

CHROMIUM STEELS FOR HIGH PERFORMANCE PM APPLICATIONS

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ABSTRACT

Chromium steels have long dominated the landscape of the wrought industry because of their high performance capabilities at modest cost levels. Historically, chromium steels have had difficulty penetrating the powder metallurgy market because of oxidation issues. Recent powder manufacturing advances, however, have resulted in low-oxygen chromium steels such as Ancorsteel 4300, which enables the production of high performance parts with conventional processing techniques. The current work reviews the capabilities of this Cr-Si-Ni-Mo alloy and its derivatives. Static properties, dynamic properties, and dimensional stability data are reviewed with an emphasis on a sintering temperature of 1120 °C (2050 °F). Comparisons are made to traditional powder metallurgy materials in both the as-sintered and heat-treated conditions as well as to heat-treated wrought alloys.

INTRODUCTION

Wrought materials containing Cr have found widespread use in high performance components because of improvements in hardenability and mechanical properties at a modest cost. The powder metallurgy (PM) industry has adopted Cr through a range of commercially available products. Because Cr tends to form stable oxides, PM alloys containing this element have traditionally been high temperature sintered above 1205 °C (2200 °F) to avoid the adverse effects of oxygen on mechanical properties [1-2]. The recent instability of raw material prices has forced an increased desire to develop alloys that jointly utilize the benefits of Cr and can be effectively sintered at conventional temperatures using a 30 minute time-at-temperature cycle.

Ancorsteel® 4300, a Cr-Si-Ni-Mo PM steel, was specifically engineered to simulate wrought steel compositions and counteract the oxygen-related problems that are associated with both Cr and Si. With a nominal chemistry of 1.0 Cr, 0.6 Si, 1.0 Ni, and 0.8 Mo (wt.%), the alloy provides sintered oxygen contents below 500 ppm at 1120 °C (2050 °F) under a typical reducing furnace atmosphere of 90N₂-10H₂ (vol.%) [3]. The low oxygen content helps maximize the performance of the alloy by enabling full use of alloying elements, and compliments the other advantages of this alloy that include good compressibility, high hardenability, and exceptional dimensional stability under a variety of processing conditions.

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The trade name for Ancorsteel 4300 was derived from AISI 4340, a common wrought Cr steel familiar to many part designers in the automotive industry. It was designed to be the first in a series of alloys that mimic wrought steel compositions and provide high performance capabilities. Simulating wrought compositions is a response to the desire of the PM industry to achieve higher levels of performance and further penetrate the market of demanding applications.

In reaction to the recent escalation of Mo prices, a second Cr-Si-Ni-Mo alloy (Ancorsteel 4300L) was developed to offer complimentary performance levels at a lower Mo content, while still providing excellent sinter-hardenability. This leaner alloy maintains all of the robust processing capabilities of its higher alloyed counterpart while helping to further combat recent Mo price instability. It too provides good compressibility, high hardenability, and exceptional dimensional stability under a variety of processing conditions.

A comparison of the nominal chemistries of AISI 4340 and the two PM steels along with that of AISI 8620, another common wrought steel that is widely used in automotive gearing applications, is shown in Table I [4]. A significant difference between wrought materials and PM steels is the use of Mo as a dominant alloying element. Mo has a larger contribution to hardenability compared to elements such as Cr, Si, Ni, Cu, and Mn [5]. Perhaps even more interesting is that it has a synergistic effect with Ni. In the presence of Ni levels above 0.75 wt.%, Mo contributes to an increase in approximately 25% more hardenability than at lower Ni levels. This unique synergy between Ni and Mo served as the basis for the development of both Ancorsteels 4300 and 4300L. Alloys containing only Cr and Mo fail to achieve the full benefit in hardenability that can be gained from the presence of Mo.

This study was undertaken to investigate the performance capabilities of Ancorsteels 4300, 4300L, and their derivatives. Comparisons are made to FD-0405 and wrought Q&T AISI 8620 and 4340 grades under a variety of sintering temperatures and cooling rates. Static and dynamic properties are presented.

Table I. Nominal compositions (in wt.%) of wrought alloys and the two Cr PM steels.

