PERFORMANCE CAPABILITIES OF HIGH STRENGTH POWDER METALLURGY CHROMIUM STEELS WITH TWO DIFFERENT MOLYBDENUM CONTENTS

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ABSTRACT

The desire for advanced ferrous powder metallurgy materials has led to the development of alloys that simulate wrought steel compositions. A recently commercialized Cr-Si-Ni-Mo steel can be effectively sintered at conventional temperatures and provides good compressibility, high hardenability, and excellent dimensional stability while maintaining oxygen contents below 500 ppm. This alloy has demonstrated static and dynamic properties that exceed those of conventional powder metallurgy alloys and approach wrought gearing materials. A second Cr-Si-Ni-Mo alloy has now been developed to offer complimentary performance levels at a lower Mo content, while still providing excellent sinter-hardenability. The current work reviews static and dynamic properties of the two Cr steels with an emphasis on accelerated cooling rates after sintering at 1120 ºC (2050 ºF). Comparisons are made to traditional powder metallurgy materials processed in both the sinter-hardened and heat-treated conditions as well as to heat-treated wrought alloys.

INTRODUCTION

The use of wrought materials containing Cr and Si in high performance components is widespread because of improvements in hardenability and mechanical properties obtained at a modest cost. Both of these alloying elements have been used independently in a range of commercially available powder metallurgy (PM) materials, and have been found to dramatically improve performance capabilities [1-3]. Because Cr and Si tend to form stable oxides, PM alloys containing either of these elements have traditionally been sintered above 1205 °C (2200 °F) to avoid the adverse effects of oxygen on mechanical properties [4-5]. Given the recent instability of raw material prices, it is advantageous to develop alloys that utilize the benefits of Si and Cr in one system and have the ability to be effectively sintered at conventional temperatures.

A recently commercialized Cr-Si-Ni-Mo PM steel, Ancorsteel® 4300, was specifically engineered to simulate wrought steel compositions and counteract the oxygen-related problems that are associated with Cr and Si. This alloy is available as a binder-treated system and has a nominal chemistry of 1.0 Cr, 0.6 Si, 1.0 Ni, and 0.8 Mo (wt.%). Under a typical reducing furnace atmosphere of $90N_2$-$10H_2$ (vol.%), it provides sintered oxygen contents below 500 ppm at 1120 °C (2050 °F), which helps maximize the performance of the alloy by enabling full use of alloying elements [6]. Other advantages of this alloy

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include good compressibility, high hardenability, and exceptional dimensional stability under a variety of processing conditions.

The simulation of 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. Combining Cr and Si within one system provides attractive strength, hardenability, and fatigue levels without the need for secondary quench treatments. The total alloy content in the PM steel was engineered to optimize high performance and compressibility. As a result, this system provides single-pressed green densities above 7.0 g/cm^3 at 550 MPa (40 tsi) using room temperature compaction [7]. Such a unique combination of properties provides a cost-effective solution for potential placement in a wide range of applications, including wrought steel components, high temperature sintered components, double-pressed components, and quench or induction hardened parts.

The trade name for this PM steel was derived from AISI 4340, a common wrought Cr steel familiar to many part designers in the automotive industry. It is the first in a series of alloys that will mimic wrought steel compositions and provide high performance capabilities. A second Cr-Si-Ni-Mo alloy has now been 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. Table I shows 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 [8].

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

ID	Fe	Cr	Si	Ni	Mo	Mn	C
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	-
4300-modified	Bal.	1.0	0.6	1.0	0.3	0.1	-

One of the noticeable differences between wrought materials and PM steels is the use of Mo as a dominant alloying element. Mo has been used widely as a prealloyed element for two decades because of its large effect on hardenability. Figure 1 shows a plot of hardenability factor for various elements as a function of percentage alloying content [9]. Mo has by far the greatest contribution to hardenability of the elements shown. 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 the two alloying elements has previously been exploited in PM sinter-hardening grades such as FLNC-4408 [10]. It was also the basis for the development of the two Cr steels. By employing at least 0.75 wt.% Ni in both of the alloys, maximum hardenability was achieved while being able to simultaneously maintain lean and compressible alloy systems. Alloys containing Cr and Mo that are Ni-free do not achieve the full benefit in hardenability that can be gained from the presence of Mo.

[§] 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.

