

Tensile, Impact and Fatigue Performance of a New Water Atomized Low-Alloy Powder - Ancorsteel 85 HP

John J. Fulmer and Robert J. Causton
Hoeganaes Corporation
Riverton, NJ 08077

*Presented at the Annual Powder Metallurgy Conference
Pittsburgh, Pennsylvania, May 20 - 23, 1990.*

Abstract

A new water atomized, prealloyed powder has been developed containing 0.85% molybdenum as the alloying addition. The as-sintered and heat treated tensile, impact and fatigue performance have been determined for a range of graphite additions using both single and double pressing techniques.

Results indicate that the new powder, Ancorsteel 85 HP, has a unique ability to be compacted and repressed to densities not attainable with existing prealloyed nickel-molybdenum powders. The higher densities achieved produce performance equivalent to or better than Ancorsteel 12000 or Ancorsteel 14600V using conventional single compaction techniques. However, the additional density increment achieved during repressing results in mechanical properties in excess of what is possible with the existing low-alloy steels.

It is expected that the new prealloyed powder will be used in high-density applications requiring good hardenability. It will also provide a base for our high performance ferrous material development program.

Introduction

Development efforts in the area of ferrous powder metallurgy materials have paralleled the demand for cost effective solutions to high performance part applications. As part of a continuing program in this area a systems approach was introduced [1] in which the material and processing techniques are optimized with the goal of achieving increased part densities without the need to apply the double press/double sinter process.

The first step in this approach is to optimize the raw materials used in the parts making process. The mechanical properties of P/M materials are controlled by their microstructure and porosity. Therefore, the alloy composition and manner with which the powder is constituted will significantly influence the performance characteristics of the material. The ANCORBOND mixing process [2-5] offers the potential for combining the best features of prealloyed, partially alloyed and admixed materials. The application of this binder assisted mixing process is a key element in the optimization of the raw material.

In order to achieve the best combination of strength and toughness the alloy additions must be made to strengthen the inner-particle matrix and inter-particle boundary regions of the microstructure simultaneously [6]. Prealloyed low-alloy powders are preferred for use as the base material since they improve the hardenability and strength of the inner-particle matrix. Conventional nickel-molybdenum prealloyed powders such as Ancorsteel 12000 [7] and Ancorsteel 4600V [8] have sufficient alloy content for the desired effect but lack the compressibility of admixed or partially alloyed powders. This is due to the combined solution strengthening and work hardening effects of the pre alloyed nickel and molybdenum. Prealloyed chromium-manganese steels [9,10] are attractive because they yield good combination of hardenability and compressibility. However, their use is limited because of the special precautions required during powder manufacture and subsequent parts processing to avoid preferential oxidation of the alloying elements. Oxide films at interparticle boundaries may severely impair the mechanical properties of finished components, and preferential components may also cause effective loss of alloying elements.

To achieve the desired degree of alloying without detrimental effects on compressibility a new water atomized, prealloyed

low-alloy powder, Ancorsteel 85 HP, has been developed. The powder contains a nominal addition of 0.85% molybdenum as the primary alloying element. The result is a prealloyed powder with exceptional compressibility and good response to heat treatment.

The purpose of this initial study is to characterize the basic green, sintered, tensile and impact performance of Ancorsteel 85 HP with graphite additions of 0.2 ~ 0.8 weight percent. Tensile and rotating bending fatigue (RBF) properties are also presented for selected samples. Comparisons are made with the existing low-alloy steels Ancorsteel2000 and Ancorsteel14600V.

Experimental Procedure

Materials

The chemical and physical properties of the Ancorsteel 85 HP, Ancorsteel 2000, and Ancorsteel 4600V used in the investigation are presented in Table I. All Premixes were prepared using flake natural graphite (Southwestern 1651) and zinc stearate (Witco Lubrazinc W) or atomized ethylene bisstearamide (Lonza Acrawax C) as indicated.

Test Specimen Preparation

All tensile properties were generated using as-pressed ASTM E8 'dog-bone' tensile specimens. Transverse rupture strength was tested using standard ASTM B528 specimens. Charpy impact testing was performed using unnotched specimens as shown in ASTM E23. Rotating bending fatigue (RBF) specimens were machined from 1 cm x 1 cm x 7.6 cm rectangular compacts to the dimensions shown in Figure I.

Sintering was carried out in a laboratory belt furnace. The specimens were sintered at 2050 °F for 30 minutes in a dissociated ammonia atmosphere unless otherwise indicated.

Heat treatment included austenitizing at 1650 °F in a muffle furnace for 30 minutes in a dissociated ammonia atmosphere with methane added to maintain a carbon potential equal to that of the samples. The samples were quenched in oil preheated to 150 °F. Tempering was performed for 60 minutes in argon to prevent decarburization.

Testing

Tensile testing was performed on an Instron tester at a crosshead speed of 0.05 cm/minute. All dimensional change measurements were made with reference to die size using transverse rupture specimens. Apparent hardness measurements were taken from the tensile specimens. Low temperature impact testing was conducted on specimens stabilized in liquid nitrogen/methanol baths. RBF specimens were tested at 3300 r.p.m, with survival to 10^7 cycles considered a 'runout'. Twenty -five specimens were used for each test. Bending moments were chosen by the 'staircase' method [11] until appropriate stress levels were determined for a two-point estimate of the fatigue endurance limit, which for the purpose of this study was defined as the 99.9% survival stress.

Results

The green, tensile, impact and fatigue properties of Ancorsteel 85 HP are presented in Tables 2 - 5. Graphical representation of the data and comparisons with Ancorsteel 2000 and Ancorsteel14600V are shown in Figures 2 - 21.

Discussion

Compressibility and Green Strength

The high compressibility of the prealloyed molybdenum steel is accompanied by high green strength. The compressibility (Figure 2a) and green strength (Figure 2b) were measured for mixes containing two levels (0.5% and 1.0%) of Acrawax and zinc stearate. The compressibility is generally highest when mixed with zinc stearate. At lower compaction pressures the 1.0% lubricant addition resulted in the highest density for both lubricant types. This is followed by a crossover point at a compaction pressure of approximately 40 tsi where the compressibility is relatively insensitive to lubricant content. At the highest compaction pressure tested (50 tsi) compressibility is favored at the 0.5% lubricant addition.

The green strength of Ancorsteel 85 HP is similar for all lubricant additions at the lower compaction pressure of 30 tsi. As the compaction pressure is increased the green strength shows continued improvement for lower lubricant content.

The compressibility and green strength of Ancorsteel 85 HP are considerably higher over the range of compaction pressures in comparison with Ancorsteel 2000 and Ancorsteel 4600V (Figure 3). This difference is attributed to both the low oxygen and residual (C,N,S) content as well as the lower solution strengthening and work hardening characteristics of the nickel free alloy. Additional improvements in compressibility for the nickel-molybdenum steels are possible. However, the prealloyed nickel has a compounding effect on the solution strengthening and work hardening characteristics resulting in an intrinsically lower compressibility compared with the nickel free Ancorsteel 85 HP - see Figure 4 [12].