<u>ID</u>	<u>Fe</u>	<u>Cr</u>	<u>Si</u>	<u>Ni</u>	<u>Mo</u>	<u>Mn</u>	<u>C</u>
AISI 4340 [§]	Bal.	0.8	0.2	1.8	0.2	0.8	0.4
AISI 8620 [§]	Bal.	0.5	0.2	0.5	0.2	0.8	0.2
Ancorsteel 4300	Bal.	1.0	0.6	1.0	0.8	0.1	-
Ancorsteel 4300L	Bal.	1.0	0.6	1.0	0.3	0.1	-

[§] Note: Compositional equivalents to AISI 4340 are BS 817M40, ISO 683/VIII Type 4, DIN 40NiCrMo6, and JIS SNCM439. AISI 8620 matches the compositions of BS 805M20, DIN 20CrNiMo2 and JIS SNCM220H.

EXPERIMENTAL PROCEDURE

Pilot scale mixes were made with 0.6 wt.% graphite for 4300, 4300L, and diffusion-alloyed FD-0405. Compositions of these three mixes along with those of AISI 8620 and AISI 4340 are shown in Table II. Several other pilot mixes of 4300L with varying Ni contents were made. All PM mixes were made with Asbury 3203H graphite and contained 0.75 wt.% Acrawax C as a lubricant. Standard bar stock of AISI wrought grades 8620 and 4340 were used to acquire Q&T wrought properties.

Table II. Nominal compositions (in wt.%) of the alloys studied. Balance for all alloys is Fe.

<u>Designation</u> [*]	<u>Cr</u>	<u>Si</u>	<u>Ni</u>	<u>Mo</u>	<u>Mn</u>	<u>Cu</u>	<u>Gr</u>
4300+0.6gr	1.0	0.6	1.0	0.8	0.1	-	0.6
4300L+0.6gr	1.0	0.6	1.0	0.3	0.1	-	0.6
FD-0405	-	-	4.0	0.5	0.1	1.5	0.6
AISI 8620	0.5	0.2	0.5	0.2	0.8	-	0.2
AISI 4340	0.8	0.2	1.8	0.2	0.8	-	0.4

Transverse rupture strength bars, dogbone tensile bars, and unnotched Charpy impact bars were compacted at room temperature for the PM materials at 690 MPa (50 tsi). Sintering was conducted for 30 minutes time-at-temperature in an Abbott belt furnace using an atmosphere of 90N₂-10H₂ (vol.%). Three average cooling rates over the range of 650 to 315 °C (1200 to 600 °F) were obtained by varying the belt speed and the frequency of the convection unit at the rear of the furnace: 0.7, 1.6, and 2.2 °C/sec (1.3, 2.8, and 4.0 °F/sec). Tensile specimens machined from blanks of the wrought alloys were austenitized at 900 °C (1650 °F) for 30 minutes in 25N₂-75H₂ (vol.%) and quenched in agitated oil that was maintained at 65 °C (150 °F). All samples were tempered at 205 °C (400 °F) for 1 hour.

Percent dimensional change, sintered density, and apparent hardness were measured for the PM materials from the transverse rupture samples using standard MPIF procedures. Tensile testing was performed using a crosshead speed of 0.065 cm/min (0.025 in/min). The machine is equipped with a 25 mm (1 in) extensometer, which was left on until failure.

Axial fatigue testing was performed according to ISO 3928 in load control, R = -1, using a frequency of 40 Hz, and a prescribed runout level of 2,000,000 cycles [6]. Impact testing was conducted for the PM materials at room temperature.

^{*} Base alloy used for FD-0405 was Distaloy 4800A.

RESULTS AND DISCUSSION

Effect of Sintering Temperature with Conventional Cooling

Plots of yield strength and tensile strength for 4300, 4300L, and FD-0405 as a function of sintering temperature are shown in Figures 1 and 2, respectively. A conventional cooling rate of 0.7 °C/sec (1.3 °F/sec) was used to generate these data. Correlating data for sintered density, dimensional change, transverse rupture strength, apparent hardness, and impact performance are shown in Table III.