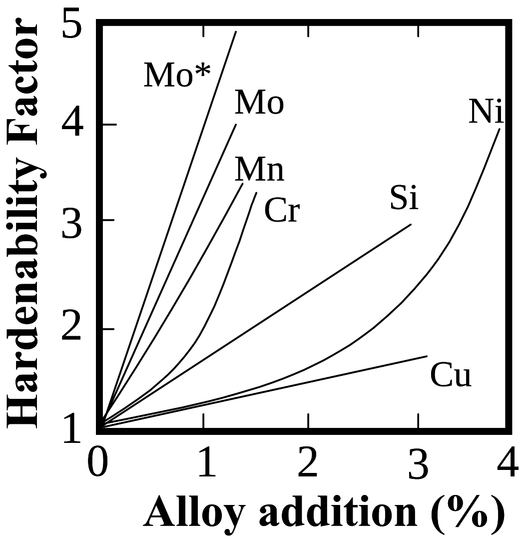

Figure 1. Hardenability factors for various prealloyed elements [9].
Mo* is the hardenability factor of Mo when Ni is > 0.75 wt.%.

The objective of this study is to investigate the performance capabilities of the two Cr PM steels under both standard cooling and sinter-hardening conditions. Comparisons of these data are made to: 1) PM materials FD-0408 and FLNC-4408 processed under sinter-hardening conditions, and 2) PM material FLN2-4405 and wrought AISI 8620 and 4340 subjected to oil quenching and tempering. All PM materials are compared at identical density levels to eliminate the role of porosity in performance comparisons. Both static and dynamic (axial fatigue) properties are presented. Although the focus of this paper is on processing high performance PM materials at 1120 °C (2050 °F), several data sets are also presented at 1260 °C (2300 °F).

EXPERIMENTAL PROCEDURE

Pilot scale mixes of the Cr steels were made with 0.6 wt.% graphite (Cr-Si-Ni-Mo-1 and Cr-Si-Ni-Mo-2). Similar premixes were made for diffusion-alloyed FD-0408 and hybrid alloy FLNC-4408 with 0.8 wt.% graphite to serve as sinter-hardening reference compositions. An FLN2-4405 binder-treated premix was produced with 0.6 wt.% graphite to obtain Q&T PM properties. All PM mixes were made from commercially available powders and contained 0.75 wt.% Acrawax C as a lubricant. Asbury 3203H graphite, Alcan 8081 Cu, and Inco 123 Ni were used as respective elemental additions. Standard bar stock of AISI wrought grades 8620 and 4340 were used to acquire Q&T wrought properties. Table II provides a comparison of the nominal compositions for the seven alloys.

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

Alloy #	**Designation**[♣]	**Cr**	**Si**	**Ni**	**Mo**	**Mn**	**Cu**	**C**
1	Cr-Si-Ni-Mo-1	1.0	0.6	1.0	0.8	0.1	-	0.6
2	Cr-Si-Ni-Mo-2	1.0	0.6	1.0	0.3	0.1	-	0.6
3	FD-0408	-	-	4.0	0.5	0.1	1.5	0.8
4	FLNC-4408	-	-	2.0	0.8	0.1	2.0	0.8
5	FLN2-4405	-	-	2.0	0.8	0.1	-	0.6
6	AISI 8620	0.5	0.2	0.5	0.2	0.8	-	0.2
7	AISI 4340	0.8	0.2	1.8	0.2	0.8	-	0.4

Laboratory test specimens were room temperature compacted for the PM materials to achieve nominal green densities of 7.1 g/cm^3. The compaction pressures required to obtain this density level ranged from 605 to 690 MPa (44 to 50 tsi). Sintering was conducted for 30 minutes time-at-temperature in an Abbott belt furnace using an atmosphere of $90N_2$-$10H_2$ (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 attached to the rear of the furnace: 0.7, 1.6, and 2.2 °C/sec (1.3, 2.8, and 4.0 °F/sec). Alloys 5-7 were austenitized at 900 °C (1650 °F) for 30 minutes in $25N_2$-$75H_2$ (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 [11]. Impact testing was conducted for the PM materials at room temperature on unnotched Charpy samples.

