table 6 — Effect of 0.1% Element Varied on Average Composition[(a)]

Variable	Range, %	Variation, %	Cracking in six faces: SMA HAZ	Cracking in six faces: SMA weld	Cracking in six faces: GTA HAZ	Cracking in six faces: GTA weld	Ferrite, %: CE HAZ	Ferrite, %: GTA HAZ	Ferrite, %: GTA weld	Ferrite, %: GTA	Ferrite, %: Vacuum extraction
C	.06-.16	.05	3.74	4.00	2.38	-2.50	-.88	-1.00	-1.15	-1.06	-1.22
Si	.50-1.7	.60	.02	.42	.01	.60	.01	0	.03	.10	.05
Ni	17-21	2.0	.29	- .06	.21	.72	-.03	- .04	- .05	- .07	- .12
Ti	0-.25	.12	-1.46	-2.50	- .57	-8.12	.05	.21	.55	.78	.38
Cb	0-.25	.12	3.43	2.71	1.92	14.06	.03	- .08	.11	.24	.86
MM[(b)]	0-.10	.05	.50	-5.24	.38	13.74	.13	- .10	- .46	- .75	-1.52
Avg.	—	—	8.25	9.75	6.69	43.62	.56	.63	1.02	1.44	2.53

(a) Average composition: C-0.11, Si-1.1, Ni-19.0, Ti-.12 added, Cb-.12, Misch metal-.05 added, Mn-1.0, S-.015, P-.015, Bal. Fe

(b) Misch metal — 50%Ce, 27%La, 16%Nd, 5%Pr, 2% Ore; 99% combined rare earths

the heat-affected zone when welded using commercially available austenitic E310-16 electrodes and Alloy 21 had only one small crack. Minor cracking was observed in the deposits of welds made with Codes 9, 12 and 18 (one or two cracks) whereas those made with Alloys 11 and 21 cracked severely (35 and 36 cracks respectively). The chemical composition range of the "best" alloys, that is, 9, 12 and 18, was .058-0.15% carbon, 0.65-1.72% silicon, 17.1-17.2% nickel, 25.5-26.6% chromium, 0.91-0.99% manganese with 0.25% titanium and/or 0.10% misch metal added. At the high carbon level, 0.15%, the titanium addition was necessary otherwise cracking increased in both the weld and heat-affected zone as shown by Alloy 4 (Tables 1 and 4). Increasing the nickel content to 20% in an alloy containing titanium and misch metal (Alloy 15) resulted in minor cracking in the weld and heat-affected zone, a total of three cracks in six faces examined at 30X. It appears that an upper level of slightly less than 20%Ni, possibly 19%, would still result in defect-free heat-affected zones when welded by the SMAW process. Alloy 15, like Alloys 11 and 21, was very prone to cracking when welded by the GTAW process with matching composition.

The alloys in the statistical series with the poorest heat-affected zone crack resistance for both processes (Alloys 8, 13 and 16) contained high nickel and 0.25% columbium.

Effects of the Variants on Cracking

The effects of the variables in the factorial design on cracking in the heat-affected zones and welds were established for each weld process (Table 6). The effects described for the GTAW process are straightforward since matching composition base metal and filler metal were used. Also, the effects described for the heat-affected zone of the SMAW process are directly related to the composition variables of the base metal. However, the statistical results reported for the weld metal deposited by the SMAW process are more qualitative in nature than the GTAW results. The reason for this is that the calculations are based upon the variables of the base metal composition although a common electrode, E310-16, was used and the base metal composition varied. Consequently, the effect of variation of the base metal composition on weld metal composition would primarily be obtained through dilution.

The effects of each of the elements on the heat-affected zone or weld metal cracking for both processes may be summarized as follows:

Heat-Affected Zone. Titanium was beneficial and silicon had a negligible effect. Carbon, columbium (up to 0.25%), misch metal and nickel were deleterious in that order when compared on an equal weight % basis (0.10% added). Also, the beneficial effect of misch metal to the weld metal in the SMAW process far outweighs the slight disadvantage in the heat-affected zone.

Weld Metal. Titanium was beneficial, columbium (up to 0.25%) was harmful particularly in the GTAW welds, and silicon was deleterious but to a lesser extent. The effects of carbon, nickel and misch metal on weld metal cracking varied with the welding process. Carbon was beneficial in the GTAW process (matching filler) and increasing carbon of the base metal was deleterious in the covered electrode weld (nonmatching composition electrode). Nickel increased crack sensitivity in the GTAW deposit and was slightly beneficial in the SMAW weld metal. Misch metal was the most beneficial on an equal weight basis in the SMAW process and deleterious in the GTAW process.

