Chromium Containing Materials for High Strength-High Fatigue Applications

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As the use of P/M in advanced applications continues to grow, the industry continues to encounter increasing demands for high strength-high fatigue alloys. Ancorsteel 4300, a developmental alloy, has been engineered for high performance applications and employs the use of silicon, chromium, and molybdenum. This alloy will be the first in a new line of engineered high performance binder-treated products that simulate wrought steel compositions and can be processed at conventional sintering temperatures. Advanced fabrication techniques prevent the alloy from being susceptible to the common oxygen-related problems that are often seen with chromium-containing P/M materials. The presence of chromium and silicon with a low oxygen content serves to increase hardenability, strength, and fatigue life. This manuscript presents the effects of compaction pressure, cooling rate, and sintering temperature on the performance of the developmental alloy.

Introduction

Powder manufacturers have accelerated the drive to develop advanced material systems as a response to the marketplace in recent years. The use of silicon has been shown to provide enhanced property combinations at high sintering temperatures [1,2]. These properties, achieved in the single press / single sinter condition, were previously only possible in ferrous P/M by using expensive double press / double sinter or secondary thermal processing.

The advantages of using chromium-containing P/M materials have traditionally been hindered by the necessity to reduce oxides at high sintering temperatures. A new developmental alloy system - Ancorsteel® 4300* - was engineered to counteract the common oxygen-related problems that are associated with the presence of chromium. This binder-treated alloy has a nominal composition of 1.0 wt.% Cr, 1.0 wt.% Ni, 0.8 wt.% Mo, and 0.6 wt.% Si.

By combining chromium and silicon within one system, the alloy provides attractive strength, hardenability, fatigue, and toughness characteristics without the need for expensive secondary thermal treatments. The advanced processing route of this system provides a low oxygen level and enables for processing in conventional belt furnaces at a temperature of 1120 °C. The current work summarizes the effects of compaction pressure, furnace cooling rate, and sintering temperature on mechanical properties of this high performance alloy system.

®Ancorsteel is a registered trademark of Hoeganaes Corporation. *Ancorsteel 4300 is a developmental alloy and was not commercially available as of the manuscript submission date.

Experimental Procedure

Premixes of hybrid alloy FLN4-4405 and diffusion alloyed FD-0405 were prepared to serve as reference compositions for Ancorsteel 4300. All three mixes contained 0.75 wt.% total organic and 0.6 wt.% graphite. Nominal chemistries of the alloys are shown in Table I. It is important to note that 4300 is a much leaner alloy than both of the reference compositions.

Table I. Nominal compositions of the alloys. All mixes had 0.6 wt.% admixed graphite.

ID	Fe (wt.%)	Mo (wt.%)	Cr (wt.%)	Si (wt.%)	Ni (wt.%)	Cu (wt.%)	Total Alloy (wt.%)
4300	Bal.	0.8	1.0	0.6	1.0	-	3.4
FLN4-4405	Bal.	0.8	-	-	4.0	-	4.8
FD-0405	Bal.	0.5	-	-	4.0	1.5	6.0

Transverse rupture, tensile, and impact samples were compacted at room temperature using pressures of 415 to 830 MPa. After compaction, the test pieces were sintered for 30 minutes in an Abbott belt furnace at 1120 °C in an atmosphere of $90N_2$-$10H_2$ (vol.%) with a dew point of -40 °C. The furnace is equipped with a variable convection-cooling unit that was also used to examine the sinter-hardening behavior of the new alloy. All samples were stress-relieved after sintering for 1 hour at 205 °C in nitrogen.

Testing of transverse rupture, tensile, and impact specimens followed standard MPIF procedures [3]. Rotating bending fatigue data were acquired for 4300 at a nominal density of 7.15 g/cm^3 at 8,000 rpm with a prescribed limit of 10^7 cycles. The median fatigue endurance limits (50% FEL) were calculated by using the "staircase" method [4] until there were failures and runouts at two stress levels. These data were not yet complete at the time of publication.