RESULTS AND DISCUSSION

Comparisons of PM Cr Steels to Sinter-Hardening PM Alloys

Plots of yield strength, tensile strength, and apparent hardness are shown in Figure 2 for alloys 1-4 sintered at 1120 °C (2050 °F) and cooled at various rates. Both FLNC-4408 and FD-0408 are considered high performance materials and are used fairly extensively in industry. Nonetheless, the more highly alloyed Cr steel, Cr-Si-Ni-Mo-1, has superior mechanical properties compared to all of the other alloys evaluated under these conditions. Over the three cooling rates studied, Cr-Si-Ni-Mo-1 provided on average 20% higher yield strength, 10% higher tensile strength, and 3-5 HRC higher apparent hardness compared to FLNC-4408. Likewise, this Cr steel had 60% higher yield strength, 30% higher tensile strength, and 10-12 HRC higher apparent hardness versus diffusion-alloyed FD-0408.

[♣] Base alloys used for the PM reference mixes were Distaloy 4800A for FD-0408 and Ancorsteel 85 HP for FLNC-4408 and FLN2-4405.

Also interesting to note from Figure 2 is that Cr-Si-Ni-Mo-2 provides comparable performance versus FLNC-4408 and superior performance versus FD-0408. In all three plots, there exists a crossover in properties between the faster cooling rates for Cr-Si-Ni-Mo-2 and FLNC-4408. The Cr steel is more responsive to the accelerated cooling because of the hardenability-enhancing effects of Cr and Si.

Photomicrographs of the four alloys under the most rapid cooling rate of 2.2 °C/sec (4.0 °F/sec) are shown in Figure 3. Cr-Si-Ni-Mo-1 contains approximately 90% martensite and 10% bainite, which correlates well with it having the highest yield strength and hardness. FLNC-4408 and Cr-Si-Ni-Mo-2 both contain about 60% martensite and 40% bainite. FD-0408, which had the lowest yield strength and apparent hardness at all cooling rates, is the only alloy that contains pearlite in its microstructure. As a result, it had significantly lower strength and apparent hardness compared to the other alloys.

Axial fatigue data for Cr-Si-Ni-Mo-1 and FD-0408 are summarized in Figure 4. At the fastest cooling rate, the Cr steel has significantly higher fatigue performance. More noteworthy, however, is that the Cr steel cooled at a conventional rate of 0.7 °C/sec (1.3 °F/sec) provides a higher fatigue limit than FD-0408 sinter-hardened at 2.2 °C/sec (4.0 °F/sec) due to the formation of more martensite.