From Figures 1 and 2 it is clear that 4300 and 4300L are high strength alloys. Both have considerably less alloying ingredients than FD-0405 (Table II), a point that is extremely critical in a period of raw material price instability. In particular, FD-0405 contains 4.0 wt.% Ni, which recently was at more than three times its historic level. 4300L also contains less Mo than FD-0405, which makes it even less susceptible to radical fluctuations in raw material prices.

All three alloys have increased performance levels with high temperature sintering. Interestingly, the higher sintering temperatures affect the Cr-containing alloys less than FD-0405. Comparing properties at 1260 °C (2300 °F) to 1120 °C (2050 °F), FD-0405 provided an increase in yield strength of 29% versus 8% and 16% for 4300 and 4300L, respectively. Similarly, the tensile strength increased 22% for FD-0405 compared to 19% for 4300 and 18% for 4300L.

The lesser effect of high temperature sintering on the Cr steels is a tribute to their ability to be effectively sintered at conventional temperatures using a 30 minute time-at-temperature cycle. Historically, PM Cr-containing steels have been sintered at high temperatures to avoid oxidation issues. However, the unique engineering design of 4300 and 4300L enables these alloys to have low oxygen contents even at 1120 °C (2050 °F).

Evaluation of the other data (Table III) for these three materials shows that the Cr steels are fairly robust over a range of properties. As would be expected from the yield and tensile strength data, the transverse rupture strength and apparent hardness data are significantly higher for 4300 and 4300L compared to FD-0405. The Cr steels have the ability to harden even at a conventional cooling rate. Elongation and impact data are lower for the Cr steels, but still fairly good considering the high level of strength that they provide.

Lastly, the dimensional stability of the Cr steels is important to note. FD-0405, as well as other diffusion-alloyed steels, are well known in the PM industry for their dimensional consistency over a range of parameters. In this case, both 4300 and 4300L provide a tighter dimensional range than FD-0405 when comparing 1260 °C (2300 °F) to 1120 °C (2050 °F).

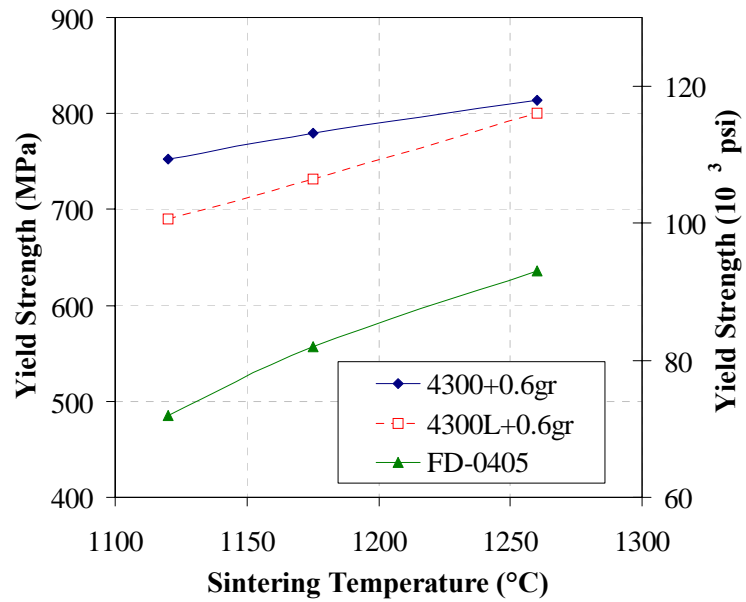


Figure 1. Yield strength as a function of sintering temperature at 0.7 °C/sec (1.3 °F/sec).