Effect of Columbium. Whereas columbium was very deleterious in the weld metal with the GTAW process at the 0.25% level it was beneficial at higher levels such as 1.38% and 2.90%. Weld cracking decreased with increasing columbium content and defect-free weldments were obtained at 2.90% with matching composition filler and base metal (Table 4, Fig. 4). When welded using E310-16 electrodes, the higher columbium base metals had minor heat-affected zone cracking (1 crack each), but weld metal cracking increased severely with increasing columbium content of the base metal (17 and 36 cracks). The latter is probably associated with an increasing difference in hot strength between the columbium-free (except by dilution) weld metal and the higher strength base metal (15). The difference in strength between base metal and weld metal would not be as much of a factor in the GTAW weldments since matching composition base and filler metals were used.

The effect of columbium on weld metal cracking in stainless steel weldments has been the subject of many investigations (Refs. 15,21-29) and reviewed by Borland, et al (Ref. 25). Most work has been on covered electrode deposits and generally refers to the effect of columbium in conjunction with some other element such as carbon (Ref. 18,22,29) or silicon (Refs. 23,26). It also has been shown that in the presence of carbon, that the columbium/silicon ratio determines whether columbium forms a carbide or silicide (Ref. 24). An excess of silicon in columbium bearing 19Cr-13Ni alloy is said to promote cracking (Ref. 26) whereas 1.9-2.9% columbium in the presence of excessive silicon overcomes cracking in 25Cr-20Ni weld metal (Ref. 17). The latter results were based on tensile tests obtained from weld pads deposited from covered electrodes. No fissuring was observed but a loss in tensile

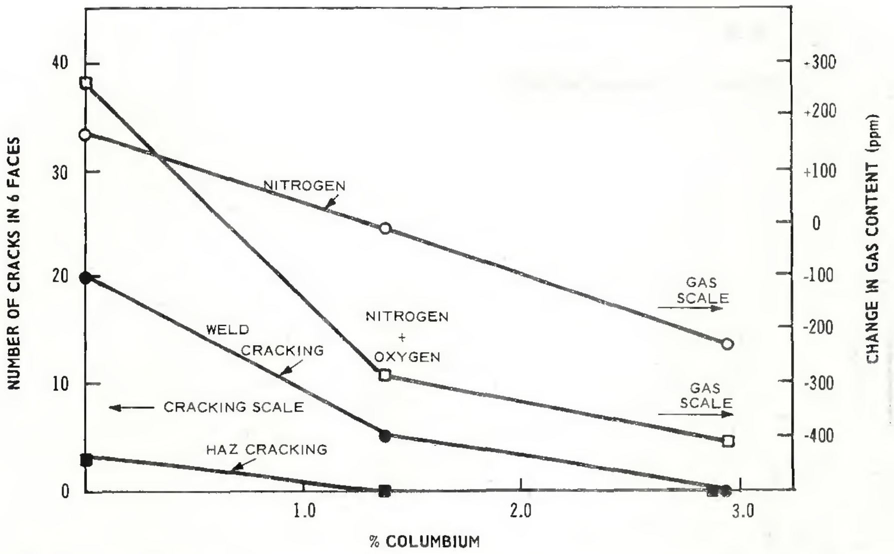


Fig. 4 — Change in gas content and cracking as a function of columbium content in GTA weldments of 25Cr-20Ni alloys

ductility was obtained and attributed to the presence of ferrite. Since these were weld pad results and base metal was not involved no report was made on heat-affected zone effects. Several investigators have reported on the varied effect of columbium on weld cracking in relation to the amount present. One author established a detrimental effect in 18Cr-8Ni between 0.6 and 0.8% and a beneficial effect between 1 and 2% (Ref. 27), whereas, in the second case, in 16Cr-13Ni-2Mo the range of 0.35-1.57% columbium was detrimental and above 1.57% beneficial (Ref. 28). The effect of columbium appears to be complex and dependent upon the balance of composition. Therefore, the results of the present investigation indicating columbium to be deleterious at the 0.25% level and beneficial at the 1.38-2.90% level are not considered to be unusual. As will be shown later the columbium effect in the present work is related to the decrease in gas contents of the deposited weld metal.