Results and Discussion

A compressibility plot of the materials is shown in Figure 1 (a). These densities were obtained from transverse rupture samples that included 0.6 wt.% graphite and 0.75 wt.% organic additions. Chromium and silicon reduce the green density slightly compared to the two reference materials. The compressibility of the developmental alloy, however, is better than many existing Cr-bearing P/M alloys. Densities after sintering are shown in Figure 1 (b). The large amount of nickel in FLN4-4405 causes shrinkage during sintering and leads to enhanced densification. Since the Cr-containing alloy is close to die-size after sintering, the sintered densities in this alloy are very similar to the green densities.

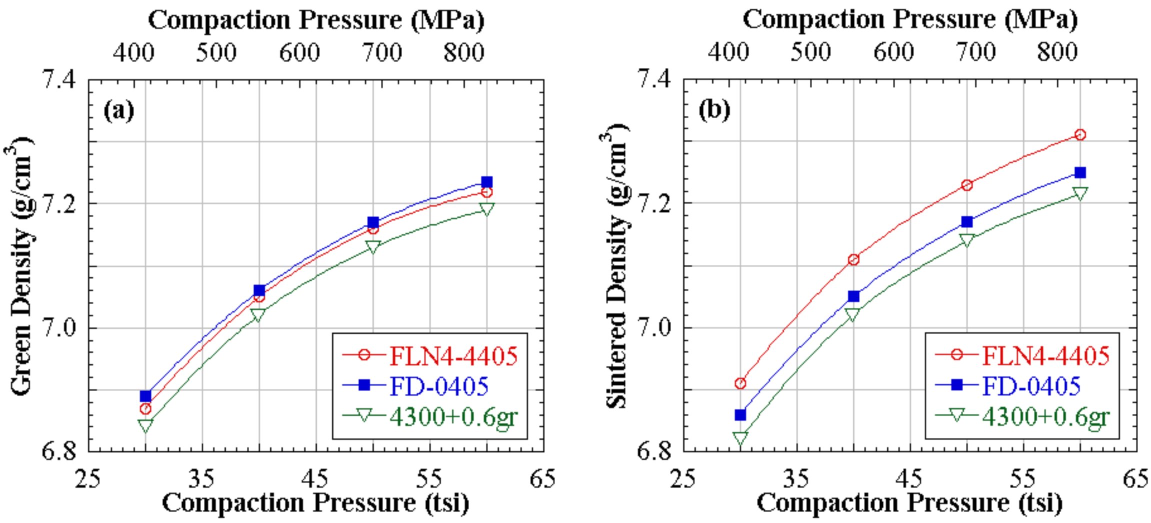

Figure 1. Plots of (a) green density and (b) sintered density of samples sintered for 30 minutes at 1120 °C in $90N_2$-$10H_2$ and stress-relieved for 1 h in nitrogen at 205 °C.

Ancorsteel 4300 is very dimensionally stable as a function of compaction pressure and graphite content, as shown in Figure 2 (a) and (b), respectively. The stability of this alloy under varying processing conditions and carbon levels allows for possible improvements in part-to-part variability in a manufacturing setting.

Shown in Figure 3 are the effects of compaction pressure on apparent hardness, yield strength, and tensile strength. A modest average cooling rate of 0.7 °C/sec as measured from 650 to 315 °C was used to produce these data. The most striking feature in these graphs is that 4300, though it is much leaner in total alloy content than both FLN4-4405 and FD-0405, has superior hardness and strength. The presence of the chromium and silicon is clearly a dominant contributor to the improvement in properties, and overrides the differences in sintered densities between the materials.

Though both chromium and silicon have a high affinity for oxygen, the advanced processing route of 4300 allows for sintering at conventional temperatures without worry of high oxygen levels degrading the properties. Sintered chemistries are shown in Table II for the three alloys. The Ancorsteel 4300 oxygen content of 0.05 wt.% (500 ppm) at 1120 °C is much lower than other Cr-bearing P/M alloys reported in the literature under similar processing conditions [5]. With a low oxygen presence, the level of chromium and silicon that is tied up in the form of oxides is significantly reduced. This enables more use of the chromium and silicon alloying, which results in the attractive property combinations that make this alloy ideal for high performance applications.

