

CHROMIUM ADDITIONS TO THE ANCORLOY MD SERIES

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ABSTRACT

Ancorsteel 41AB, introduced several years back, demonstrated the benefits of chromium and manganese additions to molybdenum steels. The more recently developed Ancorloy MD series provides enhanced ductility and strengths in P/M steels. This paper examines the mechanical properties achieved through the combination of high performance materials with chromium additions and high temperature sintering. Two chromium-modified materials were developed by replacing a portion of admixed nickel with a high carbon ferroalloy to improve dimensional properties and hardenability. Reviews of properties such as tensile, impact, transverse rupture, rotating bending fatigue, hardenability, and compressibility are presented.

INTRODUCTION

The ever-increasing demand for superior mechanical properties has accelerated the drive to develop high performance alloys. Several years ago, Hoeganaes introduced the Ancorloy[®] MD series of materials which were designed to replace malleable and ductile cast irons [1,2]. Designated MDB, MDC, and MDCL, these materials employ the use of silicon, known to increase hardenability, enhance sintering, and provide superior mechanical properties at a modest cost [3]. Results have shown tremendous promise for the P/M industry with tensile strengths up to 1250 MPa (180,000 psi), elongations > 3%, and apparent hardness values up to 45 HRC when combined with high temperature sintering.

Chromium has long been known to enhance the hardenability - the ability to form martensite - of P/M steels. However, due to its high affinity for oxygen, reduction during powder processing and sintering is difficult. As a result, the use of chromium as a hardenability aid had previously been limited. The advent of introducing chromium into P/M steels through high carbon ferroalloys to prealloyed iron-based powders, however, has helped to alleviate these problems [4-6].

The high hardenability of chromium makes it attractive from a value-added standpoint. While superior properties are attainable in the current systems, the amount of nickel (4.0 w/o) leads to large sintered dimensional changes. Replacing a portion of the nickel offers the possibility of increased hardenability

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and dimensional properties with only a modest cost increase. This paper documents the mechanical property enhancements attainable through the modification of MDCL materials by substituting a portion of the nickel with chromium. Tensile, impact, transverse rupture, rotating bending fatigue, and hardenability data are presented.

EXPERIMENTAL PROCEDURE

Press ready binder-treated premixes were prepared for experimental evaluation with varying nickel (Inco 123) and chromium contents. A patented method of admixing a high carbon ferroalloy and prealloyed iron-based powder was used to produce those premixes that contained chromium [6]. The total lubricant content in all three premixes was 0.75 w/o. Asbury Grade 3203 HSC was used as the graphite supply. Each mix contained a total non-lube carbon content of 0.8 w/o prior to sintering. The sum of nickel and chromium in all mixes was nominally 4.0 w/o. The two modified (mod) materials, Ancorloy MDCL-Cr mod 1 and MDCL-Cr mod 2, contained chromium contents of 1.0 and 2.0, respectively (nickel contents of 3.0 and 2.0 w/o, respectively). The standard contained no admixed chromium and is hereafter referred to under its commercial designation MDCL. Nominal powder chemistries are shown in Table I.

Table I. Nominal chemistries of the three premixes.

ID	Ni (w/o)	Cr (w/o)	Si (w/o)	Mo (w/o)
Ancorloy MDCL (standard)	4.00	0.00	0.35	0.85
Ancorloy MDCL-Cr mod 1	3.00	1.00	0.35	0.85
Ancorloy MDCL-Cr mod 2	2.00	2.00	0.35	0.85

Powder, transverse rupture, tensile, impact, and apparent hardness data were acquired for the three materials. Powder properties investigated were apparent density (ASTM B-212) and Hall flow rates (ASTM B-213). Green density (ASTM B-331) and green strength (ASTM B-312) were measured at 415, 550, and 690 MPa (30, 40 and 50 tsi, respectively) at room temperature.

Transverse rupture (ASTM B-528), tensile (ASTM E-8), and impact (ASTM E-23) samples were also compacted at 415, 550, and 690 MPa (30, 40, and 50 tsi) at room temperature. These samples were sintered in an Abbott belt furnace at 1180 and 1260 °C (2150 and 2300°F, respectively). Three atmospheres were used: 90 v/o N₂ -10 v/o H₂, 50 v/o N₂ - 50 v/o H₂, and 100 v/o H₂. Following sintering, the samples were tempered at 205°C (400°F) for one hour in air. Percent dimensional change (ASTM B-610), sintered density (ASTM B-331), and apparent hardness (ASTM E-140) were measured from the transverse rupture samples after tempering.

Tensile testing was performed with standard dog-bone specimens (ASTM E-8) using a cross-head speed of 0.065 cm/min (0.025 in/min). The machine is equipped with a 25 mm (1 inch) extensometer, which was left on until failure. Impact testing was conducted at room temperature on unnotched Charpy samples (ASTM E-23).

Rotating bending fatigue data were acquired at a speed of 8,000 rpm. Specimens were machined from blanks sintered at 1260°C (2300°F) under an atmosphere of 90 v/o N₂ -10 v/o H₂ and tempered at 205°C (400°F) for 1 hour in air. The median fatigue endurance limit (50% FEL) was calculated by using the “staircase” method [7] until there were both failures and runouts at a minimum of two stress levels. Extrapolation was used to determine the 90% FEL. Approximately twenty samples of each material were tested with a prescribed runout limit of 10⁷ cycles.

Hardenability studies were conducted on Jominy samples (ASTM A-255) that were machined from blanks sintered at 2300°F in 90 v/o N₂ -10 v/o H₂. Common sintered densities of ~6.90 g/cm³ were achieved by compacting at 620 MPa (45 tsi), 470 MPa (34 tsi), and 400 MPa (29 tsi) for MDCL-Cr mod 2, MDCL-Cr mod 1, and MDCL, respectively. Jominy samples were austenitized at 900°C (1650°F) prior to quenching. Cooling rate data were acquired at four specific distances from the quenched end: 5, 25, 45, and 65 mm (0.2, 1.0, 1.8, and 2.6 in., respectively). Apparent hardness data were acquired on flats ground along the sides of the Jominy bars using the Rockwell A scale.

