

Vanadium and Silicon Alloyed PM Steels

Bruce Lindsley, Chris Schade and Thomas Murphy

Hoeganaes Corporation
1001 Taylors Lane
Cinnaminson, NJ 08077 USA

Abstract

Alternative alloying systems for ferrous PM are being developed to address price, environmental and recyclability concerns. Non-traditional PM alloying elements, such as Cr, Mn, Si and V, are being used in place of Mo, Ni and Cu. The mechanical properties and microstructure of PM steels alloyed Si and V have been explored. In the as-sintered condition, Si and V were found to refine the microstructure and strengthen the steel, providing excellent properties with limited alloy content. By optimizing Si, V and C contents, PM steel alloys with mechanical properties approaching those of FD-0405 can be produced. High temperature sintering is required to achieve these benefits however. Cooling rate was also found to have an important role on the final properties. The benefits of ferrous PM alloys containing silicon and vanadium will be discussed.

Introduction

Mo, Ni and Cu are the workhorse alloying elements in PM steels, as these steels have good compressibility, can be sintered in several different reducing atmospheres and generate good mechanical properties. Well known diffusion alloy examples are the iron powder based steels containing 0.5 wt% Mo, 1.5 wt% Cu and either 1.75 wt% or 4 wt% Ni. Higher nickel contents are often used to increase toughness of PM steels. Over the past 10 years, both price and price volatility of these elements has increased. To remain cost competitive, investigations into alternative alloying methods have been pursued. Both Cr-containing and Mn-containing steels have been introduced in the marketplace as a way to address this concern, but these materials typically contain some level of Mo, Ni and/or Cu to achieve desired properties [1-3]. An ideal low cost solution would be based on iron to which small amounts of highly effective alloying elements are added.

Micro-alloyed wrought steels provide a good example of just such an approach. Good mechanical properties are achieved with very low alloy contents. Typical alloying elements include V, Nb, Ti. While the mechanical properties of microalloyed steels are often achieved through thermo-mechanical processing, the alloy concept can still be applied to PM steels. Recent work with Si and V alloyed steels has shown excellent promise for these alloying elements [4], albeit with high temperature sintering as a requirement. The combination of Si and V has been shown to provide significant benefits in mechanical properties for several reasons. [5-10] Alloying with vanadium and silicon results in finer interlamellar pearlite, smaller pearlite colony size, smaller austenite grain size, strengthened ferrite, and the ability to increase the carbon content of the material to greater than the eutectoid composition without forming proeutectoid carbides; all of which contribute to improved properties. The use of silicon alone as an alloying element has also been reported to greatly improve toughness at higher carbon and strength levels [11]. The high temperature sintered Fe-Si-V-C alloy has similar properties to the conventionally sintered FD-0405 alloy as reported by Schade [4]. Table 1 and Figure 1 show the static properties and fatigue performance, respectively, of both alloys. This combination of higher carbon contents with Si and V contribute to these excellent properties. Additionally, this Mo-, Cu- and Ni-free alloy system reduces price volatility and minimizes recyclability and environmental concerns.

These properties are produced with fully pearlitic, non-hardened steels. In earlier work [12], the authors compared this alloy with 2 traditional pearlitic steels, F-0008 and FC-0208. The axial fatigue cracking characteristics of these materials was studied. The high carbon Si-V alloy was found to be fully pearlitic with little grain boundary carbide formation, resulting in higher loads at failure at approximately 50,000 cycles as compared with the other alloys. This work is a continuation of that initial study. The objective of the current work is to demonstrate the fatigue performance of the Fe-Si-V-C alloy and the feasibility of using this leaner alloy to achieve desired properties.