The effect of cooling rate on 4300 properties is shown in Table III. An average cooling rate of 1.6 °C/sec was achieved from 650 to 315 °C using the convection unit attached to the furnace. The fast cooling rate increased the amount of martensite, which significantly increased the yield strength, tensile strength, and hardness. Despite these high strengths, the alloy still maintained relatively good ductility and impact energy. Micrographs of 4300 detailing the difference in martensite content for the two cooling rates are shown in Figure 4.

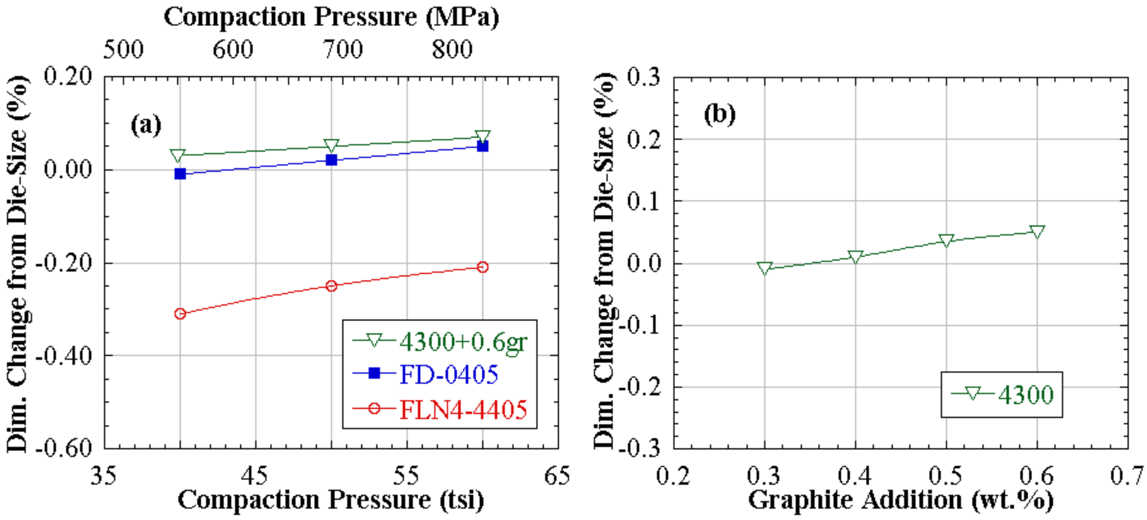

Figure 2. Net dimensional change versus (a) compaction pressure and (b) graphite content at 690 MPa for samples sintered at 1120 °C for 30 minutes in $90N_2$-$10H_2$.