RESULTS AND DISCUSSION

Powder and Green Properties

Table II. Powder properties of the three premixes. Green strength measured at 415 MPa (30 tsi).

ID	Apparent Density (g/cm ³)	Hall Flow (s/50 g)	Green Strength (MPa / 10 ³ psi)
MDCL	3.20	29	80.7 / 11.7
MDCL-Cr mod 1	3.16	30	80.0 / 11.6
MDCL-Cr mod 2	3.15	30	78.6 / 11.4

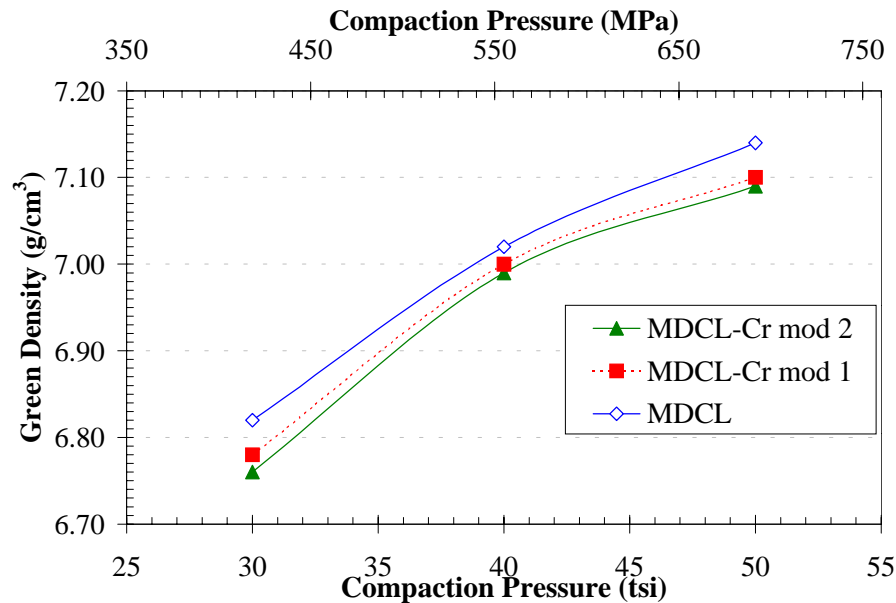


Figure 1. Compressibility plots of the three experimental premixes examined in this study.

Sintered and Tempered Properties

One clear advantage of the addition of chromium is the relatively small dimensional change (Figure 2). Due to large amounts of nickel, MDCL encounters a significant amount of shrinkage, particularly at high sintering temperatures. While this leads to higher sintered densities, the ability to produce “die-size” components is hindered. Chromium helps to offset this shrinkage, providing a dimensional change near 0.00% at a pressure of 690 MPa (50 tsi) in the 1.0 w/o chromium composition.

Comparing properties for the three materials as a function of sintered density is most prudent due to the large differences in dimensional change. In the interest of brevity and for direct comparison to acquired micrographs and fatigue results, only results from sintering in 90N₂ - 10 H₂ (v/o) at 1260°C (2300°F) are presented in figures. Complete sintered and tempered data for the six sintering conditions are shown in Tables VI - IX. In Figure 2, dimensional change values are shown as a function of sintered density. Figure 3 is a plot of yield and ultimate tensile strength vs. sintered density. Elongation values for the same samples are plotted vs. sintered density in Figure 4.

Clearly, MDCL-Cr mod 1 has the best combination of dimensional change and tensile properties of the three materials. These trends hold true for both sintering temperatures and all three atmospheres studied. All materials sintered better and provided superior mechanical properties after sintering at 1260°C (2300°F). An atmosphere of 100% H₂ provided the best mechanical properties of the three gas mixtures, but caused more dimensional shrinkage.

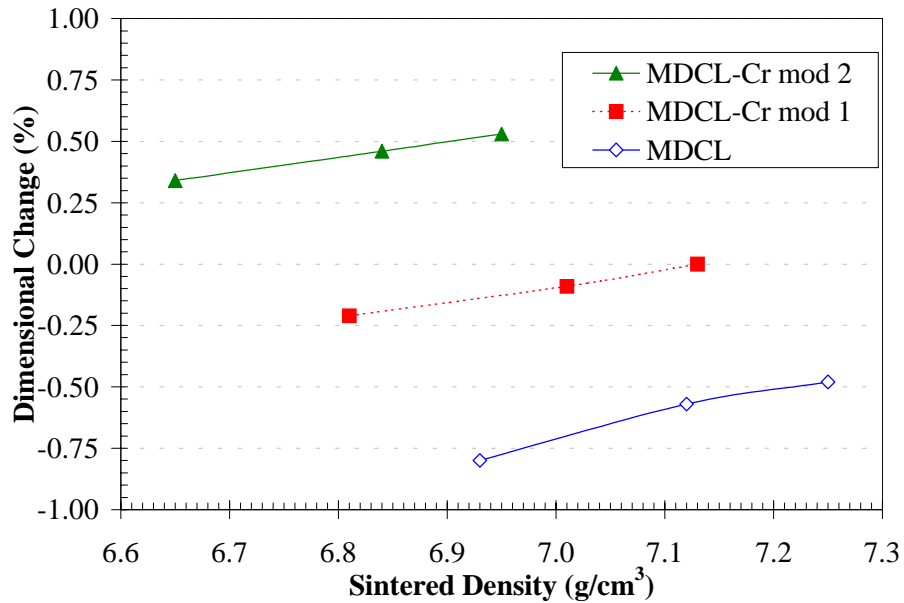


Figure 2. Dimensional change vs. sintered density for transverse rupture samples sintered at 1260°C (2300°F) in 90N₂-10H₂ (v/o) and tempered at 205°C (400°F) in air for 1 hour.