The green strength of Ancorsteel 85 HP is also consistently higher when compared with Ancorsteel 2000 and Ancorsteel 4600V. All three powders have high green strength characteristic of their irregular particle shape. The relative ranking of the three results from additional factors such as particle hardness and oxide content which affect the amount of mechanical interlocking of the powder particles that occurs during compaction. Ancorsteel 85 HP has the lowest oxygen content and highest compressibility giving it the highest green strength ranking.

Tensile and Impact Properties - Effect of Graphite Addition

The as-sintered tensile and impact properties (Figures 5 and 6) were measured for both Ancorsteel 85 HP and Ancorsteel 4600V containing graphite additions of 0.2, 0.4, 0.6, and 0.8 percent by weight. These materials were compacted at a constant compaction pressure of 40 tsi. The yield strength, tensile strength and apparent hardness of Ancorsteel 85 HP increase rapidly as the graphite addition is raised from 0.2 to 0.4%. The response of these properties to additional graphite is limited and only a marginal increase is observed through the 0.8% graphite addition. Ancorsteel 4600V responds in a similar manner except for the lower range of graphite additions (0.2 ~ 0.4%). In this range Ancorsteel 4600V exhibits higher strength and hardness than Ancorsteel 85 HP through approximately 0.3% graphite. At graphite levels above 0.4% Ancorsteel 85 HP exhibits slightly higher strength and hardness.

The elongation and impact performance (Figure 6) of both alloys show an inverse relationship to the strength and hardness properties. Both elongation and impact energy decrease rapidly as the graphite addition is raised from 0.2 to 0.4% after which they stabilize and remain constant through the 0.8% graphite addition.

The dimensional change from die size of Ancorsteel 85 HP (Figure 7) was stable at approximately +0.1% over the range of graphite additions. The dimensional change of Ancorsteel 4600V increased proportionally with the graphite addition and ranged from -0.22% at the 0.2% graphite addition to -0.08% for a graphite addition of 0.8%.

The relationship of the tensile and impact properties with graphite addition for as-sintered Ancorsteel 85 HP and Ancorsteel 4600V is similar and is explained by the resulting microstructure. The specimens containing 0.2% graphite have a mixed structure (Figure 8) of polygonal ferrite and a darker etching constituent that is an aggregate of acicular ferrite and carbides. At graphite additions above 0.4% the microstructure is a uniform aggregate of acicular ferrite and carbides throughout. The structure continues to be uniform through the 0.8% graphite addition and differs only in the morphology and distribution of the carbides (Figures 9 - 11). This uniform microstructure produces consistent mechanical and dimensional change properties over the range of graphite additions from 0.4 ~ 0.8%.

Tensile and Impact Properties - Effect of Compaction Pressure

The tensile, hardness, impact and dimensional properties of Ancorsteel 85 HP, Ancorsteel 2000, and Ancorsteel 4600V mixed with 0.6% graphite were compared at compaction pressures of 30, 40, and 50 tsi (Figures 12 - 14) The strength and hardness of all three alloys generally increases as the compaction pressure is increased. At compaction pressures above 50 tsi the tensile and hardness properties approach a parallel relationship with the abscissa as the maximum pressed density for the materials premixed with 0.6% graphite and 0.5% zinc stearate is approached. The slope of the impact energy curves generally increases with compaction pressure while the elongation of all three alloys is relatively constant at approximately 1%. The dimensional change of Ancorsteel 85 HP and Ancorsteel 4600V increases approximately 0.05 to 0.1% over the range of compaction pressures. The dimensional change of Ancorsteel 2000 did not vary significantly over the entire range of compaction pressures.

Impact Energy - Effect of Test Temperature

The variation of as-sintered impact performance from room temperature down to -280 °F was measured for Ancorsteel 85 HP and Ancorsteel 4600V mixed with 0.6% graphite and compacted at 40 tsi. The same was performed for Ancorsteel 185 HP compacted at 30 and 50 tsi to measure the effect of density on the low temperature impact performance. At equivalent compaction pressures the impact performance of both Ancorsteel 85 HP and Ancorsteel 4600V is maintained from room temperature through -25 °F (Figure 15a). Below this temperature the impact energy decreases gradually down to -280 °F. Ancorsteel 85 HP exhibits a higher impact energy over the range of test temperatures.

The effect of compaction pressure on the impact energy of Ancorsteel 85 HP is presented in Figure 15b. At the lowest compaction pressure (30 tsi) a sintered density of 6.73 g/cm³ was achieved in the impact bars. At this density level the impact performance is constant at approximately 5 ft-lbf. When tested at -280 °F the impact energy dropped down to 3 ft-lbf. As the compaction pressure (or density) is increased the impact performance is improved. Increasing the density reduces the effect of porosity and the temperature effect is more pronounced.

Double Pressing/Double Sintering

Our material development program is aimed at providing a competitive material/method for obtaining high performance P/M steels. A single press and sinter operation is desired since additional processing entails extra cost. However, if steels with even higher strengths are to be produced, further increases in density have to be achieved either by repressing after sintering, or by repressing followed by resintering. In the latter case the first sintering (i.e. presintering) is typically carried out at temperatures ranging from 1200 ~ 1550 °F and the second from 2050 ~ 2300 °F.

The effect of presintering temperature on the repressed density and transverse rupture strength was measured for Ancorsteel 185 HP, Ancorsteel 2000 and Ancorsteel 4600V. Initial compaction was performed at 45 tsi followed by presintering at a range of temperatures from 1100 - 1600 °F. The specimens were repressed at 45 tsi and sintered at 2050 °F for 30 minutes in dissociated ammonia and their transverse rupture strength and density were measured. After compaction and presintering the density difference between the three alloys is consistent over the range of presintering temperatures. This difference in density is attributable to the difference in compressibility between the alloys. However, upon repressing the three materials exhibit vastly different repressed density over the range of presintering temperatures (Figure 16a). The maximum density for Ancorsteel 2000 was approximately 7.25 g/cm³ and was achieved over the range of presintering temperatures from 1300 - 1475 °F. The repressed density for Ancorsteel 4600V increased gradually from a presintering temperature of 1200 °F to a maximum of 7.26 g/cm³ at approximately 1475 °F. Ancorsteel 185 HP exhibited a large increase in density from 1200 °F to a maximum of 7.45 g/cm³ at a presintering temperature of approximately 1400 °F. The large difference in repressed density between Ancorsteel 85 HP and the other two materials results from an optimum combination of material composition and processing (patent pending).

The result of the double pressing operation on transverse rupture strength is shown in Figure 16b. The transverse rupture strength shows a proportional relationship with density for all three powders. Due to the substantial density improvements achieved during the compaction and repressing operations Ancorsteel 85 HP gives as-sintered transverse rupture strengths well above what is possible with the nickel-molybdenum steels under the same conditions.

Based on the results of this experiment a presintering temperature of 1400 °F was employed to generate the double pressed/double sintered tensile, and impact data.