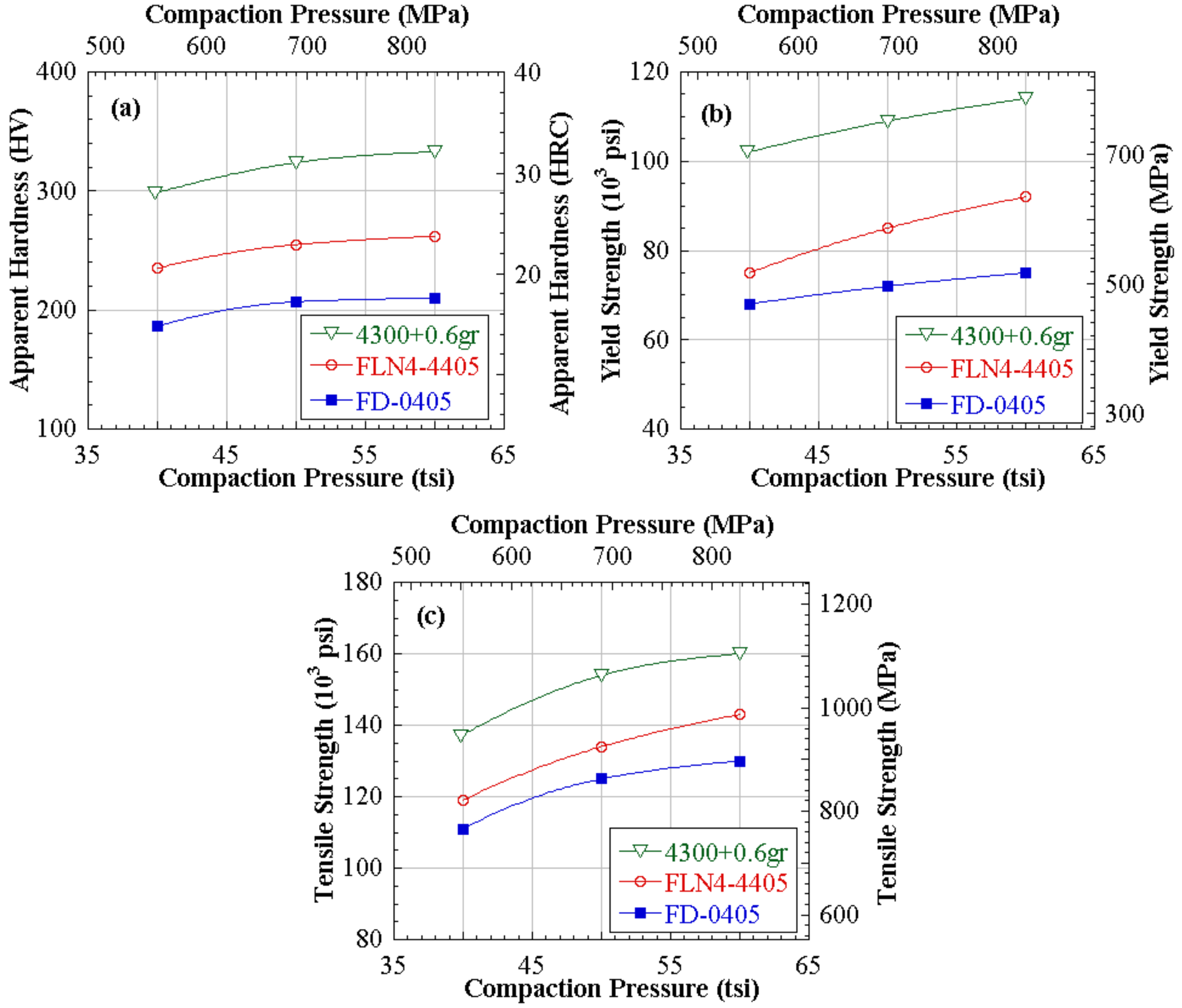

Figure 3. Plots of (a) apparent hardness, (b) yield strength, and (c) tensile strength sintered at 1120 °C in $90N_2$-$10H_2$ for 30 minutes with an average cooling rate of 0.7 °C/sec. Samples were stress-relieved for 1 h in nitrogen at 205 °C.

Table II. Sintered chemistries for samples pressed at 690 MPa and sintered at 1120 °C in $90N_2$-$10H_2$ for 30 minutes. Stress-relieved for 1 h in nitrogen at 205 °C after sintering.

ID	C (wt.%)	S (wt.%)	O_2 (wt.%)	N_2 (wt.%)
4300+0.6gr	0.57	0.005	0.05	0.03
FLN4-4405	0.56	0.004	0.02	0.03
FD-0405	0.56	0.004	0.02	0.03

Table III. Mechanical properties for 4300+0.6gr compacted at 690 MPa sintered at 1120 °C for 30 minutes in $90N_2$-$10H_2$ at two cooling rates. Stress-relieved at 205 °C for 1 h in N_2.

Average Cooling Rate (°C/sec)	SD (g/cm^3)	DC (%)	YS (MPa)	UTS (MPa)	Elg (%)	Imp (J)	App. Hard (HV / HRC)
0.7	7.14	0.05	750	1060	1.9	20	325 / 33
1.6	7.14	0.07	910	1160	1.5	18	385 / 39

The effect of sintering temperature on the performance of Ancorsteel 4300 is shown in Table IV using the standard cooling rate of 0.7 °C/sec. Though it is advocated to sinter at 1120 °C, these data clearly show that high temperature sintering of this alloy can lead to further enhanced properties. Also interesting to note is the dimensional stability as a function of sintering temperature. The ability to reproduce parts under a variety of sintering conditions is a tribute to the robust nature of this alloy system.