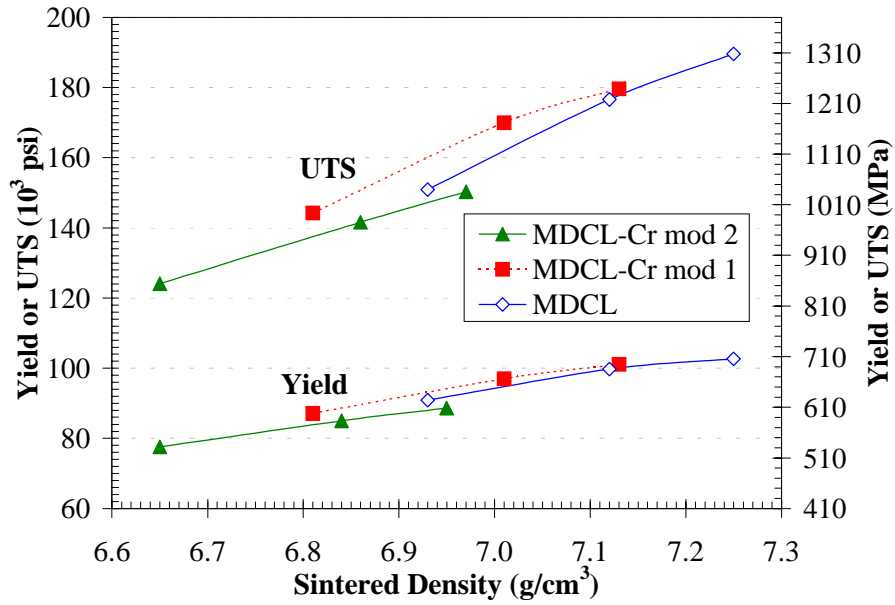


Figure 3. Plots of yield and UTS values vs. sintered density for tensile samples sintered at 1260°C (2300°F) in 90N₂-10H₂ (v/o) and tempered at 205°C (400°F) in air for 1 hour.

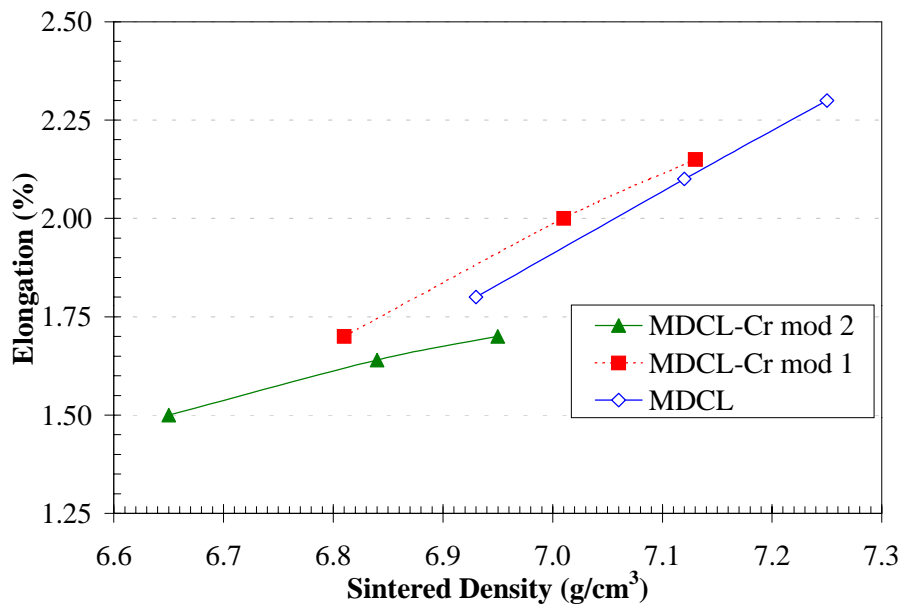


Figure 4. Plot of elongation vs. sintered density for tensile samples sintered at 1260°C (2300°F) in 90N₂-10H₂ (v/o) and tempered at 205°C (400°F) in air for 1 hour.

Rotating Bending Fatigue Properties

Rotating bending fatigue data were acquired at compaction pressures of 550 and 690 MPa (40 and 50 tsi, respectively). The 50% and 90% fatigue endurance limits determined for all three of the materials are shown in Table III and Figure 5. It is important to remember, however, that the densification characteristics are vastly different for the three materials. For better comparison, sintered densities are also reported in the table. The chromium-modified alloys appear to be superior when fatigue is measured as a function of sintered density. At a sintered density of $\sim 7.12 \text{ g/cm}^3$, the composition with 1.0 w/o chromium has fatigue endurance limits approximately 20% better than those of the standard.

Recall from Figure 2 that there was approximately 0.50% less shrinkage in the modified material at identical compaction pressures. Though this enhances die-size capabilities, unfortunately lower densities often correlate with inferior properties. Indeed, the chromium-modified materials exhibited slightly lower tensile and impact properties compared to the standard at equivalent tonnages. However, Figure 5 shows that the fatigue endurance limits of MDCL-Cr mod 1 are slightly higher than MDCL even though there is a significant difference in sintered density at a compaction pressure of 550 MPa (40 tsi).

Table III. Rotating bending fatigue data at 550 MPa (40 tsi) and 690 MPa (50 tsi) sintered at 1260°C (2300°F) in 90N₂-10H₂ and tempered at 205°C (400°F).