Effects of Elements on Delta Ferrite Formation

The effects of the variants in the factorial design on delta ferrite formation are given in Table 6. The effects on the heat-affected zone when welded with the SMAW process with a fully austenitic E310-16 electrode and in the heat-affected zone and weld with the GTAW process using matching filler and base metal were as follows: carbon and nickel decreased ferrite content as expected and titanium increased ferrite formation in all cases. Unexpectedly, silicon was shown to have only a very minor positive or no ferrite forming tendency in this series. Columbium (up to 0.25%) had a varied effect. It increased the ferrite content in the SMAW heat-affected zone and in the GTAW weld but had a negative effect in the heat-affected zone of the GTAW weldment. Columbium was three times as effective as silicon in promoting delta ferrite formation in the GTAW process deposit contrary to the Schaeffler equation (Ref. 30) which estimates that silicon is twice as effective as columbium in promoting ferrite formation in SMAW deposits. Misch metal also showed an inconsistent effect. It increased delta ferrite formation in the heat-affected zone of the covered electrode weld and had the opposite and fairly large effect in the heat-affected zone and weld of the GTAW process.

The effects of the variants on delta ferrite formation as measured from the top of the weld (the last three beads deposited) and the vacuum extractions were in the same directions as obtained from the cross sections of the weld but the magnitude of the effects were different (Table 6).

The importance of the solidification rate and the effect of the energy input of the welding process on the ferrite content of those alloys prone to ferrite formation is indicated in Table 3. As shown, considerable difference was obtained on the measured delta ferrite content for the 1 × 3 × 6 in. sand castings, the heat-affected zone for each weld process, the GTAW deposited weld metal and the vacuum extracted samples for the same composition. Several alloys in this category are Codes 2, 3, 9, 11, 12 and 18.

Relation of Delta Ferrite to Cracking

As many investigators have noted previously, the presence of ferrite in stainless steel welds reduces cracking susceptibility. It is generally accepted that 5% ferrite in the weld is sufficient to overcome weld cracking (Ref. 26). However this is sometimes difficult to achieve for the more austenitic the base metal (based upon the Schaeffler equation) the greater the ferrite content of the electrode required for an effective minimization of weld cracking (Ref. 31). With respect to the stainless steel base being welded, additions of ferrite (regardless of the amount) to the weld deposit have no effect in preventing base metal hot cracking (Ref. 31). In the present work a definite relationship appears to exist between the presence of a small amount of ferrite and crack resistance the heat-affected zone as well as in the weld metal (Table 4).

Heat-Affected Zone. All weldments that had some ferrite formed in the heat-affected zone *during the welding process* were crack-free or essentially crack-free (3 cracks in 6 faces maximum) in the heat-affected zone (Table 4). It is also clear, however, that heat-affected zone cracking is also composition dependent since ferrite-free heats varied from zero defects (Alloys 20,21) to 28 cracks. Quantitatively, alloys which formed over 2.0% ferrite (a ferrite number of 2) were crack-free in the heat-affected zone with either process. At 2.0% ferrite or less, cracking sensitivity was apparently related to some factor other than ferrite content. For example, Code 3 (SMAW process) and Code 1 (GTAW process) each measured 2.0% ferrite and were more crack sensitive than Codes 1, 12, 20 and 21 (SMAW process) and Codes 3, 12, 20 and 21 (GTAW process) which measured from none to 2.0% ferrite. It is significant to note that the heats which formed ferrite during the welding process were compositionally prone to such behavior; that is, the Schaeffler diagram predicted 2-7% ferrite, although actual measurements showed from zero to 1.2% in the castings. In this regard, though the use of ferrite to overcome *weld deposit* cracking is well known, an extensive literature survey revealed only one reference to the use of delta ferrite to minimize heat-affected zone cracking (Ref. 40) and this referred to 5-10% ferrite in the casting before welding. No reference could be found dealing with the use of compositions that form ferrite during the welding process as a means of overcoming cracking in that area.