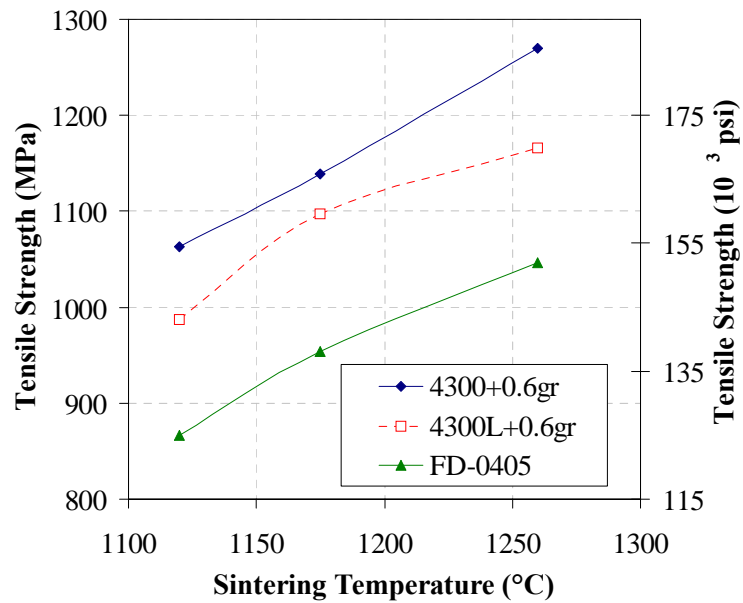


Figure 2. Tensile strength as a function of sintering temperature at 0.7 °C/sec (1.3 °F/sec).

Table III. Mechanical properties as a function of sintering temperature at 0.7 °C/sec (1.3 °F/sec).

<u>ID</u>	<u>Temp</u> °C (°F)	<u>SD</u> g/cm ³	<u>DC</u> %	<u>TRS</u> MPa (10 ³ psi)	<u>Hard</u> HRA	<u>Elong</u> %	<u>Imp</u> J (ft.lbf)
4300+0.6gr	1120 (2050)	7.14	+0.05	2006 (291)	66	1.9	20 (15)
	1175 (2150)	7.16	+0.01	2103 (305)	67	2.2	23 (17)
	1260 (2300)	7.18	-0.11	2393 (347)	68	2.3	24 (18)

<u>ID</u>	<u>Temp</u> °C (°F)	<u>SD</u> g/cm ³	<u>DC</u> %	<u>TRS</u> MPa (10 ³ psi)	<u>Hard</u> HRA	<u>Elong</u> %	<u>Imp</u> J (ft.lbf)
4300L+0.6gr	1120 (2050)	7.13	+0.03	1903 (276)	62	2.4	20 (15)
	1175 (2150)	7.16	-0.06	2062 (299)	65	2.7	27 (20)
	1260 (2300)	7.17	-0.17	2193 (318)	66	2.8	37 (27)

<u>ID</u>	<u>Temp</u> °C (°F)	<u>SD</u> g/cm ³	<u>DC</u> %	<u>TRS</u> MPa (10 ³ psi)	<u>Hard</u> HRA	<u>Elong</u> %	<u>Imp</u> J (ft.lbf)
FD-0405	1120 (2050)	7.17	+0.01	1765 (256)	59	3.2	27 (20)
	1175 (2150)	7.19	-0.05	1875 (272)	61	3.3	30 (22)
	1260 (2300)	7.22	-0.23	1979 (287)	64	3.5	31 (23)

Effect of Cooling Rate at Conventional Sintering Temperatures

The previous section focused on properties at a conventional cooling rate over a range of sintering temperatures. This section highlights the effect of various cooling rates on mechanical properties at a conventional sintering temperature of 1120 °C (2050 °F).

Tables IV and V show mechanical properties at three cooling rates for 4300+0.6gr and 4300L+0.6gr, respectively. Both alloys performed well under accelerated cooling conditions, a result of the presence of high hardenability alloying ingredients Cr, Mo, Si, and Ni. Response to the accelerated cooling is greater for 4300 compared to 4300L because of the higher Mo content. However, given recent instability of Mo prices, the fact that 4300L+0.6gr at the fastest cooling rate can provide comparable properties to 4300+0.6gr at the conventional cooling rate may be extremely valuable to parts manufacturers.

Light optical photomicrographs of 4300+0.6gr at the three cooling rates are shown in Figure 3. The microstructures support the data shown in Table IV; i.e. 4300 is a highly hardenable alloy that consists of a fair amount of martensite even at a conventional cooling rate. At the fastest cooling rate, the microstructure of 4300+0.6gr is almost entirely martensitic.