ID	Pressure (MPa / tsi)	Sintered Density (g/cm ³)	50% FEL (MPa / 10 ³ psi)	90% FEL (MPa / 10 ³ psi)
MDCL	550 / 40	7.12	365 / 53.0	352 / 51.0
	690 / 50	7.25	412 / 59.8	403 / 58.5
MDCL-Cr mod 1	550 / 40	7.01	370 / 53.7	355 / 51.5
	690 / 50	7.13	430 / 62.3	421 / 61.1
MDCL-Cr mod 2	550 / 40	6.84	301 / 43.7	287 / 41.6
	690 / 50	6.95	332 / 48.1	323 / 46.8

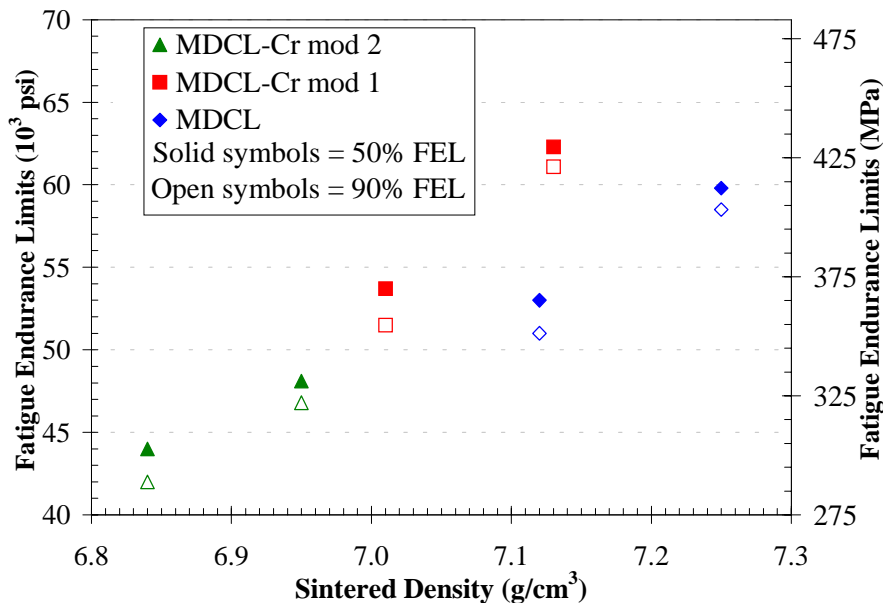


Figure 5. Plots of rotating bending fatigue endurance limits (FEL) vs. sintered density for samples sintered at 1260°C (2300°F) in 90N₂-10H₂ (v/o) and tempered at 205°C (400°F) in air for 1 hour.

Hardenability and Metallography

Hardenability is a function of alloy composition, carbon content, and grain size, and can be quantified in terms of an ideal diameter, D_I , the diameter of a cylindrical bar that will form 50% martensite at the core during an ideal quench. Thus, larger D_I values are indicative of more hardenable materials. The individual multiplying factors to estimate hardenability are

$$D_I = D_C \times F_{Mn} \times F_{Cr} \times F_{Ni} \times F_{Mo} \times F_{Si} \times F_{Cu} \quad (\text{Eq. 1})$$

where D_C is the base diameter dependent upon grain size and carbon content, and F_x is the hardenability factors of the respective element. P/M compositions are often compared with a common carbon content and grain size. Shown in Table IV are the hardenability effects of various alloying elements at 1.0 and 2.0 w/o concentration levels. Clearly, different elements offer various levels of hardenability. Most relevant to the current study is the difference in hardenability in chromium and nickel. The effect on D_I of replacing portions of nickel in MDCL with chromium is shown in Table V. The sintered carbon content was set at 0.75 w/o, which was the measured value in this experiment. Both chromium-modified materials have better theoretical hardenability than the standard.

Figure 6 shows experimental hardenability and cooling curves for the three materials. A schematic of the locations used for cooling rate data acquisition overlays the hardenability plot. As predicted by the D_I calculations, the modified materials provide better hardenability than the standard. For comparison, a temperature profile from the sintering furnace used in this study is shown with the cooling rate data [9]. This profile was adapted such that 0 seconds correlates with a sample temperature of 900°C (1650 °F) as the parts cooled from a sintering temperature of 1260°C (2300°F). The sintering furnace cooling rates are significantly slower than those observed in the quenched Jominy specimens.

Representative microstructures of the three materials studied are shown in Figures 7, 8, and 9. All images were recorded on transverse rupture samples pressed at 690 MPa (50 tsi), sintered at 1260°C (2300°F) in 90N₂-10H₂ (v/o), and tempered at 205°C (400°F) in air for 1 hour. The standard has a microstructure consisting of martensite, divorced pearlite, unresolved pearlite, and bainite. Significant amounts of martensite, alloy-rich martensitic areas (lighter regions), unresolved pearlite, and some retained austenite can be seen in the chromium-containing materials.

The presence of more martensite in these two materials correlates well with both the fatigue and hardenability results. This microconstituent, readily formed in hardenable alloys, has been found to enhance fatigue properties in P/M steels [10,11]. This lends to the most plausible reason why significantly better fatigue endurance limits are observed in the 1.0 w/o chromium composition compared to the standard at a similar sintered density.

Table IV. Hardenability factors of various elements at concentration levels of 1.0 w/o and 2.0 w/o as abstracted from [8].

Element	Multiplying Factor at 1.0 w/o	Multiplying Factor at 2.0 w/o
Manganese	2.72	5.04
Chromium	2.09	5.58
Nickel	1.31	1.61
Molybdenum	3.80	7.50
Silicon	1.68	2.37
Copper	1.25	1.50

Table V. Ideal diameters for the three materials for a carbon content of 0.75 w/o and an ASTM 6 grain size as abstracted from [8].