Weld Metal. Crack sensitivity of the GTAW deposits followed the same pattern as the heat-affected zone in relation to ferrite content (number) except that the ferrite content was generally higher in the welds (Table 4). Three defect-free welds contained from 3.9 to 6.6% ferrite. Below 2.1% ferrite behavior was inconsistent. Code 12 with 2.1% measured ferrite in the weld was essentially crack-free and Code 21 (2.9%Cb) with 0.6% ferrite was crack-free. On the other hand, heats 3 and 10 with 1.4 and 1.0% ferrite were very crack sensitive whereas Code 1 was only slightly crack sensitive with 1.1% ferrite. The high cracking sensitivity of some of the GTAW welds may be related, at least in part, to the greater sensitivity of austenitic stainless steel weld metals to sulfur and phosphorus when welded by inert gas processes (Refs. 16, 17). In the latter, the limit for sulfur and phosphorus has been set at 0.015% each whereas covered electrode deposits up to 0.025% sulfur and 0.030-0.035% phosphorus may be tolerated (Ref. 12). The presence of ferrite increases these tolerances (Refs. 18, 19). The sulfur and phosphorus ranges of the experimental alloys were 0.012-0.015% sulfur and 0.014-0.021% phosphorus.

A relationship between SMAW weld cracking and ferrite content was not established since all the welds were essentially fully austenitic. The highest ferrite content measured was 0.2%. Since the same E310-16 electrode was used the difference in deposit composition would be that obtained by dilution of base metals of varying composition. The importance of base metal composition on weld metal cracking is shown in the range of cracking obtained for the same electrode from none to 37 cracks.

Gas Content Effects

Since it was thought that gas content of the base metal or gas pick-up during the weld process may have affected crack resistance the H_2, N_2 and O_2 contents of the base and weld metals were determined (Table 7). Gas content in the range obtained in these weldments could not be directly related to cracking except as described below for the columbium series.

A Yates analysis of the effects of the individual elements on the change in gas content during the GTAW process is given in Table 8. The change in gas content was very readily obtained since matching composition base and filler metals were used in these weldments. The results show that titanium had a strong effect in lowering the nitrogen content whereas carbon had a strong deoxidizing effect on the weld puddle. With columbium up to 0.25% and misch metal the oxygen content increased.

The welds made by the GTAW process with the alloys containing 1.28 and 2.90% columbium, Alloys 20 and 21, were the only welds to show a decrease in both oxygen and nitrogen content during the welding process. The change in nitrogen, nitrogen plus oxygen, and cracking as a function of columbium content in 25%Cr-20%Ni alloys (Alloys 19, 20 and 21) are depicted in Fig. 4. Although not shown, the nitrogen content of the welds also decrease as a function of columbium content (Table 7). A definite correlation appears to exist between decrease in nitrogen or nitrogen plus oxygen, cracking and columbium content.

General Discussion — Effects of Ferrite

In addition to the beneficial effects on cracking in stainless steel welds and castings reported earlier, other effects of delta ferrite described in the literature are: (a) increases room temperature strength (Refs. 8, 36, 39, 43), (b) lowers hot strength (Refs. 13, 33), (c) improves corrosion resistance (Refs. 6, 8, 32, 34, 35, 36, 39) with particular reference to stress corrosion cracking and (d) increases magnetic permeability.

It has been reported that up to 12% delta ferrite in 18%Cr-8%Ni-3%Mo castings did not impair impact resistance down to minus 320 F (−196 C) (Refs. 41, 42).

The tolerable amount of delta ferrite in the "as-welded" or "as-cast" condition in stainless steels when exposed to elevated temperatures has been the subject of many investigations. One study concluded that ferrite is not a factor in the chemical process industries from a standpoint of transformation to sigma (Ref. 6). Several investigators concluded that 10% delta ferrite was permissible without pronounced embrittlement as follows: in welds in the range of 1380-1560 F (749-849 C) (Ref. 32), up to 850 F (455 C) (Ref. 33), at 900 F (482 C) (Ref. 37), or in overlays exposed in the range of 650-950 F (343-510 C) or 1100-1700 F (593-927 C) (Ref. 7), or in castings (Ref. 40).