Ancorsteel 4300 is a unique alloy that offers a cost-effective solution for high performance applications. By achieving good property combinations through single press / single sinter processing of this alloy, significant cost savings can be attained by eliminating expensive secondary thermal treatments. Low oxygen contents at conventional sintering temperatures allow for the improved performance of this system. The capability of sintering this system at 1120 °C creates a considerable processing advantage compared to other Cr-bearing P/M materials that require sintering temperatures of 1200 °C or greater to reduce the oxygen content below 0.10 wt.%.

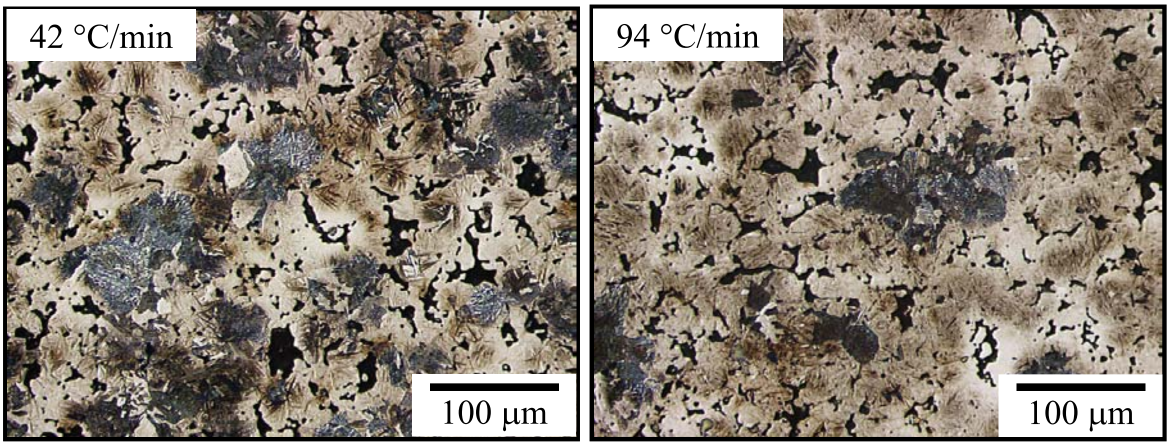

Figure 4. Representative micrographs of 4300+0.6gr after sintering at 1120 °C with two cooling rates in 90N_2-10H_2. Stress-relieved for 1 h in N_2 at 205 °C. Densities ~ 7.14 g/cm^3.

Table IV. Mechanical properties for 4300+0.6gr compacted at 690 MPa sintered at various sintering temperatures for 30 minutes in 90N_2-10H_2. Stress-relieved at 205 °C for 1 h in N_2.

Temp (°C)	**SD (g/cm^3)**	**DC (%)**	**YS (MPa)**	**UTS (MPa)**	**Elg (%)**	**Imp (J)**	**App. Hard (HV / HRC)**
1120	7.14	+0.05	750	1060	1.9	20	325 / 33
1150	7.14	+0.03	765	1105	2.0	22	325 / 33
1175	7.16	+0.01	780	1140	2.2	23	325 / 33
1260	7.18	–0.11	815	1270	2.3	24	345 / 35

Conclusions

The performance of a developmental high performance alloy system containing chromium and silicon was evaluated, and compared to hybrid alloy FLN4-4405 and diffusion alloyed FD-0405. Ancorsteel 4300 is a binder-treated alloy that simulates wrought steel compositions and can be processed at conventional sintering temperatures and maintains low oxygen levels. The alloy displayed exceptional single press / single sinter properties at 1120 °C, a result of sintered oxygen levels of 500 ppm. These exceptional properties without the need for secondary thermal treatments make 4300 an economic alternative for high performance applications. Good compressibility, near die-size response after sintering, and dimensional stability with respect to graphite content, compaction pressure, and sintering conditions make this system attractive from a processing standpoint. Tensile strengths > 1000 MPa, yield strengths above 700 MPa, and apparent hardnesses of 33 HRC (325 HV) with good ductility and impact properties were achieved at a 7.14 g/cm^3 density using a cooling rate of 0.7 °C/sec.

Acknowledgements

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