Table I. Mechanical Properties of High Performance Alloys. Diffusion alloys sintered at conventional 1120 °C temperature, Fe-Si-V-C alloy sintered at 1260 °C. [4]

Alloy	Alloy Content (%)	Sintered Density (g/cm ³)	Impact Energy		Apparent Hardness (HRA)	UTS		0.20% OFFSET		Elongation (%)
			(J)	(ft.lbf)		(10 ³ psi)	(MPa)	(10 ³ psi)	(MPa)	
Ancorsteel FD-4600A + 0.60 w/o C	4	7.09	26	19	53	90.3	621	54.5	375	3.0
Ancorsteel FD-4800A + 0.60 w/o C	6	7.13	28	21	58	105.7	727	55.6	383	2.5
Ancorsteel 1000B + 1.1 w/o C + 0.16 w/o V and 0.60 w/o Si	<1	7.02	19	14	60	118.0	812	87.5	602	2.3

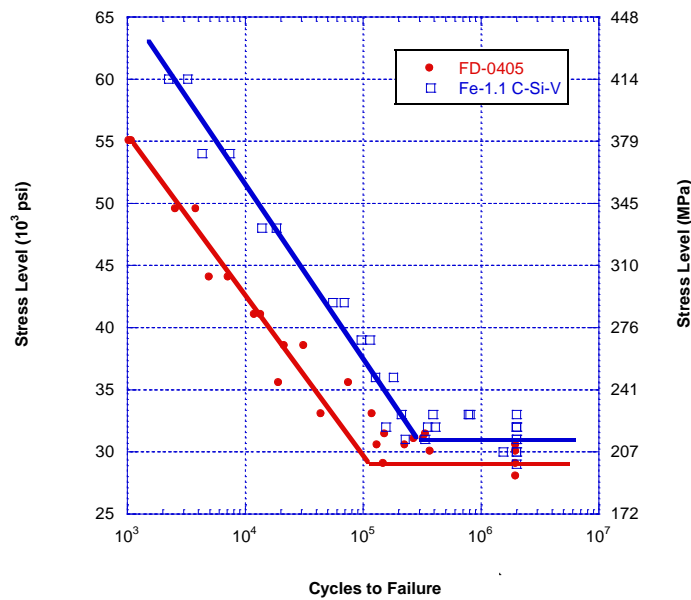


Figure 1. Axial fatigue response (R= -1) of FD-0405 and the Fe-Si-V-C alloy (density 7.05 g/cm³). [4]

Experimental Procedure

Three near-eutectoid alloy mixtures were used in this study to evaluate the effects of cooling rate and alloy composition on axial fatigue performance of pearlitic PM steels, Table 2. The nominal chemical compositions of the mixes were: F-0008 (Ancorsteel® 1000B + 0.8 w/o Asbury 3203H graphite), FC-0208 (Ancorsteel 1000B + 2 w/o ACuPowder 8081 Cu + 0.8 w/o graphite) and a patent pending steel microalloyed with silicon and vanadium (Ancorsteel 1000B + a proprietary additive system containing silicon and vanadium + 1.1 w/o graphite). Additionally, Acrawax C was used in all mixes as the lubricant. Transverse rupture strength (TRS), dog-bone tensile, impact, and axial fatigue bars were pressed from these mixtures to achieve a 7.0 g/cm³ sintered density. Both the graphite contents and green density were altered slightly in the F-0008 and FC-0208 materials to achieve a constant sintered density and carbon content.

Table 2. Nominal composition of alloys used in this study

ID	Fe (wt%)	Cu (wt%)	Si (wt%)	V (wt%)	Gr (wt%)
F-0008	Bal.	-	-	-	0.8
FC-0208	Bal.	2.0	-	-	0.8
FeSiVC	Bal.	-	0.6	0.16	1.1