An aim of 10% delta ferrite in CF8M to obtain a gain in yield strength at room temperature and 660 F (349 C) is recommended (Ref. 43). On the other hand two studies concluded that ferrite content should be limited in Type 347 stainless welds for elevated temperature service (~1100 F) (593 C) to 2-5% (Ref. 33) and 1-4% (Ref. 38) followed by a post-weld heat treatment (Ref. 33). However, it was also suggested that the use of Type 304L in place of Type 347 is a viable solution since the alloy does not embrittle at normal ferrite levels without a post-weld heat treatment (Ref. 33). A third paper (Ref. 44) based on the results of one heat of welded Type 347 showed that in three month exposures sigma did not form below 1000 F (538 C) but did form between 1050 and 1550 F (568-843 C) and concluded that sigmatized Type 347, particularly weld metal, should not be subject to impact loadings. The degree of embrittlement induced by sigma formed from ferrite is dependent on the original ferrite content, its distribution and amount of ferrite transformed to sigma. Sigma formed directly from austenite occurs more slowly but usually is in grain boundaries forming a continuous network and the embrittlement tends to be more harmful than that produced from ferrite (Ref. 7).

As described earlier in this investigation the ferrite content formed during the welding process was affected by composition as well as welding process. Therefore both composition and welding process should be considered when establishing service temperature limitations based upon ferrite content. Based upon a maximum of 5% ferrite in a weldment for service in the sigma forming temperature range, Alloy 9 welded by either process and Alloy 21 welded by the GTAW process with matching composition filler would not have a limited service temperature due to ferrite content. Alloy 18 welded by the GTAW process with matching filler formed 6.2% ferrite in the weld. This type weldment should be useful up to 850-1000 F (454-538 C) and possibly higher. The high temperature limitation may be strength rather than embrittlement.

Mechanical Properties and Corrosion Resistance

The mechanical properties and corrosion resistance have not been determined. It would be expected that the 2.90%Cb alloy would have increased strength over the standard CK-20 (Ref. 17). However, the small changes in composition of the other crack resistant weldable alloys should not result in a significant change in mechanical properties from the standard CK-20. The small amounts of ferrite may result in a small increase in room temperature strength. The small amount of ferrite and lower carbon content should be beneficial to intergranular corrosion whereas the 2.90%Cb addition should have a stabilizing effect on that alloy.

The higher alloy content of these materials, particularly chromium content, should result in an improvement in corrosion properties and possible upgrading from the CF-8 or 19Cr-9Ni type (Ref. 45).

Table 7 — Effect of Weld Process on Gas Content[a] of Weld Metal

	Base			SMA weld			SMA difference from base			GTA weld			GTA difference from base		
Code	H	N	O	H	N	O	H	N	O	H	N	O	H	N	O
1	3.4	490	435	2.4	700	830	–1.0	+210	+ 435	0.6	415	520	–2.8	– 75	+135
2	2.3	445	235	8.0	650	930	+4.7	+205	+ 695	1.7	630	240	– .6	+185	+ 5
3	5.8	450	280	3.0	500	1700	–2.8	+ 50	+1420	1.5	490	860	–4.3	+ 40	+580
4	3.2	566	135	3.2	620	960	0	+ 55	+ 825	1.4	600	445	–1.8	+ 35	+310
5	3.2	415	385	4.3	760	990	+1.1	+345	+ 605	1.2	740	1000	–2.1	+325	+615
6	3.0	445	355	2.7	750	800	–0.3	+305	+ 445	1.4	760	410	–1.6	+315	+ 55
7	2.4	380	320	1.4	490	910	–1.0	+110	+ 590	1.2	710	445	–1.2	+330	+125
8	3.5	495	295	2.4	720	1000	–1.1	+325	+ 705	1.3	1100	510	–2.2	+605	+315
9	2.1	510	425	2.7	530	930	+0.6	+ 20	+ 505	1.4	560	440	–0.7	+ 50	+ 15
10	2.1	485	340	2.1	470	990	0	– 15	+ 650	1.4	320	740	–0.7	–165	+400
11	2.1	475	175	2.3	550	990	+0.2	+ 75	+ 815	1.1	475	720	–1.0	+ 0	+545
12	2.9	410	140	2.7	470	1300	–0.2	+ 60	+1160	1.5	485	370	–1.4	+ 75	+230
13	1.8	475	350	2.3	490	1300	+0.5	+ 15	+ 950	2.2	540	495	–0.4	+ 75	+145
14	2.0	555	320	2.6	430	1100	+0.6	+125	+ 780	1.6	530	440	–0.4	– 25	+120
15	1.4	505	215	2.5	530	1100	+1.1	+ 25	+ 885	1.5	580	420	+0.1	+ 75	+205
16	1.8	420	205	2.3	475	1000	+0.5	+ 55	+ 795	4.6	440	290	+2.8	+ 20	+ 85
17	1.3	485	275	2.9	510	1200	+1.6	+ 25	+ 925	1.6	510	590	+0.3	+ 25	+315
18	2.0	435	175	3.6	660	940	+1.6	+225	+ 765	4.3	670	700	+2.3	+235	+525
19	1.1	515	400	2.3	520	930	+1.2	+ 5	+ 530	1.9	680	500	+0.8	+165	+100
20	1.6	475	465	1.9	475	1000	+0.3	0	+ 535	1.6	465	290	0	– 10	–275
21	1.6	445	515	1.4	530	1000	–0.2	+ 95	+ 485	2.0	215	335	+0.4	–230	–180
22	2.1	415	72	2.1	570	1200	0	+155	+1128	0.8	310	395	–1.3	–105	+323
23	2.6	340	145	3.3	480	1000	+0.7	+140	+ 855	—	—	—	—	—	—
29	—	—	—	—	—	—	—	—	—	2.1	400	620	–0.5	+ 60	+575
24	3.1	395	155	3.4	430	1200	+0.3	+ 35	+1045	—	—	—	—	—	—
30	—	—	—	—	—	—	—	—	—	1.0	340	455	–2.1	– 55	+300
25	3.3	445	220	1.8	540	1500	–1.5	+ 95	+1280	—	—	—	—	—	—
31	—	—	—	—	—	—	—	—	—	3.8	580	300	+0.5	+135	+ 80
26	2.4	435	210	2.6	520	980	+0.2	+ 85	+ 770	—	—	—	—	—	—
32	—	—	—	—	—	—	—	—	—	0.7	455	465	–1.7	+ 20	+255
27	4.3	390	180	2.3	495	1000	–2.0	+105	+ 820	—	—	—	—	—	—
33	—	—	—	—	—	—	—	—	—	0.8	530	405	–3.5	+140	+225
28	2.5	520	175	4.4	630	1700	+1.9	+110	+1525	—	—	—	—	—	—
34	—	—	—	—	—	—	—	—	—	1.5	540	395	–1.0	+ 20	+220
36	5.4	440	255	3.5	560	860	–1.9	+120	+ 605	2.7	500	940	–2.7	+ 60	+695
35[b]	—	—	—	11.0	510	860	—	—	—	—	—	—	—	—	—