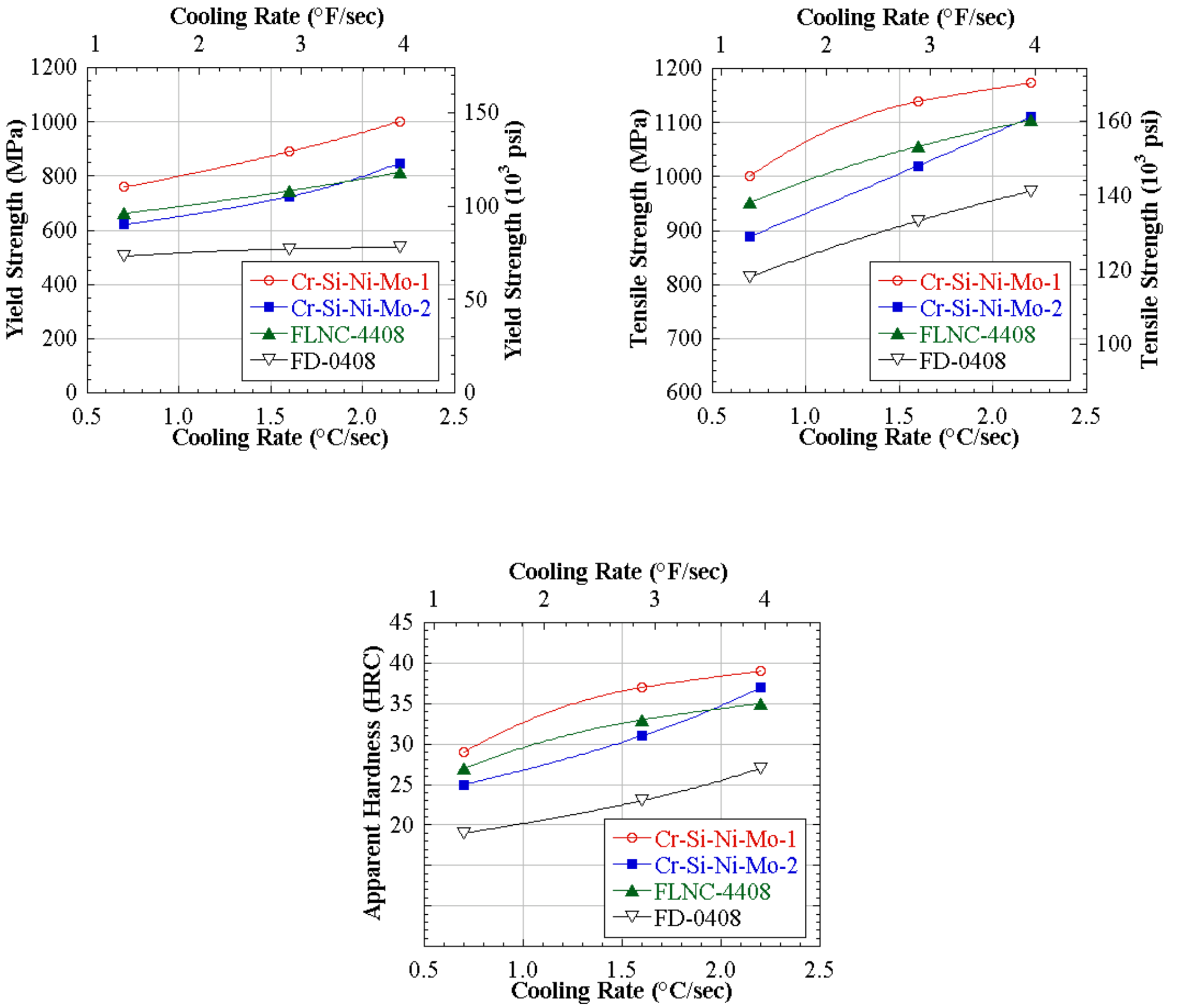

Figure 2. Mechanical properties as a function of cooling rate for samples sintered at 1120 °C (2050 °F).