Heat Treatment Effect of Tempering Temperature

In the design of our heat treatment process the effect of tempering temperature on the tensile properties was examined for Ancorsteel 85 HP, Ancorsteel 2000 and Ancorsteel 4600V mixed with a 0.6% graphite and compacted at 40 tsi. The heat treatment process consisted of austenitizing at 1650 °F for 30 minutes at temperature followed by quenching in oil heated to 150 °F. The specimens were then tempered at a range of temperatures from 400 - 1100 °F for 30 minutes in argon. The effect of tempering temperature on the tensile properties and hardness is illustrated in Figures 17 and 18. The strength and hardness is maintained for tempering temperatures below approximately 575 °F after which they decrease rapidly to a shelf at 750 °F. At 930 °F Ancorsteel 85 HP exhibits a modest secondary strengthening effect. The heat treated elongation for all of the materials at all tempering temperatures was less than 1%.

From these results a tempering temperature of 650 °F was chosen for use in generating the subsequent quenched and tempered tensile, impact, and fatigue data. This temperature provides a compromise between tensile elongation and strength, which should enhance the fatigue and impact performance.

Ancorsteel 85 HP

Tensile, Fatigue, and Impact Performance

The tensile, impact, and fatigue performance of Ancorsteel 85 HP mixed with 0.6% graphite has been characterized in the as-sintered and quenched and tempered conditions (Table 5). Processing was performed using a conventional compaction pressure of 45 tsi and sintering temperature of 2050 °F.

At high densities (i.e. $> 7.2 \text{ g/cm}^3$) small increases in density produce significant improvements in mechanical properties (Figure 19). Double pressing increased the density of as-sintered Ancorsteel 85 HP from 7.14 to 7.51 g/cm^3 resulting in an increase in impact energy from 10.6 to 44.0 ft-lbf. Double pressing gave the best combination of as-sintered yield strength (65,975 psi) and elongation (3.0%). The treatment produced a homogeneous microstructure of tempered martensite (Figure 21). Heat treatment produced a large increase in tensile strength and was generally more effective than density improvements. However, heat treatment reduced the impact energy from 44.0 to 22.0 ft-lbf.

Ancorsteel 4600V has been shown [13 - 15] to give a combination of high fatigue and tensile strength. The same was expected for Ancorsteel 85 HP and its fatigue performance was measured under a variety of processing conditions. Single pressing Ancorsteel 85 HP to a density of 7.14 g/cm^3 gave an as-sintered tensile strength of 58,682 psi and an endurance limit of 21,504 psi. Increasing the density to 7.51 g/cm^3 by double pressing resulted in a tensile strength of 85,434 psi and increased the endurance limit 65 % to 35,496 psi. Heat treatment of double pressed Ancorsteel 85 HP gave the highest tensile and fatigue strengths of 182,671 and 63,336 psi respectively. These data are compared with Ancorsteel 4600V in Figure 21.

Previous work [15] has shown that both double pressing to high density and high temperature sintering improve the impact performance by modifying the pore size, shape, and distribution. Double pressing eliminates the large pores while high temperature sintering reduces the number of smaller pores and produces beneficial pore rounding. Double pressing and heat treating the Ancorsteel 85 HP increased the tensile and fatigue strength by 9,425 psi and 5,839 psi respectively compared with Ancorsteel 4600V processed under equivalent conditions. High temperature (2425 °F) sintering, improved the tensile and fatigue strength of Ancorsteel 4600V by 10 and 15% respectively. This is roughly equivalent to Ancorsteel 85 HP sintered at 2050 °F. It is anticipated that high temperature sintering will produce similar improvements in Ancorsteel 85 HP.

Conclusions:

A new prealloyed powder, Ancorsteel 85 HP, has been developed with the unique ability to be processed to high densities. The 0.85% prealloyed molybdenum in the powder provides good heat treatment response for use in high strength applications. The powder will be useful in applications requiring a combination of good compressibility and hardenability. The results of this investigation indicate that this new powder will be useful as a platform for future development of high performance ferrous P/M materials.

Acknowledgements:

The authors wish to thank R. J. Fitzpatrick, C. Gamble, and W. R. Bentcliff for their help in mechanical property specimen preparation and testing.

References

1. W. B. James, "Alloying Methods for High Performance Ferrous Powder Metallurgy Parts", Metallurgia Do Po Seminario Proceedings, pp. 93, Associacao Brasileira de Metals, São Paulo, Brazil, Oct. 24-26, 1989.

2. F. J. Semel, "Properties of Parts Made from a Binder Treated 0.45 % Phosphorus Containing Iron Powder Blend", *Progress in Powder Metallurgy*, Volume 43, 1987, pp. 723, published by MPIF, Princeton, NJ.
3. F. J. Semel, D. J. Kasputis, and P. Uff Gummesson, "Statistical Process Control in Iron Powder Production and New Product Development", SAE Technical Paper 880114, Society of Automotive Engineers, Cobo Hall, Detroit, MI, 1988.
4. F. J. Semel, "Properties of Parts Made From AncorBond® Processed F-0008 / Carbon Steel Mix", *Modern Developments in Powder Metallurgy*, Vol. 21, 1988, pp. 101, Published by MPIF, Princeton, NJ.
5. F. J. Semel, "Properties of Parts Made from an AncorBond® Processed Carbon-Nickel-Steel Powder Mix (FN-0208)", *Advances in Powder Metallurgy*, Vol. 1, 1989, pp.9, published by MPIF, Princeton, NJ.
6. T. Saito and M. Obayashi, "High Strength Sintered Steel Without Heat Treatment", *Modern Developments in Powder Metallurgy*, Vol. 21, 1988, pp. 197, Published by MPIF, Princeton, NJ.
7. "Ancorsteel 2000", Technical Product Bulletin Form KM187, February, 1988, Hoeganaes Corporation, Riverton, NJ.
8. "Ancorsteel14600V", Technical Product Bulletin Form KM187, February, 1988, Hoeganaes Corporation, Riverton, NJ.
9. E. Tamura, I. Karasuno, M. Ichida and T. Kubo, "Properties of Oil-Atomized 4100 Low Alloy Steel Powder", *Progress in Powder Metallurgy*, Volume 41, 1985, pp. 13, published by MPIF, Princeton, NJ.
10. K. Ogura, R. Okabe, S. Takajo, N. Yamato, and Y. Maeda, "Production and Properties of Chromium-Containing Low-Oxygen Steel Powders", *Progress in Powder Metallurgy*, Volume 43, 1987, pp. 619, published by MPIF, Princeton, NJ.
11. R. C. Rice, "Fatigue Data Analysis", ASM International, *Metals Handbook*, Vol. 8, 9th Edition, 1985, pp. 695-720.
12. C. DurdaUer, "Powders for Forging", Technical Bulletin D211, October, 1971, Hoeganaes Corporation, Riverton, NJ.
13. R. C. O'Brien, "Impact and Fatigue Characterization of Selected Ferrous P/M Materials", *Progress in Powder Metallurgy*, Vol. 43, 1987, pp. 749, published by MPIF, Princeton, NJ.
14. R.C. O'Brien, "Fatigue Properties of P/M Materials", SAE Technical Paper 880165, Society of Automotive Engineers, Cobo Hall, Detroit, MI, 1988.
15. W.B. James, "Fatigue Properties of Ferrous P/M Materials", *Metallurgia Do Po Seminario Proceedings*, pp.193, Associacao Brasileira de Metals, São Paulo, Brazil, Oct. 24-26, 1989.