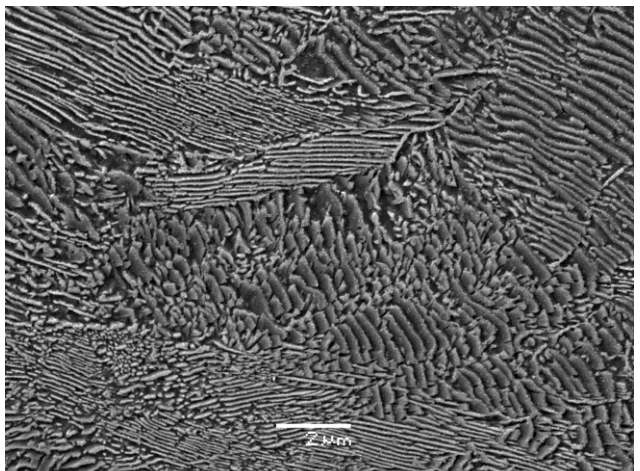
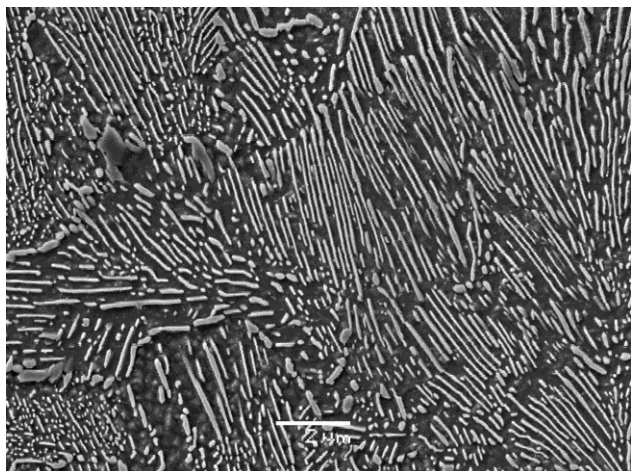
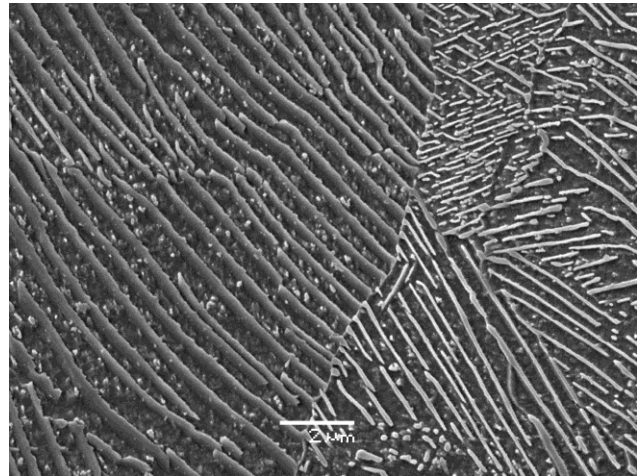
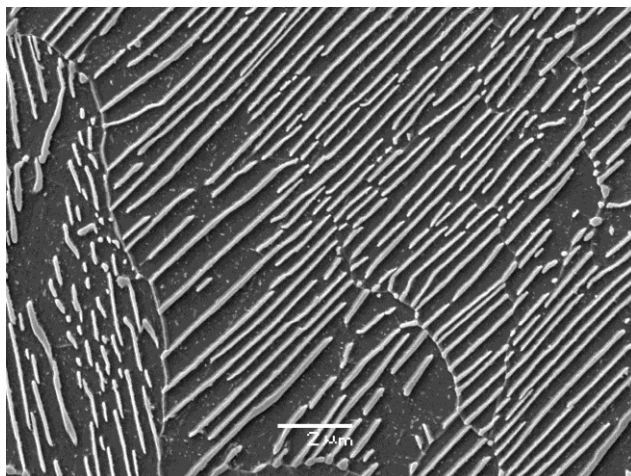
The F-0008 and FC-0208 samples were sintered in an Abbott belt furnace at 1120 °C (2050 °F) and 1260 °C (2300 °F) in a 90/10 nitrogen/hydrogen atmosphere and cooled at two rates, approximately 0.4 °C/sec and 2.2 °C/sec. The Fe-Si-V-C alloy bars were processed at only the higher sintering temperature but cooled with the two cooling rates. In all cases, the two cooling rates were intended to provide a difference in pearlite spacing within each material/sintering temperature group. The appropriate mechanical properties, hardness, and dimensional values were determined for each sintered bar. After mechanical and physical testing, representative specimens were selected for metallographic analysis.