ID	Ni (w/o)	Cr (w/o)	D _I (cm / in)
MDCL	4.00	0.00	14.03 / 5.52
MDCL-Cr mod 1	3.00	1.00	17.30 / 6.81
MDCL-Cr mod 2	2.00	2.00	32.16 / 12.66

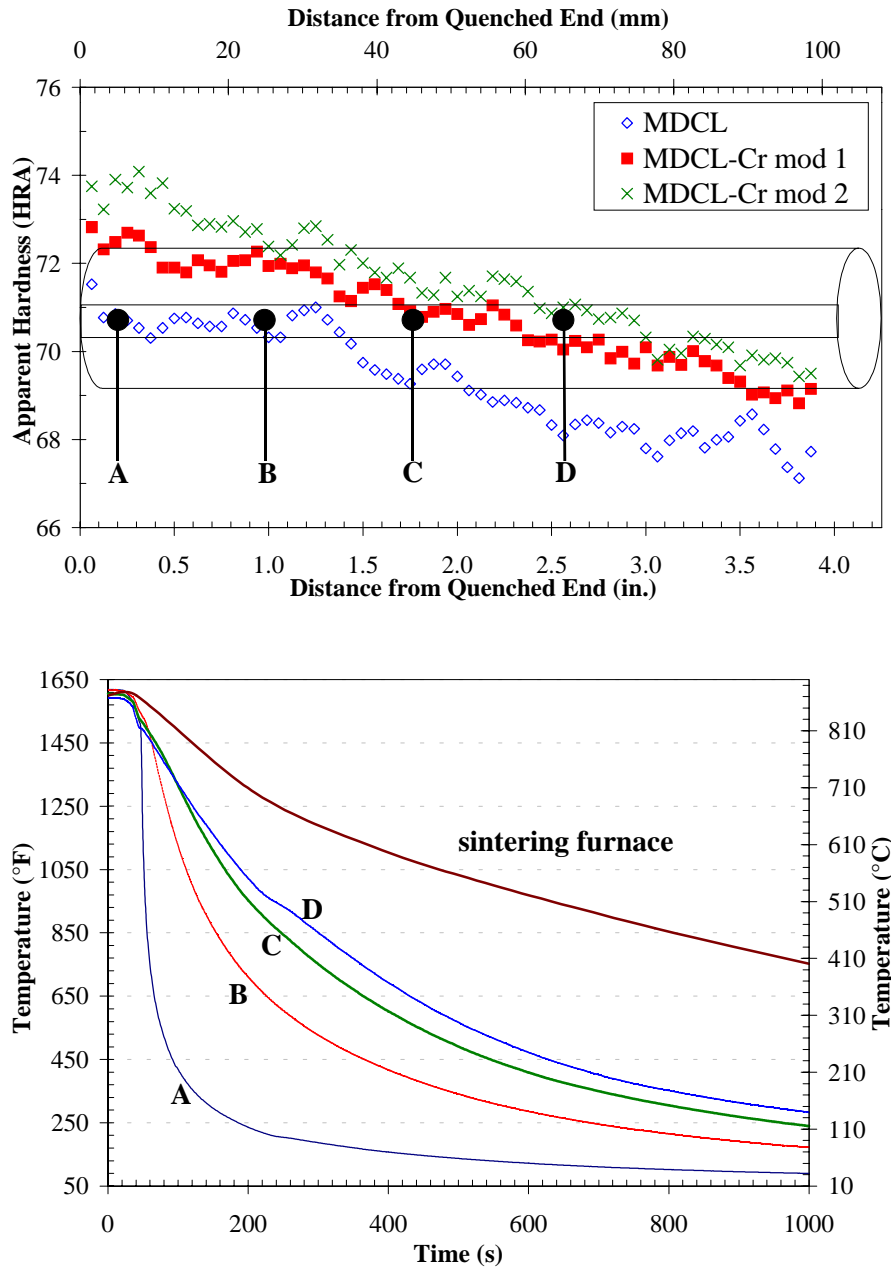


Figure 6. Hardenability and cooling curves for the three materials. Samples were sintered at 1260°C (2300°F) in 90N₂-10H₂ prior to machining. Sintering furnace profile is representative of the cooling rate for microstructures shown on the following pages [9].

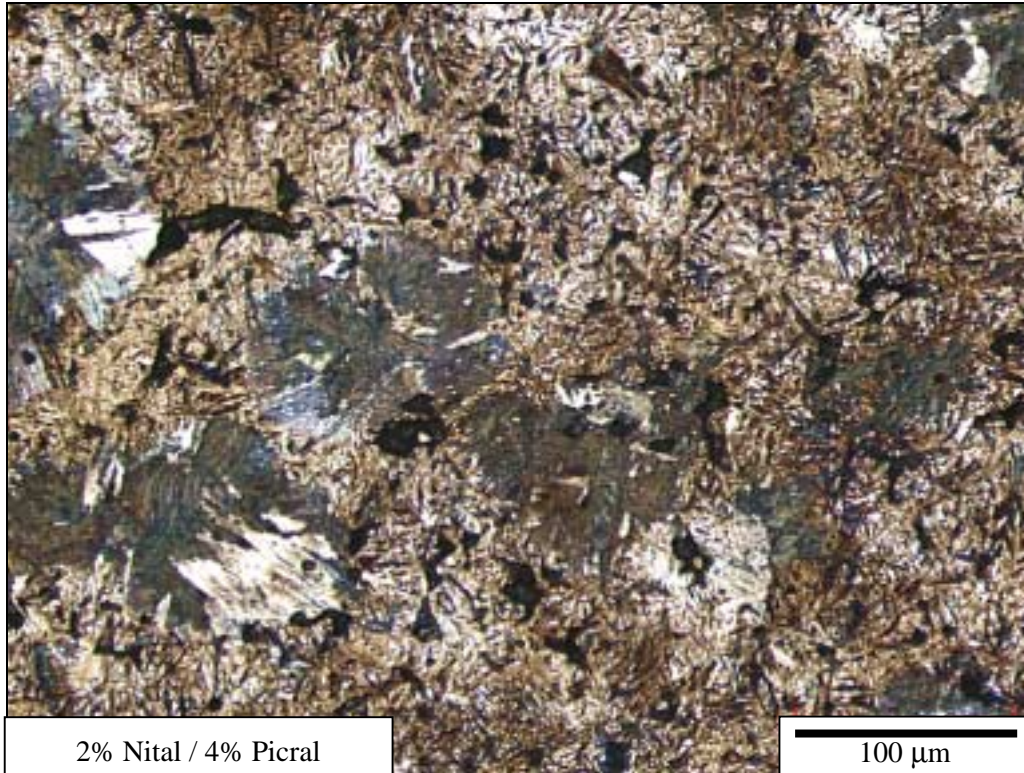


Figure 7. Typical microstructure of MDCL pressed at 690 MPa (50 tsi), sintered at 1260°C (2300°F) in 90N₂-10H₂ (v/o), and tempered at 205°C (400°F) in air for 1 hour.