Axial fatigue data for 4300+0.6gr are shown in Figure 4 at two cooling rates. For dynamic properties the alloy is also very responsive to the faster cooling rate, with an approximate increase of 10% in the fatigue endurance limit at 2.2°C/sec (4.0 °F/sec). The ratio of axial fatigue endurance limit to tensile strength was approximately 25%, consistent with what has typically been observed in the industry.

Table IV. Mechanical properties of 4300+0.6gr as a function of cooling rate at 1120 °C (2050 °F).

<u>Cool Rate</u> °C/sec (°F/sec)	<u>SD</u> g/cm ³	<u>DC</u> %	<u>Hard</u> HRA	<u>YS</u> MPa (10 ³ psi)	<u>UTS</u> MPa (10 ³ psi)	<u>Elong</u> %	<u>Imp</u> J (ft.lbf)
0.7 (1.3)	7.14	+0.05	66	752 (109)	1062 (154)	1.9	19 (14)
1.6 (2.8)	7.13	+0.08	69	896 (130)	1172 (170)	1.5	18 (13)
2.2 (4.0)	7.13	+0.09	71	1069 (155)	1241 (180)	1.3	15 (11)

Table V. Mechanical properties of 4300L+0.6gr as a function of cooling rate at 1120 °C (2050 °F).

<u>Cool Rate</u> °C/sec (°F/sec)	<u>SD</u> g/cm ³	<u>DC</u> %	<u>Hard</u> HRA	<u>YS</u> MPa (10 ³ psi)	<u>UTS</u> MPa (10 ³ psi)	<u>Elong</u> %	<u>Imp</u> J (ft.lbf)
0.7 (1.3)	7.13	+0.03	62	690 (100)	986 (143)	2.4	20 (15)
1.6 (2.8)	7.12	+0.07	65	738 (107)	1020 (148)	1.9	18 (13)
2.2 (4.0)	7.12	+0.08	67	827 (120)	1055 (153)	1.5	16 (12)