(a) Parts per million
(b) E310-16 weld pad

Table 8 — Effect of 0.1% Element on Change[a] in Gas Content During Welding by the GTAW Process

Element	Range, %	Variation, %	H_2 ppm	N_2 ppm	O_2 ppm
C	.06- .16	.05	+.92	+9.4	–105.6
Si	.50-1.70	.60	-.07	+5.2	+9.2
Ni	17-21	2.00	+.03	+4.9	-1.7
Ti	0-.25	.12	+.86	– 86.2	-2.1
Cb	0-.25	.12	+.23	+9.7	+77.8
MM[b]	0-.10	.05	+.22	– 16.0	+98.6
Avg	—	—	1.14	116.6	243.4

(a) Based upon difference in gas content of original base metal and weld deposited by GTAW process using matching composition filler
(b) Misch metal

Conclusions

1. Several experimental alloys had better crack resistance than the standard CK-20 alloy, and based on zero defects in weldments were equivalent to CF-8. These were of two types:
   (a) Those containing about 0.06%C, 17%Ni, 26%Cr, 0.6-1.4%Si, 1%Mn with 0.25%Ti and/or 0.10% misch metal added to the melt
   (b) A 0.15%C, 20%Ni, 25%Cr, 0.55%Si, 1%Mn, 2.90%Cb alloy

2. In the columbium-free alloys above, the best cracking resistance was associated with the presence of small amounts of delta ferrite formed during the welding process. This was true in the case of the heat-affected zone with both weld processes and in the GTAW deposits made with matching composition filler metals.

3. Cracking decreased with increased columbium content in 25%Cr-20%Ni GTAW weldments made with matching composition filler metals and was correlated with a decrease in nitrogen or nitrogen plus oxygen content of the deposited weld metal.

4. Based upon ferrite content, these alloys appear to have utility as weldments up to 850-1000 F (454-538 C) and possibly higher dependent upon composition and weld process.

5. The degree of crack susceptibility even in ferrite-free alloys was strongly dependent upon composition and weld process. The effects of carbon, silicon, nickel, columbium, titanium and misch metal have been statistically determined on a 25% chromium, 1% manganese, iron base.

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