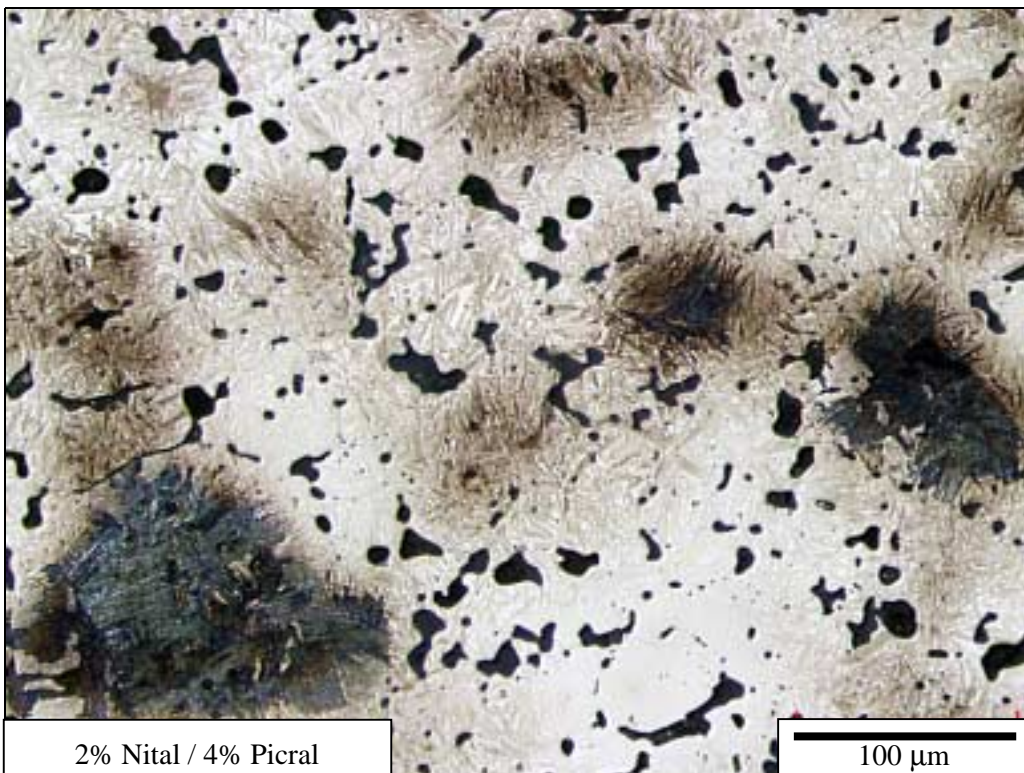


Figure 8. Typical microstructure of MDCL-Cr mod 1 pressed at 690 MPa (50 tsi), sintered at 1260°C (2300°F) in 90N₂-10H₂ (v/o), and tempered at 205°C (400°F) in air for 1 hour.

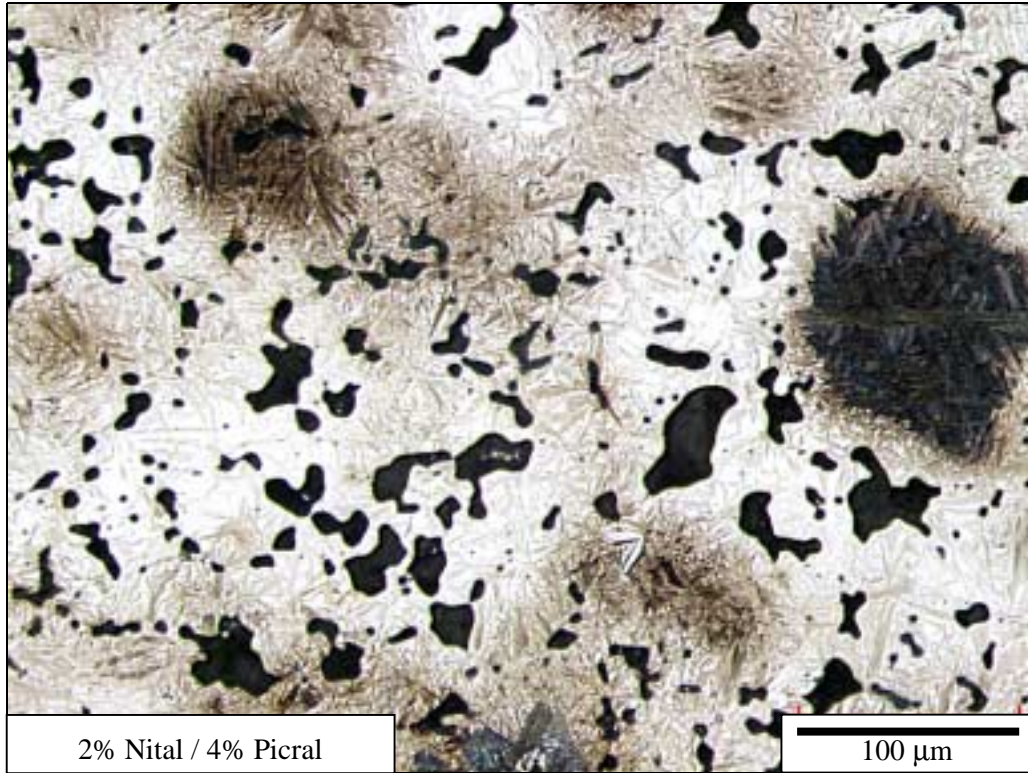


Figure 9. Typical microstructure of MDCL-Cr mod 2 pressed at 690 MPa (50 tsi), sintered at 1260°C (2300°F) in 90N₂-10H₂ (v/o), and tempered at 205°C (400°F) in air for 1 hour.