Table 1 - Chemical and physical analysis of the prealloyed base powders.

Chemical Analysis % by weight	Ancorsteel 85 HP	Ancorsteel 2000	Ancorsteel 4600V
----------------------------------	------------------	-----------------	------------------

Table 3 - Effect of graphite addition on the as-sintered tensile and impact properties of Ancorsteel 85 HP compacted at 40 tsi.

Graphite addition (weight %)	Sintered Carbon (weight %)	Yield Strength (psi)	Tensile Strength (psi)	Elongation (%)	Impact Energy (ft-lbf)	Apparent Hardness (HRB)	Dimensional Change * (%)
0.2	0.18	22,142	33,916	3.9	14.0	44	+0.09
0.4	0.37	45,023	52,418	1.1	9.0	72	+0.10
0.6	0.53	46,545	55,622	1.1	8.8	74	+0.11
0.8	0.69	49,416	58,464	1.1	8.7	79	+0.12

Table 4 - Effect of Compaction Pressure on the tensile and impact properties of Ancorsteel 85 HP with a 0.6% graphite addition.

Compaction Pressure (tsi)	Sintered Carbon (weight %)	Yield Strength (psi)	Tensile Strength (psi)	Elongation (%)	Impact Energy (ft-lbf)	Apparent Hardness (HRB)	Dimensional Change * (%)
30	0.53	42,268	48,706	1.0	9.0	63	+0.13
40	0.53	47,836	56,333	1.0	9.0	75	+0.17
50	0.52	51,954	59,929	0.9	12.0	81	+0.19

* From Die Size

Table 5 - Tensile and Fatigue Properties of Ancorsteel 85 HP mixed with 0.6% graphite.

Process	Compaction Pressure (tsi)	Density (g/cm ³)	Yield Strength (psi)	Tensile Strength (psi)	Elongation (%)	Impact Energy (ft-lbf)	Apparent Hardness	Endurance Limit (psi)	Endurance Ratio
Single-Pressed	45	7.14	50,025	58,682	1.2	10.6	78 HRB	21,504	0.37
Same, Q & T	45	7.15	No Yield	108,837	0.5	9.0	32 HRC	40,006	0.37
DP/DS	45/45	7.51	65,975	85,434	3.0	44.0	89 HRB	35,496	0.42
Same, Q & T	45/45	7.51	151,989	182,671	0.9	22.0	36 HRC	63,336	0.35

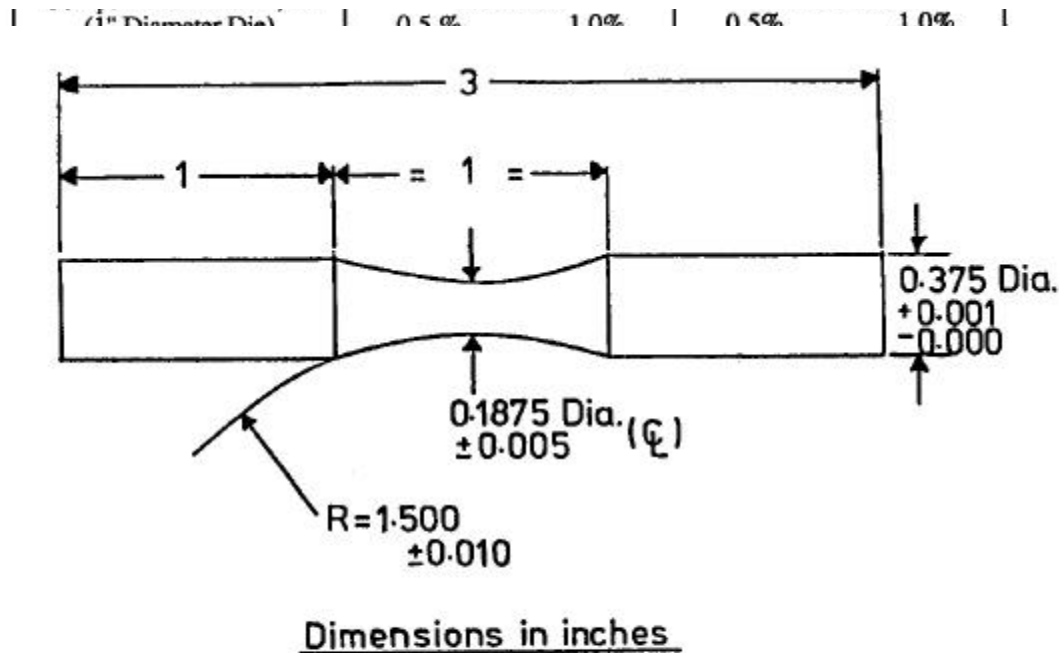
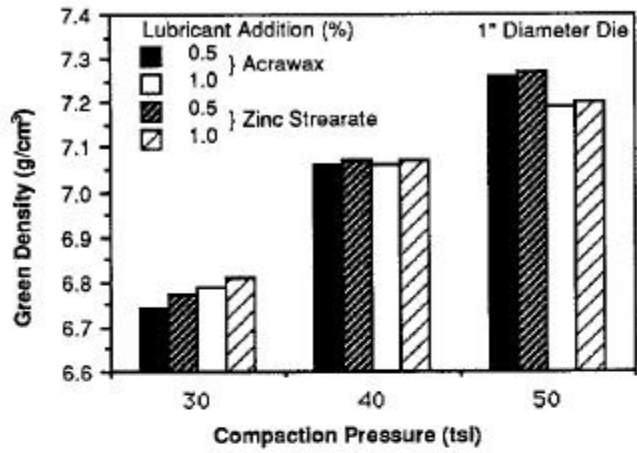
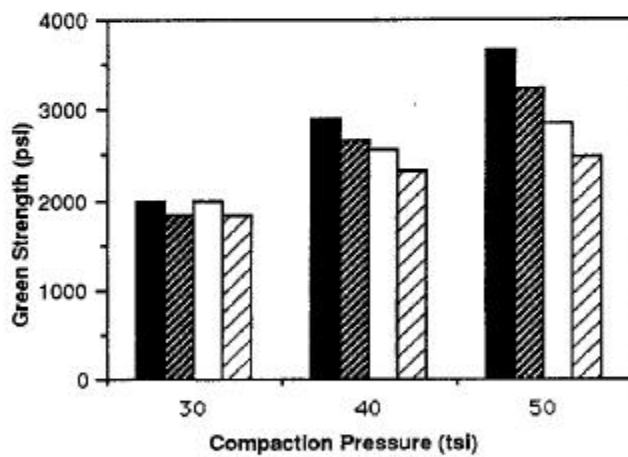


Figure 1 - Schematic illustration of the rotating bending fatigue specimen dimensions. [Ref. 1]