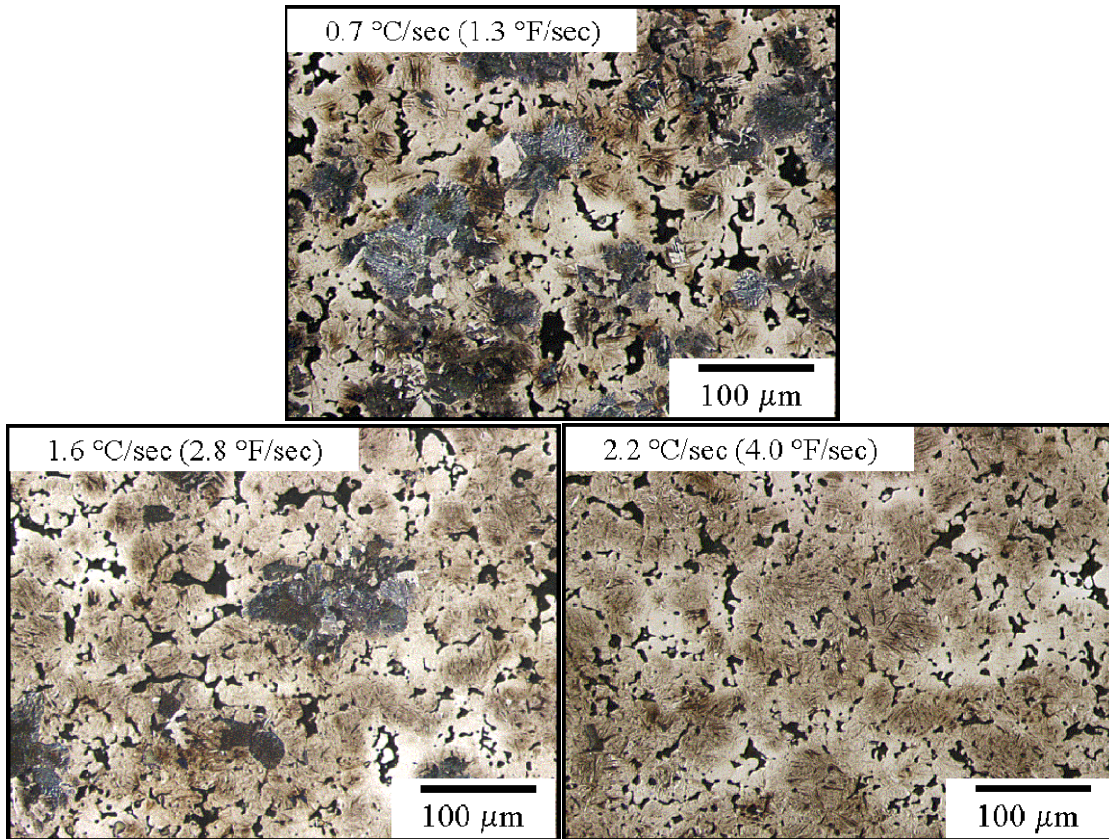


Figure 3. Light optical photomicrographs of 4300+0.6gr at various cooling rates, sintered at 1120 °C (2050 °F).

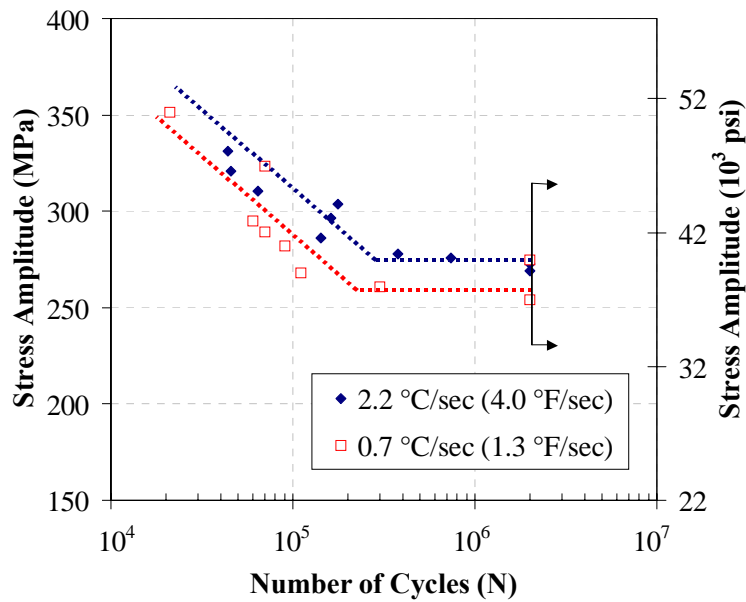


Figure 4. Axial fatigue S-N plot for 4300+0.6gr at two cooling rates, sintered at 1120 °C (2050 °F).

Effect of Ni Additions and Comparisons to Q&T Wrought Alloys

It is clear that the Cr steels offer intriguing performance capabilities relative to conventional materials such as FD-0405 at 1120 °C (2050 °F). When high temperature sintering is used, however, further oxide reduction and improved diffusion of Ni into the base powder can substantially enhance performance. Understandably, the recent rise of Ni prices could lend the addition of Ni powder to high performance Cr alloys to be cost-prohibitive. However, in an effort to be complete, data are presented here that may be worthwhile in the future should Ni prices return to their historical levels.

Shown in Table VI are mechanical properties at two sintering temperatures for 4300+0.6gr and additions of 0 to 2 wt.% for 4300L+0.6gr. Although Ni additions to the leaner Cr steel at conventional sintering temperatures improve properties, the benefit is compounded at higher sintering temperatures. At 1120 °C (2050 °F) the yield strength of 4300L is inferior to that of 4300 regardless of the amount of additional Ni up to 2 wt.%. When sintered at 1260 °C (2300 °F), however, only 1 wt.% additional Ni is required to match the performance of the 4300, and an addition of 2 wt.% provides superior properties. The relative economic benefit of the alloys will depend on fluctuations in the raw material prices of Ni and Mo, as noted above. Nonetheless, this table demonstrates that parts manufacturers can tailor the composition of the Cr steels to the desired performance level while still maintaining a cost-effective processing route for high performance components.

Table VI. Mechanical properties at two sintering temperatures, cooling rate of 0.7 °C/sec (1.3 °F/sec).