Table VI. Transverse rupture properties for samples sintered at 1180°C (2150°F) and tempered at 205°C (400°F).

ID	Atmos. (N ₂ /H ₂)	Press. (MPa / tsi)	GD (g/cc)	Gr. Exp. (%)	SD (g/cc)	DC (%)	App. Hard. (HRA)	TRS (MPa / 10 ³ psi)
MDCL	90/10	415 / 30	6.82	0.11	6.87	-.47	61.7	1526 / 221
		550 / 40	7.02	0.17	7.08	-.36	64.2	1800 / 261
		690 / 50	7.16	0.19	7.20	-.27	65.2	2066 / 300
	50/50	415 / 30	6.82	0.11	6.88	-.47	61.9	1555 / 226
		550 / 40	7.02	0.17	7.09	-.34	63.7	1935 / 281
		690 / 50	7.16	0.19	7.19	-.25	64.2	2054 / 298
	0/100	415 / 30	6.82	0.11	6.91	-.59	61.4	1688 / 245
		550 / 40	7.02	0.17	7.09	-.45	64.4	2162 / 314
		690 / 50	7.16	0.19	7.21	-.37	67.6	2288 / 332
MDCL-Cr mod 1	90/10	415 / 30	6.78	0.18	6.76	-.03	60.8	1398 / 203
		550 / 40	7.00	0.20	6.97	.07	63.8	1620 / 235
		690 / 50	7.10	0.25	7.07	.13	64.5	1693 / 246
	50/50	415 / 30	6.78	0.18	6.76	-.03	59.4	1451 / 211
		550 / 40	7.00	0.20	6.95	.08	62.7	1731 / 251
		690 / 50	7.10	0.25	7.05	.13	65.2	1875 / 272
	0/100	415 / 30	6.78	0.18	6.78	-.11	62.6	1517 / 220
		550 / 40	7.00	0.20	6.98	.01	64.6	2003 / 291
		690 / 50	7.10	0.25	7.08	.07	65.7	2200 / 319
MDCL-Cr mod 2	90/10	415 / 30	6.76	0.19	6.65	.34	60.3	1009 / 146
		550 / 40	6.99	0.21	6.86	.46	61.3	1207 / 175
		690 / 50	7.09	0.25	6.97	.53	63.9	1305 / 189
	50/50	415 / 30	6.76	0.19	6.63	.39	58.4	987 / 143
		550 / 40	6.99	0.21	6.85	.49	60.3	1246 / 181
		690 / 50	7.09	0.25	6.91	.56	62.4	1314 / 191
	0/100	415 / 30	6.76	0.19	6.67	.31	59.5	1060 / 154
		550 / 40	6.99	0.21	6.86	.41	61.2	1298 / 188
		690 / 50	7.09	0.25	6.96	.52	62.0	1444 / 209

Table VII. Transverse rupture properties for samples sintered at 1260°C (2300°F) and tempered at 205°C (400°F).

ID	Atmos. (N ₂ /H ₂)	Press. (MPa / tsi)	GD (g/cc)	Gr. Exp. (%)	SD (g/cc)	DC (%)	App. Hard. (HRA)	TRS (MPa / 10 ³ psi)
MDCL	90/10	415 / 30	6.82	0.11	6.93	-.80	64.3	1834 / 266
		550 / 40	7.02	0.17	7.12	-.57	65.6	2227 / 323
		690 / 50	7.16	0.19	7.25	-.48	66.9	2468 / 358
	50/50	415 / 30	6.82	0.11	6.92	-.78	65.1	1931 / 280
		550 / 40	7.02	0.17	7.12	-.59	67.4	2234 / 324
		690 / 50	7.16	0.19	7.23	-.47	69.8	2482 / 360
	0/100	415 / 30	6.82	0.11	6.93	-.91	63.9	1979 / 287
		550 / 40	7.02	0.17	7.13	-.72	66.2	2358 / 342
		690 / 50	7.16	0.19	7.25	-.55	67.8	2593 / 376
MDCL-Cr mod 1	90/10	415 / 30	6.78	0.18	6.81	-.21	64.2	1813 / 263
		550 / 40	7.00	0.20	7.01	-.09	66.6	2165 / 314
		690 / 50	7.10	0.25	7.13	.00	67.5	2289 / 332
	50/50	415 / 30	6.78	0.18	6.79	-.22	65.0	1751 / 254
		550 / 40	7.00	0.20	6.99	-.08	68.2	2124 / 308
		690 / 50	7.10	0.25	7.09	.01	69.2	2248 / 326
	0/100	415 / 30	6.78	0.18	6.81	-.34	62.0	1896 / 275
		550 / 40	7.00	0.20	6.99	-.16	64.5	2213 / 321
		690 / 50	7.10	0.25	7.11	-.04	66.9	2331 / 338
MDCL-Cr mod 2	90/10	415 / 30	6.76	0.19	6.65	.34	61.8	1469 / 213
		550 / 40	6.99	0.21	6.84	.46	64.3	1772 / 257
		690 / 50	7.09	0.25	6.95	.53	65.2	1869 / 271
	50/50	415 / 30	6.76	0.19	6.65	.34	63.2	1510 / 219
		550 / 40	6.99	0.21	6.84	.48	65.2	1717 / 249
		690 / 50	7.09	0.25	6.95	.57	66.0	1910 / 277
	0/100	415 / 30	6.76	0.19	6.65	.25	61.4	1662 / 241
		550 / 40	6.99	0.21	6.85	.42	63.4	2006 / 291
		690 / 50	7.09	0.25	6.94	.55	65.3	2069 / 300

Table VIII. Tensile and impact properties for samples sintered at 1180°C (2150°F) and tempered at 205°C (400°F).