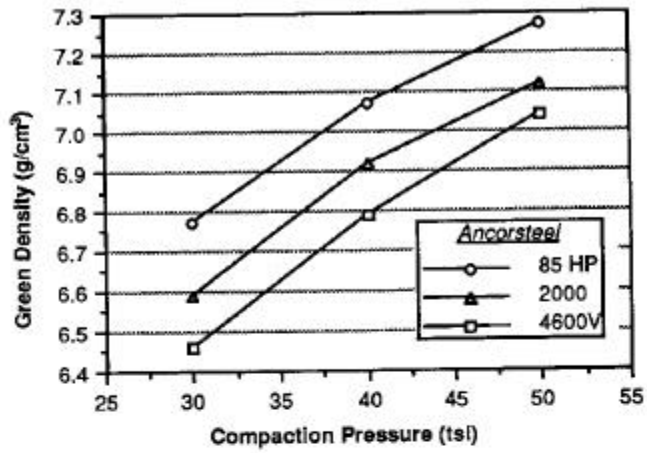


(a)

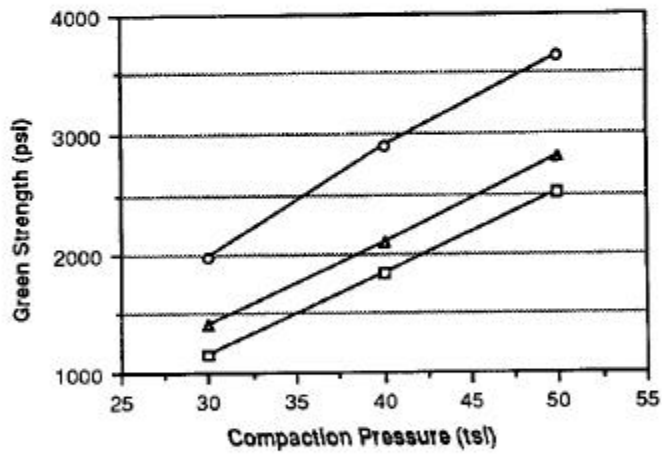


(b)

Figure 2 - Compressibility (a) and green strength (b) of Ancorsteel 85 HP mixed with 0.5 and 1.0 Acrawax and Zinc Stearate.

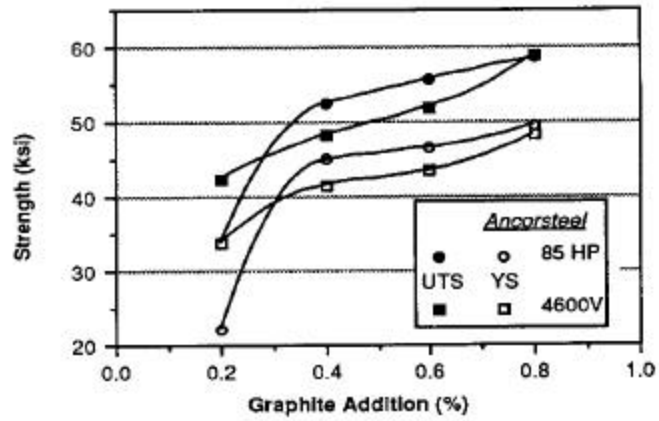


(a)

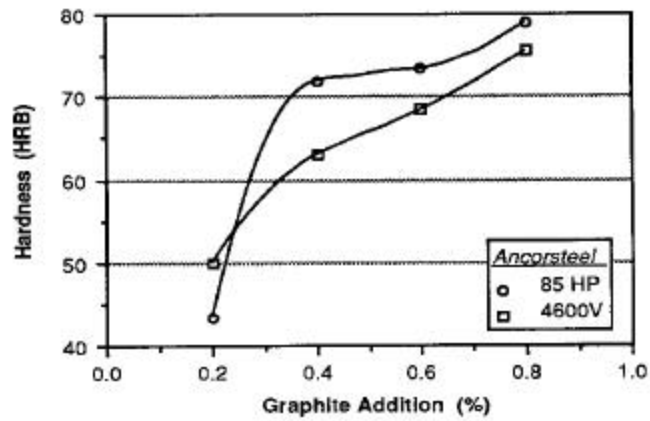


(b)

Figure 3 - Compressibility (a) and green strength (b) of Ancorsteel 85 HP, Ancorsteel 2000, ; Ancorsteel 4600V Mixed with 0.5% zinc stearate.

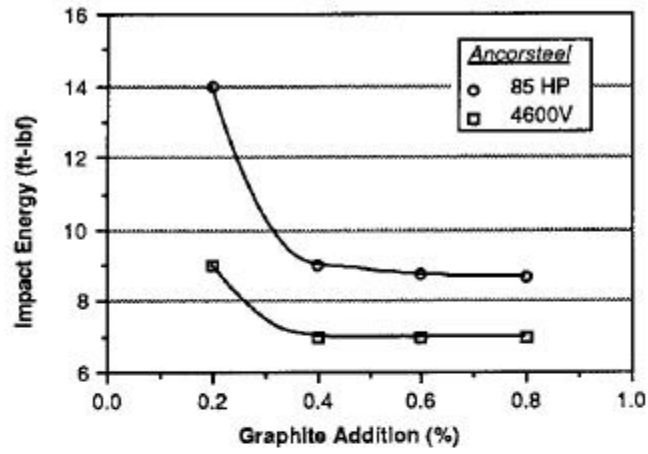


(a)

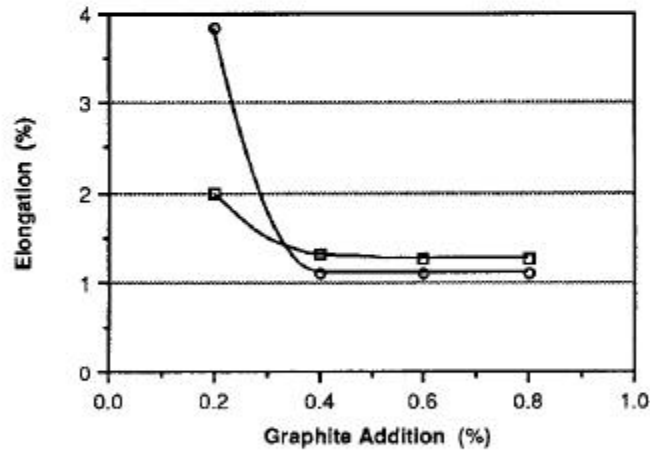


(b)

Figure 5 - Effect of graphite addition on the as-sintered strength (a) and hardness (b) of Ancorsteel 85 HP and Ancorsteel 4600V compacted at 40 tsi.



(a)



(b)

Figure 6 - Effect of graphite addition on the as-sintered unnotched charpy impact energy (a) and elongation (b) for Ancorsteel 85 HP and Ancorsteel 4600V compacted at 40 tsi.