Axial fatigue tests were carried out using unnotched, as-sintered bars with a continuous radius between the ends and a rectangular cross-section. The tests were run at a frequency of 60 Hz and a stress ratio of $R = -1$. The fatigue endurance limit (FEL) was estimated based on the applied stress to achieve a runout, similar to performing a staircase method. The runouts were defined as 2×10^6 cycles with no failure.

Results & Discussion

Microstructures

All of the materials were fully pearlitic after sintering. Figure 2 shows a typical pearlite microstructure for all five samples in the fast cool condition. All images were taken at the same magnification for direct visual comparison. The pearlite spacing is considerably coarser in the F-0008 samples as compared with the FC-0208 and Fe-Si-V-C alloy.



Material Type & Sintering Temperature	
F-0008	
1120 °C	1260 °C
FC-0208	
1120 °C	1260 °C
Fe-Si-V-C	
	1260 °C
Secondary Electron Images (SEI)	

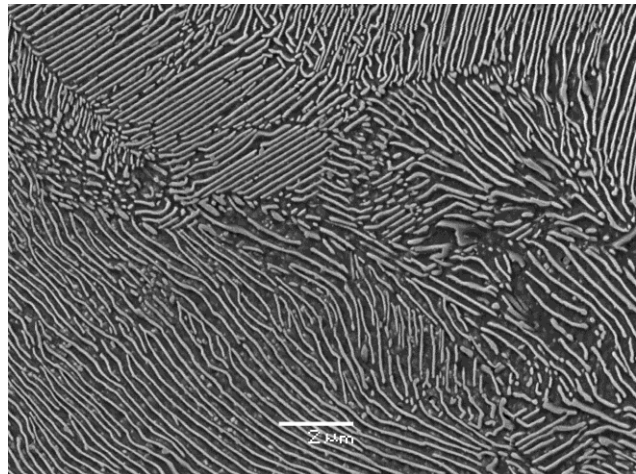


Figure 2. Examples of the pearlite interlamellar spacing from the faster cooled (2.2 °C/s) specimens in each sintering condition. F-0008 samples were etched with a combination of 2 v/o nital & 4 w/o picral while all other samples were etched with 1 v/o nital & 4 w/o picral.

Static Properties

The mechanical properties of the materials studied are shown in Table III. Increases in sintering temperature and cooling rate improve the mechanical properties of these pearlitic steels. The Fe-Si-V-C alloy exhibits the best combination of strength, hardness and toughness. Even with higher carbon content, the microalloyed steel has the highest impact toughness of all materials. Figure 3 displays the ultimate tensile strength of each alloy and condition, with ultimate tensile strengths approaching 800 MPa for the Fe-Si-V-C alloy.

Table 3. Mechanical properties

ID	YS (MPa)	UTS (MPa)	Elong. (%)	Impact (J)	Hardness HRA	Axial Fatigue 90% Endurance Limit (MPa)
Fast Cooled 2.2 °C/s						
Fe-Si-V-C, 1260 °C	647	785	1.6	19	61	198
FC-0208, 1260 °C	527	636	1.4	14	57	165
F-0008, 1260 °C	337	494	2.6	16	49	144
FC-0208, 1120 °C	461	537	1.2	14	54	149
F-0008, 1120 °C	258	344	1.8	9	45	110
Slow Cooled 0.4 °C/s						
Fe-Si-V-C, 1260 °C	533	713	2.0	20	58	189
FC-0208, 1260 °C	453	565	1.6	15	54	160
F-0008, 1260 °C	263	430	3.2	16	45	118
FC-0208, 1120 °C	376	487	1.7	14	50	142
F-0008, 1120 °C	209	309	2.6	11	39	94