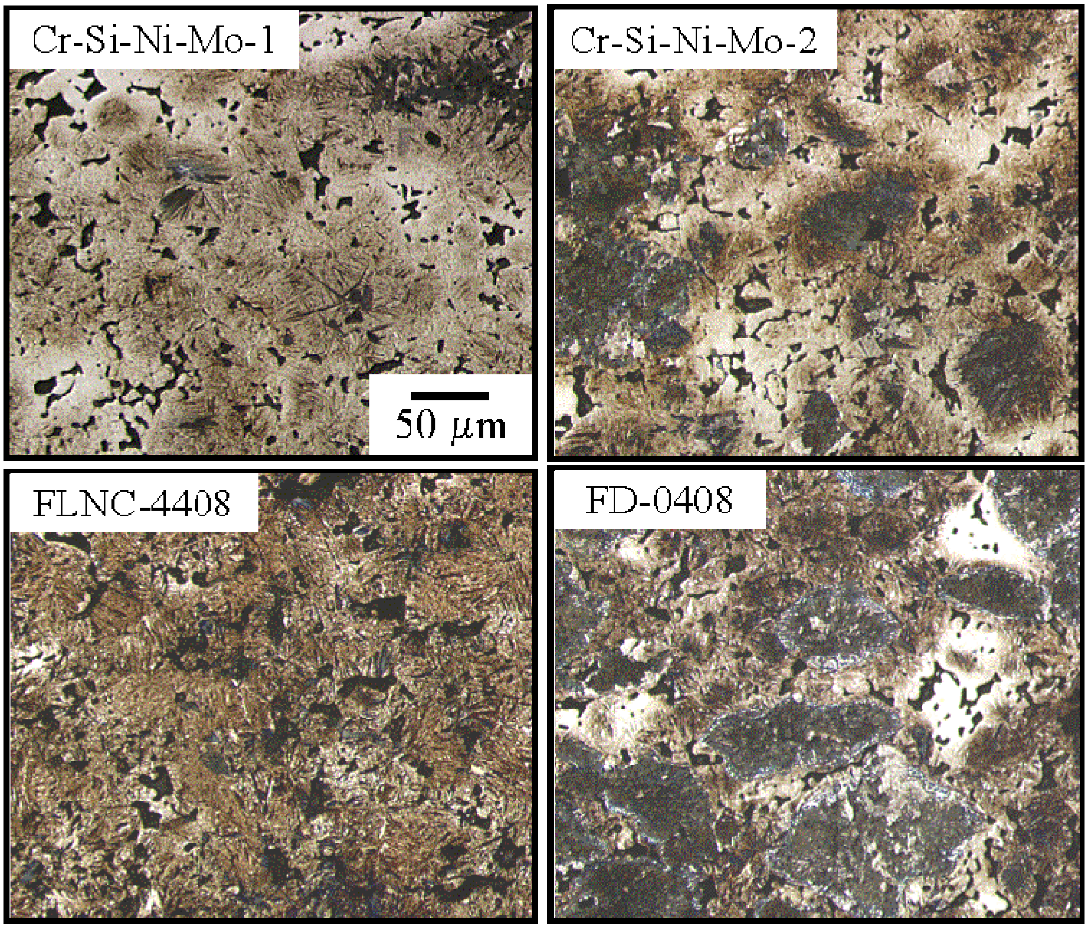

Figure 3. Photomicrographs for samples sintered at 1120 °C (2050 °F) and cooled at 2.2 °C/sec (4.0 °F/sec). All images are displayed at identical magnification.

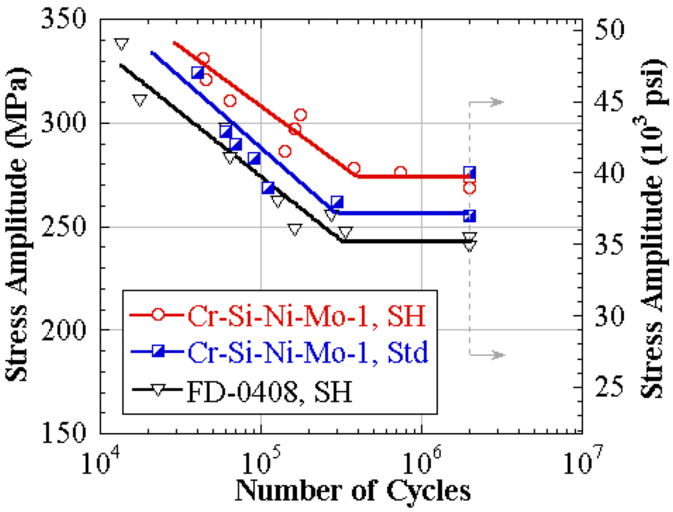

Figure 4. Stress amplitude vs. number of cycles for axial fatigue data generated from samples sintered at 1120 °C (2050 °F). Testing in load control, R = –1, 40 Hz, runout = 2 x 10^6 cycles. SH denotes sinter-hardening at 2.2 °C/sec (4.0 °F/sec) while Std indicates standard cooling at 0.7 °C/sec (1.3 °F/sec).

Effect of Sintering Temperature and Ni Additions on PM Cr Steel Performance

From the previous section, it is clear that the Cr steels offer intriguing performance capabilities relative to conventional sinter-hardening materials such as FLNC-4408 and FD-0408 at 1120 °C (2050 °F). The ability to effectively sinter Cr steels at conventional temperatures is a noteworthy attribute, and enables both of these alloys to be used in a wider variety of manufacturing settings. However, it has been found previously that the performance of these steels can be further improved through high temperature sintering [6]. When high temperature sintering is used, further oxide reduction and improved diffusion of Ni into the base powder can substantially enhance performance.

Shown in Table III are mechanical properties at two sintering temperatures for Cr-Si-Ni-Mo-1 and Ni additions of 0 to 2 wt.% for Cr-Si-Ni-Mo-2. 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 Cr-Si-Ni-Mo-2 is inferior to that of Cr-Si-Ni-Mo-1 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 Cr-Si-Ni-Mo-1, 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. 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 III. Mechanical properties at two sintering temperatures, cooling rate of 0.7 °C/sec (1.3 °F/sec).