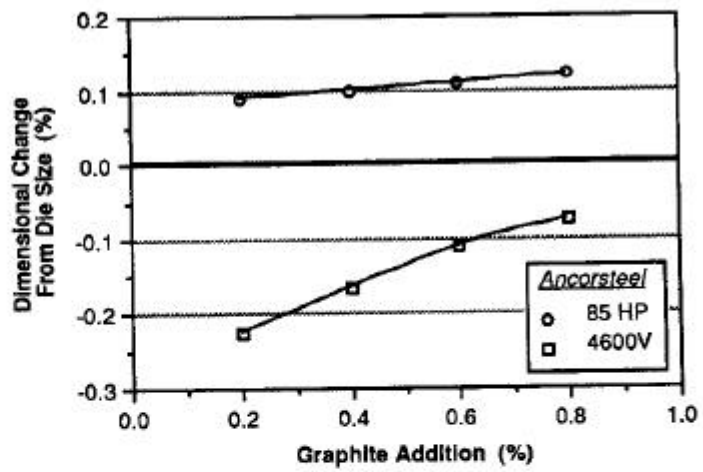


Figure 7 - Effect of graphite addition on as-sintered dimensional change from die size of Ancorsteel 85 HP and Ancorsteel 4600V compacted at 40 tsi.

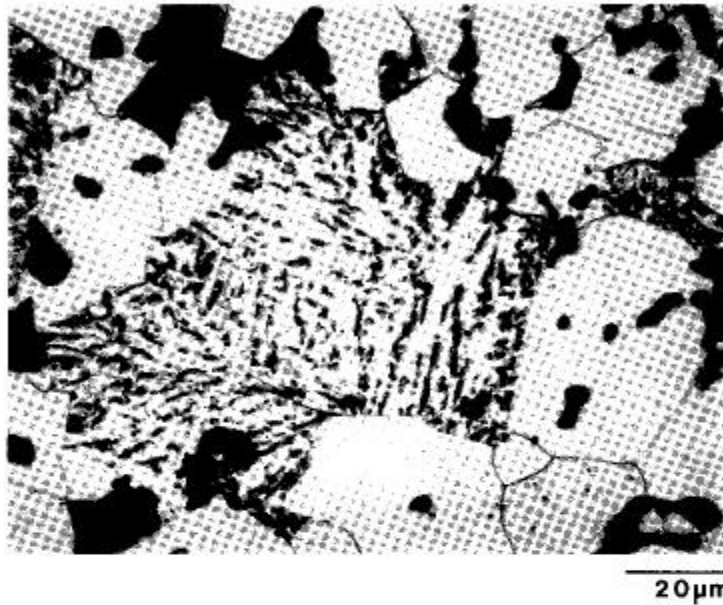


Figure 8 - Photomicrograph of Ancorsteel 85 HP mixed with 0.2% graphite in the as-sintered condition. The structure is made up of two constituents; polygonal ferrite grains and an aggregate of accicular ferrite and carbide (dark etching). The etchant was 2% nital, 4% picral.

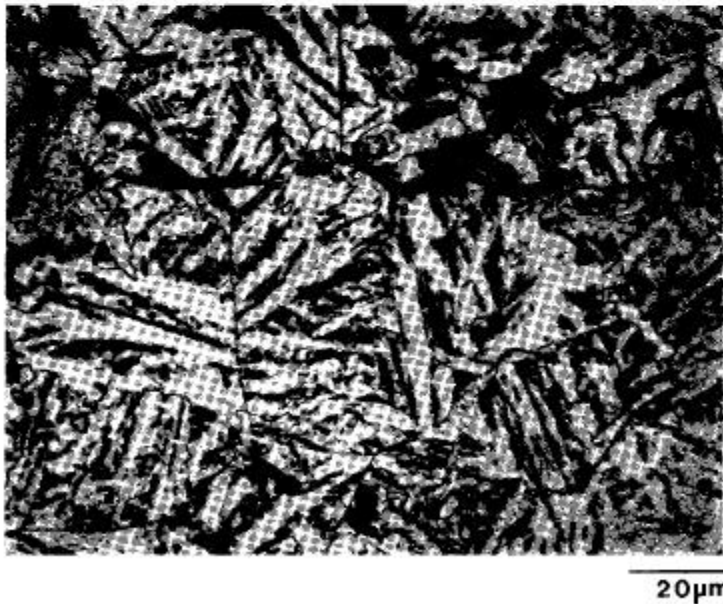
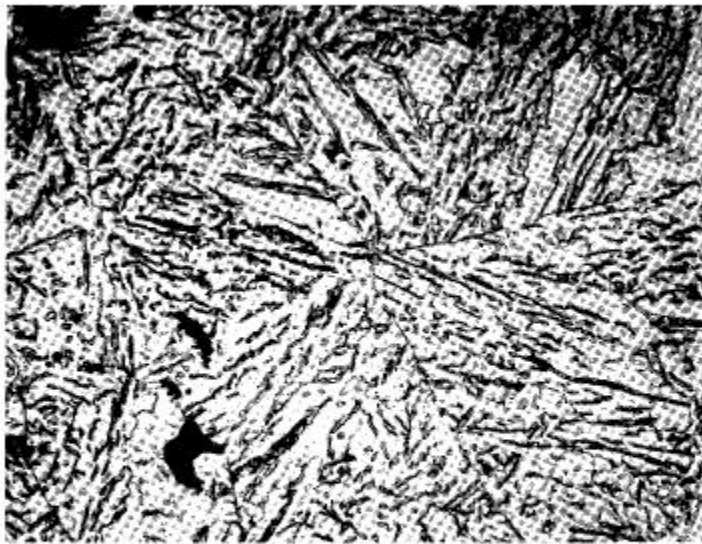


Figure 9 - Photomicrograph of Ancorsteel 85 HP mixed with 0.4% graphite in the as-sintered condition. The structure is a uniform aggregate of accicular ferrite and carbide. The etchant was 2% nital, 4% picral.



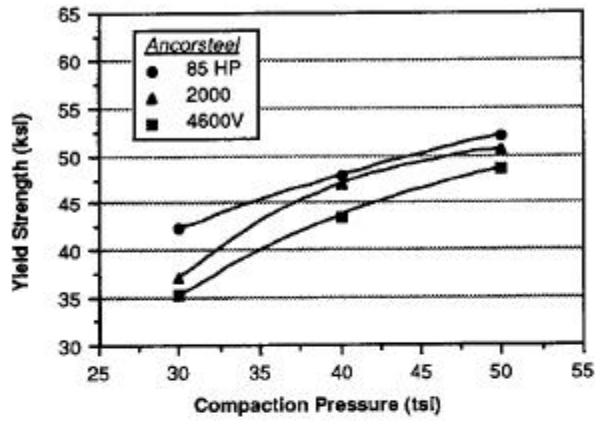
20 μ m

Figure 10 - Photomicrograph of Ancorsteel 85 HP mixed with 0.6% graphite in the as-sintered condition. This sample contains coarse carbides compared with the sample containing 0.4% graphite (Figure 9). The etchant was 2% nital, 4% picral.