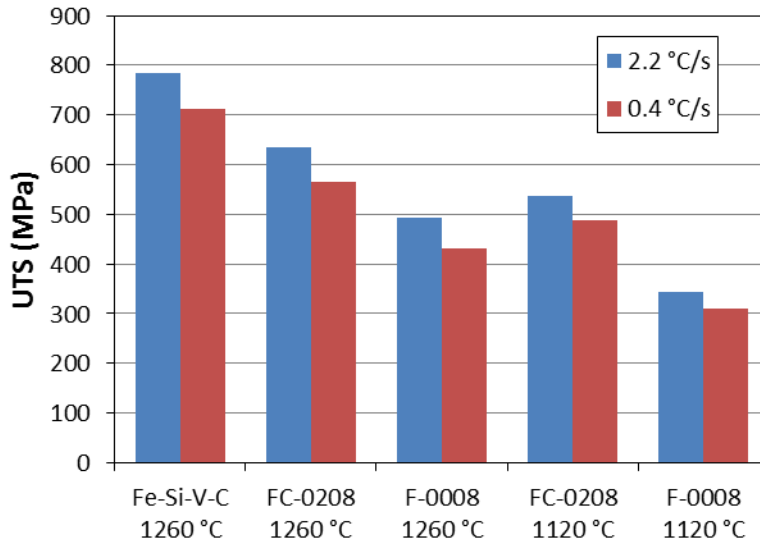


Figure 3. Ultimate tensile strength of the materials and conditions tested.

Axial Fatigue Properties

Axial fatigue tests were run and S-N curves were developed for the R=-1 condition. Endurance limits were then calculated from the data (Table 3) and the results are plotted in Figure 4. A similar pattern to that of the ultimate tensile strength is observed. The Fe-Si-V-C alloy has the highest endurance limit of all materials at both cooling rates. The fast cooled microalloyed steel has an endurance limit of nearly 200 MPa, which is 20% higher than FC-0208. The endurance limit of FC-0208 exhibits little effect with both sintering temperature and cooling rate, as there is only an 23 MPa difference between all four conditions. There is a much greater effect of sintering conditions on F-0008 fatigue behavior. A 50 MPa difference was found between different conditions, with the high temperature sintering plus high cooling rate sample FEL approaching that of the conventionally sintered FC-0208. It is thought that the liquid phase present during sintering in Cu steels will cause a beneficial change in pore structure, whereas HTS is required to get a similar pore structure when Cu is not present. The authors also found that the pearlite spacing exhibited a large change with cooling rate in the F-0008 HTS sample, and may explain the large change in fatigue performance.

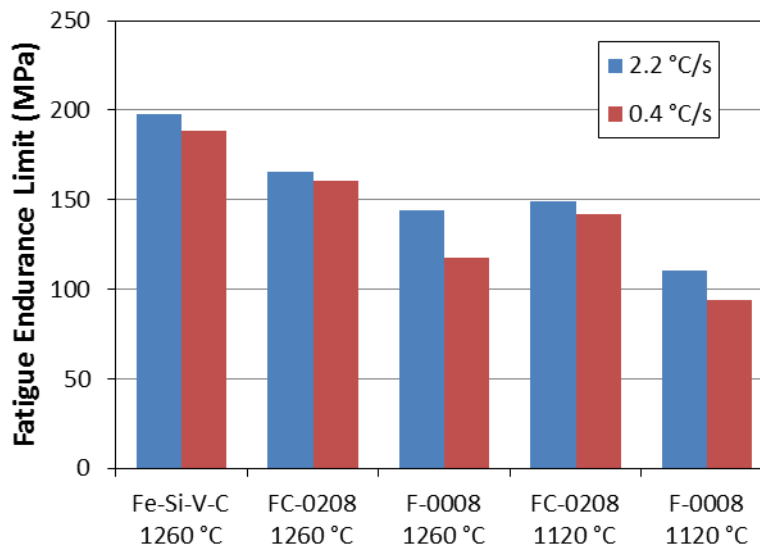


Figure 4. 90% axial fatigue endurance limit of the materials and conditions tested (R=-1).