Processing	**Alloy**	**DC (%)**	**YS MPa (10^3 psi)**	**UTS MPa (10^3 psi)**	**Elong (%)**	**Hard (HRC)**
1120 °C (2050 °F)	Cr-Si-Ni-Mo-1	+0.07	758 (110)	1007 (145)	1.7	31
	Cr-Si-Ni-Mo-2 + 0% Ni	+0.03	621 (90)	889 (129)	2.1	24
	Cr-Si-Ni-Mo-2 + 1% Ni	–0.04	676 (98)	1007 (146)	2.4	29
	Cr-Si-Ni-Mo-2 + 2% Ni	–0.12	696 (101)	1048 (152)	2.4	31
1260 °C (2300 °F)	Cr-Si-Ni-Mo-1	–0.11	821 (119)	1145 (166)	2.5	33
	Cr-Si-Ni-Mo-2 + 0% Ni	–0.20	669 (97)	965 (140)	3.1	25
	Cr-Si-Ni-Mo-2 + 1% Ni	–0.21	827 (120)	1158 (168)	2.7	31
	Cr-Si-Ni-Mo-2 + 2% Ni	–0.25	910 (132)	1282 (186)	2.8	37

The 2 wt.% Ni addition to Cr-Si-Ni-Mo-2 helps offset the lower hardenability of this alloy when cooled at conventional rates at 1260 °C (2300 °F). When combining high temperature sintering and accelerated cooling, however, the benefit of the additional Ni is reduced. Shown in Table IV is a comparison of the different Cr steels at a cooling rate of 2.2 °C/sec (4.0 °F/sec). With no additional Ni, the leaner Cr steel provides strength levels about 10% lower than the more highly alloyed Cr steel using sinter-hardening conditions, whereas under conventional cooling the difference was greater than 20%. This demonstrates further ability for a parts manufacturer to tailor their properties with the Cr steels by choosing the most cost-effective alloy system and processing combination.

Table IV. Mechanical properties at 1260 °C (2300 °F), cooling rate of 2.2 °C/sec (4.0 °F/sec).

Alloy	**YS MPa (10^3 psi)**	**UTS MPa (10^3 psi)**	**Elong (%)**	**Hard (HRC)**
Cr-Si-Ni-Mo-1	1096 (159)	1489 (216)	2.5	41
Cr-Si-Ni-Mo-2	1007 (146)	1393 (202)	2.4	41

Comparison of PM Cr Steels to Q&T PM Alloys

The previous two sections demonstrated that the Cr steels offer attractive performance capabilities in the sinter-hardened condition. Cr-Si-Ni-Mo-2, with a Mo content of 0.3 wt.%, offers a significant cost advantage over higher alloyed sinter-hardening materials such as FLNC-4408 and FD-0408, particularly given the recent instability of Mo raw material prices. The primary advantage of both of the Cr steels is that they offer excellent properties in the one-step sinter-hardening condition, as opposed to an oil quench process that requires a secondary operation after sintering.

Table V shows a comparison of the Cr steels processed at the fastest cooling rate with FLN2-4405 samples subjected to a separate Q&T process. The nearly 100% martensitic microstructure in the sinter-hardened condition for Cr-Si-Ni-Mo-1 provides properties that are equivalent to Q&T FLN2-4405. With essentially the same Mo content in Cr-Si-Ni-Mo-1 and FLN2-4405, this provides a significant cost advantage when processing the Cr steel by achieving the performance capabilities all within a single step. Material handling costs that can be incurred by heat-treating FLN2-4405 can be foregone by designing a component with a high performance sinter-hardening grade. Additionally, the reduced severity of sinter-hardening cooling relative to that of oil quenching promotes improved dimensional control. Previous work has shown that Cr-Si-Ni-Mo-1 has equivalent dimensional stability compared to FD-040x alloys, widely considered to be among the most dimensionally stable alloys in the industry [6,7]. Combining the improved dimensional control inherent in both the alloy and the processing route can lead to a significantly lower scrap frequency in part manufacturing.

As mentioned in the previous section, Cr-Si-Ni-Mo-2 does not form a fully martensitic microstructure at 1120 °C (2050 °F) even when cooled at a rate of 2.2 °C/sec (4.0 °F/sec). The alloy is still fairly hardenable, however, and provides a yield strength only about 20% lower than that of oil quenched FLN2-4405. It is important to consider the significant cost advantages that can be obtained by processing a Cr steel with only 0.3 wt.% Mo via a one-step sinter-hardening process. Because FLN2-4405 does not have high hardenability despite containing 0.8 wt.% Mo, it cannot be effectively sinter-hardened, and must be processed via secondary heat-treat operations. As a result, components manufactured with Q&T FLN2-4405 may be over-engineered in some instances. The actual requisite properties might lie somewhere between those achieved in the fastest sinter-hardening conditions and those achieved by the much more rapid oil quench. It is therefore reasonable to infer that the properties obtained by sinter-hardening Cr-Si-Ni-Mo-2 may be sufficient for some applications currently using Q&T FLN2-4405. In most situations this would enable an economically superior route for achieving the desired properties in high performance components.