<u>Processing</u>	<u>Alloy</u>	<u>DC</u> <u>%</u>	<u>YS</u> <u>MPa</u> <u>(10³ psi)</u>	<u>UTS</u> <u>MPa</u> <u>(10³ psi)</u>	<u>Elong</u> <u>%</u>	<u>Hard</u> <u>HRA</u>
1120 °C (2050 °F)	4300+0.6gr	+0.05	752 (109)	1062 (154)	1.9	66
	4300L+0.6gr	+0.03	690 (100)	986 (143)	2.4	62
	4300L+0.6gr + 1% Ni	-0.04	676 (98)	1007 (146)	2.4	65
	4300L+0.6gr + 2% Ni	-0.12	696 (101)	1048 (152)	2.4	66
1260 °C (2300 °F)	4300+0.6gr	-0.11	814 (118)	1269 (184)	2.3	68
	4300L+0.6gr	-0.20	800 (116)	986 (143)	2.8	66
	4300L+0.6gr + 1% Ni	-0.21	827 (120)	1158 (168)	2.7	67
	4300L+0.6gr + 2% Ni	-0.25	910 (132)	1282 (186)	2.8	69

In order to truly understand the capabilities of high performance PM alloys, it is necessary to compare them to wrought alloys. A comparative analysis of the sinter-hardened PM Cr steels with Q&T wrought alloys is summarized in Table VI. In order to get maximum performance for the PM materials, the samples were sintered at 1260 °C (2300 °F) with a cooling rate of 2.2 °C/sec (4.0 °F/sec).

The most interesting aspect of these data is that both of the PM Cr steels have strength and hardness properties that match those of Q&T AISI 8620. The PM properties were generated at a density level of only 7.1 g/cm³, while the wrought samples were tested at a fully dense level of 7.8 g/cm³. Despite the difference in density of about 0.7 g/cm³, there was no sacrifice in strength or hardness with the PM material. The ability of the PM materials to achieve wrought property levels without any secondary heat-treatment or high density processing represents a significant achievement in the industry. This could potentially provide for further penetration of PM materials into components that are currently manufactured using wrought alloys.

Further improvement could be gained by using high density processing techniques. Combining high density processing of the PM Cr steels evaluated in this manuscript with high temperature sinter-hardening would likely provide static properties that are superior to that of Q&T AISI 8620 and approach those of Q&T AISI 4340.

Table VII. Comparison of sinter-hardened Cr steel properties to Q&T wrought alloys.

<u>Alloy</u>	<u>Processing Steps</u>	<u>Density</u> g/cm ³	<u>YS</u> MPa (10 ³ psi)	<u>UTS</u> MPa (10 ³ psi)	<u>Elong</u> %	<u>Hard</u> HRA
4300+0.6gr	Sinter-hardened at 1260 °C (2300 °F), 2.2 °C/sec (4.0 °F/sec)	7.1	1096 (159)	1489 (216)	2.5	70
4300L+0.6gr	Sinter-hardened at 1260 °C (2300 °F), 2.2 °C/sec (4.0 °F/sec)	7.1	1007 (146)	1393 (202)	2.4	70
AISI 8620	Q&T	7.8	1151 (167)	1420 (206)	10.8	71
AISI 4340	Q&T	7.8	1531 (222)	2006 (291)	10.4	76

CONCLUSIONS

The performance capabilities for Ancorsteels 4300 and 4300L were evaluated. Both alloys were proven viable at conventional sintering temperatures using a 30 minute time-at-temperature cycle, indicating a robust processing capability that is unique in the PM industry. Both alloys demonstrated superior mechanical properties compared to diffusion-alloyed grade FD-0405 at various temperatures. Notably, the Cr steels have significantly less alloying ingredients than FD-0405, critical in a time period of raw material price instability. The sinter-hardened PM Cr steels were found to provide static properties that are comparable to those achieved by Q&T wrought AISI 8620. By enabling the elimination of the majority of machining that is required when producing a component from a wrought alloy without sacrificing static performance, a significant cost advantage can be realized. The ability of a PM material to achieve wrought property levels without any secondary heat-treatment or high density processing is a significant step in enabling the PM industry to further penetrate high performance applications.

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