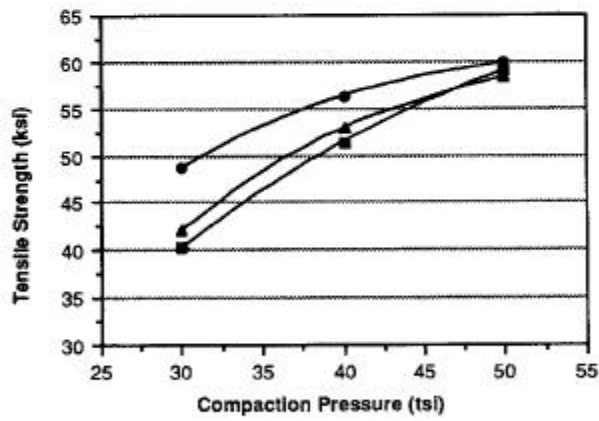


20 μ m

Figure 11 - Photomicrograph of Ancorsteel 85 HP mixed with 0.8% graphite in the as-sintered condition. The structure is an aggregate of acicular ferrite and carbide. The carbides have a lamellar appearance in certain orientations. However, the structure is not believed to be pearlite. The etchant was 2% nital, 4% picral.

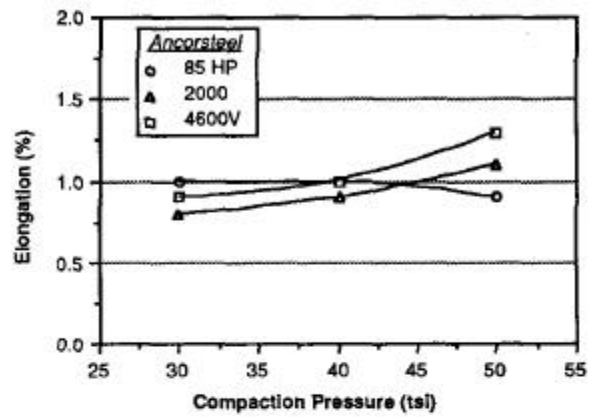


(a)

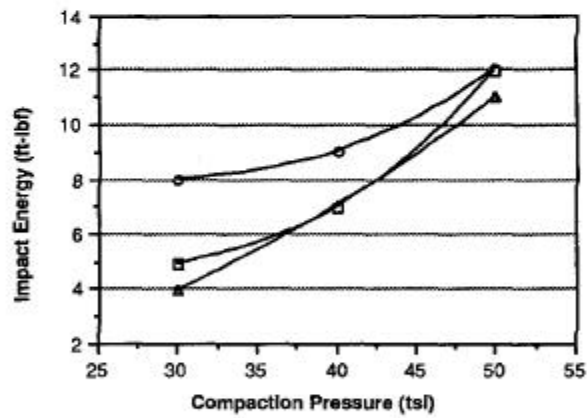


(b)

Figure 12 - Yield (a) and tensile (b) strength versus compaction pressure of Ancorsteel 85 HP, Ancorsteel 2000, and Ancorsteel 4600V mixed with 0.6% graphite and 0.5% zinc stearate.



(a)



(b)

Figure 13 - As-sintered elongation (a) and unnotched charpy impact energy (b) of Ancorsteel 85 Ancorsteel 2000, and Ancorsteel 4600V mixed with 0.6 % graphite and 0.5 % zinc stearate.

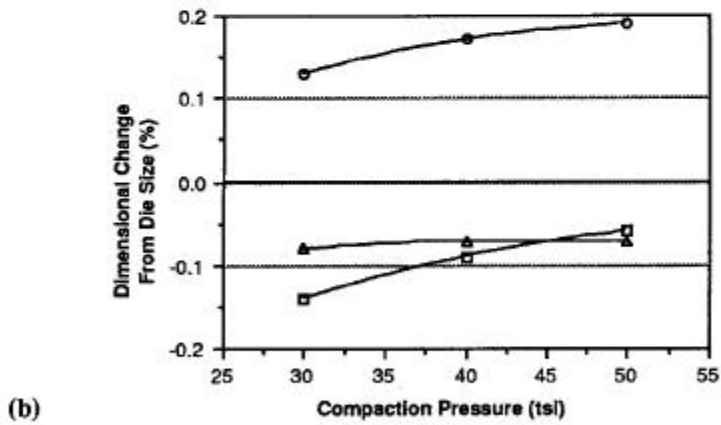
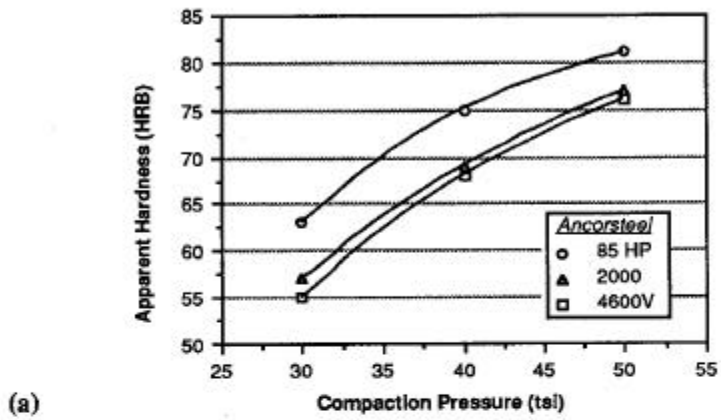
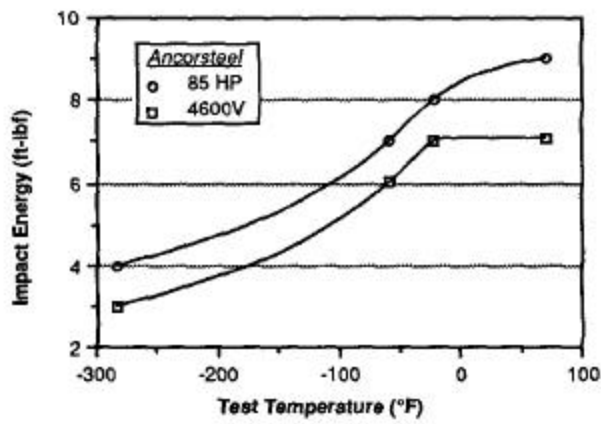
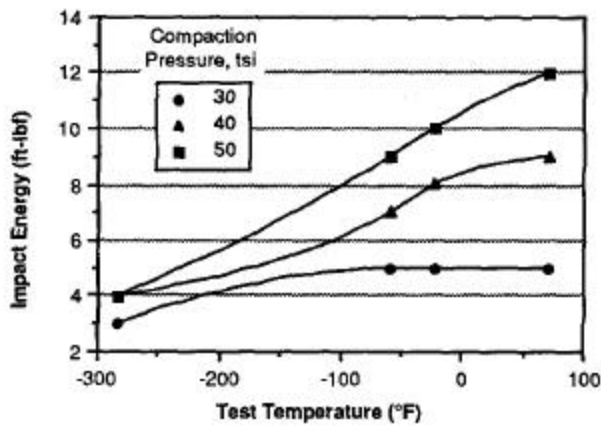


Figure 14 - As-sintered hardness (a) and dimensional change from die size (b) of Ancorsteel 85 HP, Ancorsteel 2000, and Ancorsteel 4600V mixed with 0.6% graphite and 0.5% zinc stearate.