Table V. Comparison of sinter-hardened Cr steel properties to Q&T FLN2-4405 at 1120 °C (2050° F).

Alloy	**Processing Steps**	**YS MPa (10^3 psi)**	**UTS MPa (10^3 psi)**	**Elong (%)**	**Hard (HRC)**
Cr-Si-Ni-Mo-1	Sinter-hardened at 2.2 °C/sec (4.0 °F/sec)	1001 (145)	1173 (170)	1.4	39
Cr-Si-Ni-Mo-2	Sinter-hardened at 2.2 °C/sec (4.0 °F/sec)	848 (123)	1110 (161)	1.7	37
FLN2-4405	Separate Q&T	1038 (151)	1165 (169)	1.3	39

Comparison of PM Cr Steels to Q&T Wrought Alloys

In the previous sections, the PM Cr steels have only been compared to other PM alloys. It has been shown that Cr-Si-Ni-Mo-1 is superior to other sinter-hardening grades and provides equivalent properties to Q&T PM alloys. The leaner Cr steel also provides attractive sinter-hardening properties and may be a cost-effective alternative to the replacement of either sinter-hardened PM steels or Q&T PM steels. Further penetration of PM systems into high performance components requires a better understanding of the performance capabilities of PM steels relative to wrought alloys. A comparative analysis of the sinter-hardened PM Cr steels with Q&T wrought alloys is summarized in Table VI.

The most striking feature of these data is that both of the PM Cr steels have strength and hardness properties that match those of Q&T AISI 8620. It is important to note that the PM properties were generated at a density level of only 7.1 g/cm^3, while the wrought samples were tested at a fully dense level of 7.8 g/cm^3. Despite the difference in density of about 0.7 g/cm^3, 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.

The relatively high compressibility of the two Cr-Si-Ni-Mo alloys makes them suitable for high density processing, e.g. die-heating technology or a combination of die heating and powder heating. Indeed it has been shown in prior work that a density level of 7.3 g/cm^3 can be achieved with Cr-Si-Ni-Mo-1 using die heating, an engineered lubricant/binder system, and an 1150 °C (2100 °F) sintering temperature [12]. In that work, it was observed that a significant gain in static properties is realized by increasing the density from 7.1 to 7.3 g/cm^3. 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. Furthermore, such a combination of alloy selection and high technology processing could enable properties that approach those that were obtained with Q&T AISI 4340.

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

Alloy	Processing Steps	Density (g/cm^3)	YS MPa (10^3 psi)	UTS MPa (10^3 psi)	Elong (%)	Hard (HRC)
Cr-Si-Ni-Mo-1	Sinter-hardened at 1260 °C (2300 °F), 2.2 °C/sec (4.0 °F/sec)	7.1	1096 (159)	1489 (216)	2.5	41
Cr-Si-Ni-Mo-2	Sinter-hardened at 1260 °C (2300 °F), 2.2 °C/sec (4.0 °F/sec)	7.1	1007 (146)	1393 (202)	2.4	41
AISI 8620	Q&T	7.8	1151 (167)	1420 (206)	10.8	42
AISI 4340	Q&T	7.8	1531 (222)	2006 (291)	10.4	50

CONCLUSIONS

The performance capabilities for two PM Cr-Si-Ni-Mo steels with Mo contents of 0.3 and 0.8 wt.% were evaluated. Each of these alloys were proven viable at conventional sintering temperatures, i.e. 1120 °C (2050 °F), indicating a robust processing capability that is unique in the PM industry. Both alloys demonstrated superior mechanical properties compared to diffusion-alloyed grade FD-0408 under various cooling rates. The leaner Cr steel also provided equivalent properties to sinter-hardening grade FLNC-4408 (0.8 wt.% Mo), which represents a significant cost advantage due to recent instability in Mo prices. The more highly alloyed Cr steel provided static properties in the sinter-hardening condition that were equivalent to Q&T FLN2-4405. This too indicates a significant economic advantage by removing the secondary operation required with the FLN2-4405 material as well as improving dimensional control by eliminating the severity of the oil quench. Lastly, 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 represents a breakthrough in the industry.

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