Conclusion

The mechanical properties of the lean Fe-Si-V-C microalloyed steel are quite impressive. With nominally 0.75 wt% alloy content (excluding C), an as-sintered tensile strength and fatigue strength of 785 and 200 MPa, respectively, was achieved in a fully pearlitic PM steel at 7.0 g/cm³. High temperature sintering is however required to achieve these properties. The fatigue endurance limit followed the trend in tensile strength, with the endurance limit being 0.25% that of the tensile strength for the Fe-Si-V-C alloy.

Acknowledgements

The authors wish to thank Wing Hong Chen in the Hoeganaes R&D lab for his assistance in testing the mechanical test specimens.

References

1. MPIF Standard 35, Materials Standards for PM Structural Parts, 2009 Edition.
2. King, P., "Chromium Containing Materials for High Strength - High Fatigue Applications," PM World Congress Proceedings, 2004.
3. Lindsley, B., James, W.B., "PM steels that contain Mn", Advances in Powder Metallurgy & Particulate Materials, compiled by M. Bulger and B. Stebick, Metal Powder Industries Federation, Princeton, NJ, 2010, part 10, p. 36-49.
4. C. Schade, T. Murphy, A. Lawley and R. Doherty, "Microstructure and Mechanical Properties of PM Steels Alloyed with Silicon and Vanadium", International Journal of Powder Metallurgy, 2012, 48/6, p. 41-48.
5. K. Han, D.V. Edmonds, and G.D.W. Smith, "Optimization of Mechanical Properties of High-Carbon Pearlitic Steels with Si and V Additions", Met. & Mat. Trans. A, 2001, vol. 32A, p. 1-12.
6. K. Han, T.D. Mottishaw, G.D.W. Smith, and D.V. Edmonds, "Effects of Vanadium Addition on Nucleation and Growth of Pearlite in High Carbon Steel", Mat. Sci. & Tech., 1994, vol. 10, p. 955-963.
7. K. Han, T.D. Mottishaw, G.D.W. Smith, D.V. Edmonds, and A.G. Stacey, "Effects of Vanadium Additions on Microstructure and Hardness of Hypereutectoid Pearlitic Steels", Mat. Sci. & Eng. A, 1995, vol. 190, p. 207-214.
8. K. Han, G.D.W. Smith, and D.V. Edmonds, "Pearlite Phase Transformation in Si and V Steel", Met. & Mat. Trans. A, 1995, vol. 26A, p. 1617-1631.
9. K. Han, D.V. Edmonds, and G.D.W. Smith, "Optimization of Mechanical Properties of High-Carbon Pearlitic Steels with Si and V Additions", Met. & Mat. Trans. A, 2001, vol. 32A, p. 1313-1324.
10. B. Garbarz and F.B. Pickering, "Effect of Pearlite Morphology on Impact Toughness of Eutectoid Steel Containing Vanadium", Mats. Sci. & Tech., vol. 4, no. 4, 1988, p. 328-334.
11. C. Schade, T. Murphy, A. Lawley and R. Doherty, "The Influence of Silicon on the Mechanical Properties of PM Steels", Advances in Powder Metallurgy & Particulate Materials, compiled by D. Christopherson and R. Gasior, Metal Powder Industries Federation, Princeton, NJ, 2013.
12. T. Murphy, B. Lindsley and C. Schade, "Effect of Pearlite Spacing and Chemical Composition on the Axial Fatigue Behavior of Fully Pearlitic PM Steels: A Metallographic Study", International Journal of Powder Metallurgy, 2012, 48/5, p. 23-39.