ID	Atmos. (N₂/H₂)	Press. (MPa / tsi)	Yield (MPa / 10³ psi)	UTS (MPa / 10³ psi)	Elong. (%)	Impact (J / ft- lbs)
MDCL	90/10	415 / 30	545 / 79	841 / 122	1.6	15 / 11
		550 / 40	607 / 88	1007 / 146	1.9	18 / 13
		690 / 50	627 / 91	1069 / 155	2.0	20 / 15
	50/50	415 / 30	572 / 83	862 / 125	1.7	16 / 12
		550 / 40	600 / 87	1007 / 146	2.1	20 / 15
		690 / 50	669 / 97	1110 / 161	2.2	22 / 16
	0/100	415 / 30	572 / 83	889 / 129	1.6	16 / 12
		550 / 40	593 / 86	1062 / 154	2.0	23 / 17
		690 / 50	717 / 104	1186 / 172	2.3	27 / 20
MDCL-Cr mod 1	90/10	415 / 30	434 / 63	710 / 103	1.4	14 / 10
		550 / 40	510 / 74	862 / 125	1.7	16 / 12
		690 / 50	565 / 82	972 / 141	1.8	19 / 14
	50/50	415 / 30	455 / 66	717 / 104	1.6	15 / 11
		550 / 40	510 / 74	862 / 125	1.7	19 / 14
		690 / 50	586 / 85	1041 / 151	2.2	23 / 17
	0/100	415 / 30	503 / 73	827 / 120	1.5	15 / 11
		550 / 40	538 / 78	862 / 125	1.7	22 / 16
		690 / 50	607 / 88	1076 / 156	2.2	27 / 20
MDCL-Cr mod 2	90/10	415 / 30	407 / 59	572 / 83	1.1	8 / 6
		550 / 40	455 / 66	655 / 95	1.3	11 / 8
		690 / 50	476 / 69	738 / 107	1.4	14 / 10
	50/50	415 / 30	455 / 66	545 / 79	1.0	9 / 7
		550 / 40	469 / 68	579 / 84	1.1	12 / 9
		690 / 50	483 / 70	683 / 99	1.2	15 / 11
	0/100	415 / 30	448 / 65	572 / 83	1.0	11 / 8
		550 / 40	524 / 76	738 / 107	1.3	12 / 9
		690 / 50	552 / 80	779 / 113	1.4	15 / 11

Table IX. Tensile and impact properties for samples sintered at 1260°C (2300°F) and tempered at 205°C (400°F).

ID	Atmos. (N₂/H₂)	Press. (MPa / tsi)	Yield (MPa / 10³ psi)	UTS (MPa / 10³ psi)	Elong. (%)	Impact (J / ft- lbs)
MDCL	90/10	415 / 30	627 / 91	1041 / 151	1.8	20 / 15
		550 / 40	690 / 100	1220 / 177	2.1	27 / 20
		690 / 50	710 / 103	1310 / 190	2.3	30 / 22
	50/50	415 / 30	676 / 98	1083 / 157	1.8	20 / 15
		550 / 40	772 / 112	1220 / 177	1.9	27 / 20
		690 / 50	786 / 114	1351 / 196	2.4	33 / 24
	0/100	415 / 30	724 / 105	1089 / 158	1.8	20 / 15
		550 / 40	779 / 113	1289 / 187	2.0	26 / 19
		690 / 50	800 / 116	1434 / 208	2.2	32 / 23
MDCL-Cr mod 1	90/10	415 / 30	600 / 87	993 / 144	1.7	22 / 16
		550 / 40	669 / 97	1172 / 170	2.0	27 / 20
		690 / 50	696 / 101	1241 / 180	2.1	30 / 22
	50/50	415 / 30	621 / 90	1007 / 146	1.8	19 / 14
		550 / 40	676 / 98	1158 / 168	1.9	24 / 18
		690 / 50	710 / 103	1276 / 185	2.1	32 / 23
	0/100	415 / 30	669 / 97	1083 / 157	1.9	20 / 15
		550 / 40	710 / 103	1186 / 172	2.0	27 / 20
		690 / 50	800 / 116	1351 / 196	2.1	32 / 23
MDCL-Cr mod 2	90/10	415 / 30	538 / 78	855 / 124	1.5	24 / 18
		550 / 40	586 / 85	979 / 142	1.6	26 / 19
		690 / 50	614 / 89	1034 / 150	1.7	27 / 20
	50/50	415 / 30	579 / 84	910 / 132	1.6	16 / 12
		550 / 40	600 / 87	1014 / 147	1.7	19 / 14
		690 / 50	648 / 94	1076 / 156	1.8	20 / 15
	0/100	415 / 30	627 / 91	965 / 140	1.7	19 / 14
		550 / 40	655 / 95	1103 / 160	2.0	22 / 16
		690 / 50	662 / 96	1158 / 168	2.2	23 / 17

CONCLUSIONS

The enhancement of dimensional changes and hardenability of Ancorloy MDCL through the partial replacement of nickel with chromium was demonstrated. Two chromium-modified materials were prepared by substituting a portion of admixed nickel with high carbon ferrochromium. MDCL-Cr mod 1 (1 w/o Cr, 3 w/o Ni) provided dimensional changes close to die-size, significantly better than the large shrinkage observed in MDCL (0 w/o Cr, 4 w/o Ni) during sintering. Comparison as a function of sintered density showed this composition also provided equivalent or superior yield, ultimate tensile, elongation, impact, and rotating bending fatigue properties. Both chromium-modified materials also showed superior hardenability compared to the standard at a sintered density of $\sim 6.90 \text{ g/cm}^3$.

ACKNOWLEDGMENTS

The authors would like to extend their gratitude to Ms. Irene Nakigudde for her help with specimen pressing and testing, Mr. Santino Salvo for his assistance with hardenability testing/preparation, Mr. Ronald Fitzpatrick and Mr. William Bentcliff for their assistance with fatigue testing, Mr. Jerry Golin for his acquisition of metallographic images, and Mr. Joe DeLeonardo for production of the mixes. The help of Powder-Tech Associates and Atkins Tool Co. with fabrication of the Jominy bars is also much appreciated.

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