(a)



(b)

Figure 15 - Effect of test temperature on as-sintered impact energy for: (a) Ancorsteel 85 HP and Ancorsteel 4600V mixed with 0.6% graphite and 0.5% zinc stearate and compacted at 40 tsi, (b) effect of compaction pressure for Ancorsteel 85 HP as above.

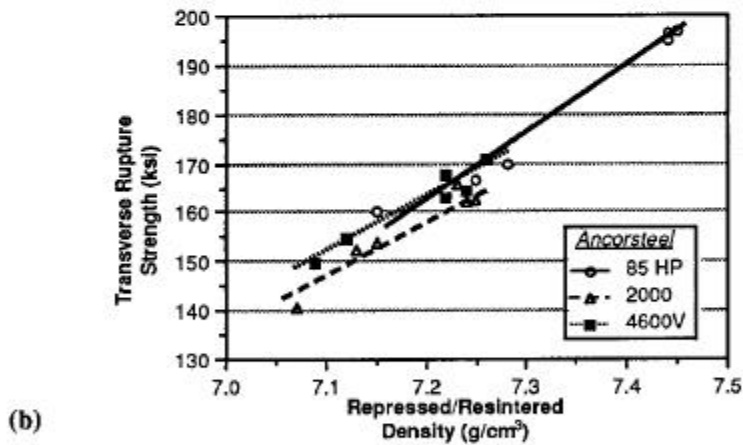
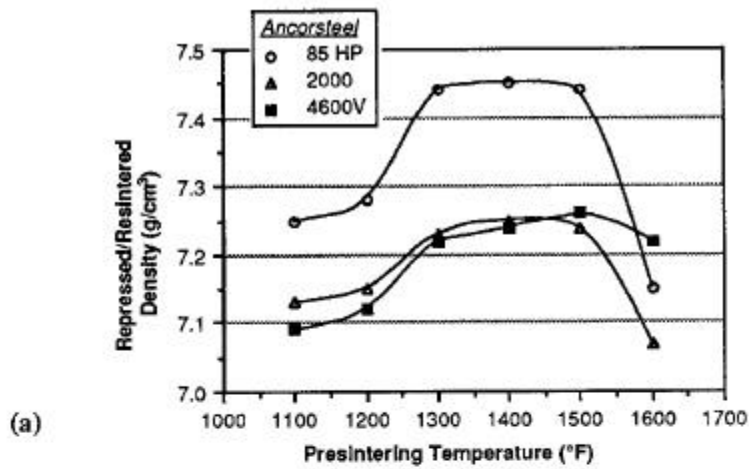
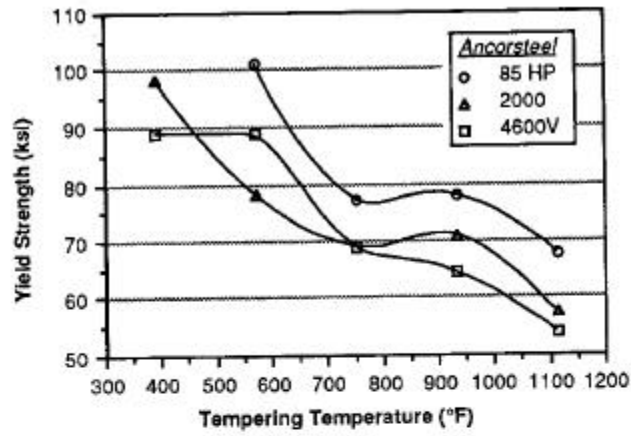
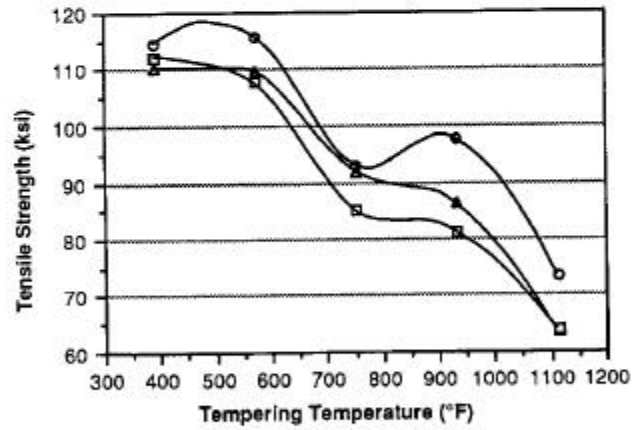


Figure 16 - Presintering reponse of Ancorsteel 85 HP, Ancorsteel 2000, and Ancorsteel 4600V mixed with 0.6% graphite and 0.5% zinc stearate: a) density after compaction at 45 tsi, presintering at the indicated temperature for 30 minutes in dissociated ammonia, repressing at 45 tsi and resintering at 2050 °F for 30 minutes in dissociated ammonia, b) double pressed and sintered transverse rupture strength.

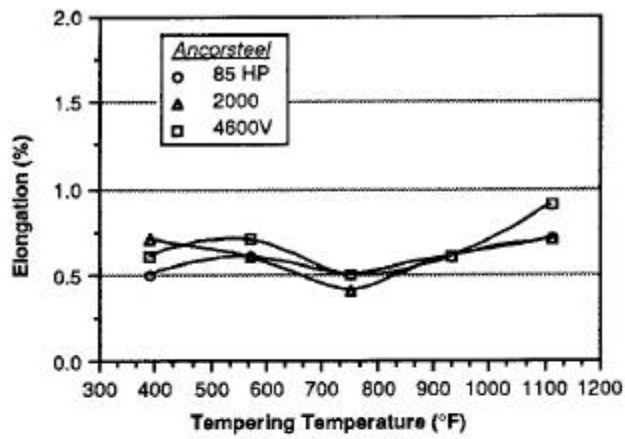


(a)

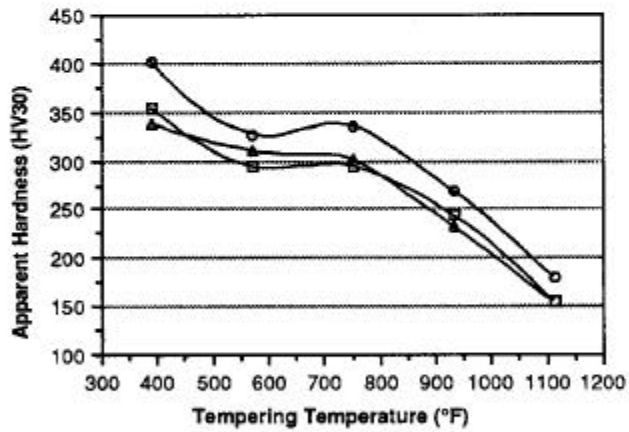


(b)

Figure 17 - Effect of tempering temperature on the quench and tempered yield and tensile strength of Ancorsteel 85 HP, Ancorsteel 2000 and Ancorsteel 4600V mixed with 0.6% graphite and 0.5% zinc stearate compacted at 40 tsi.

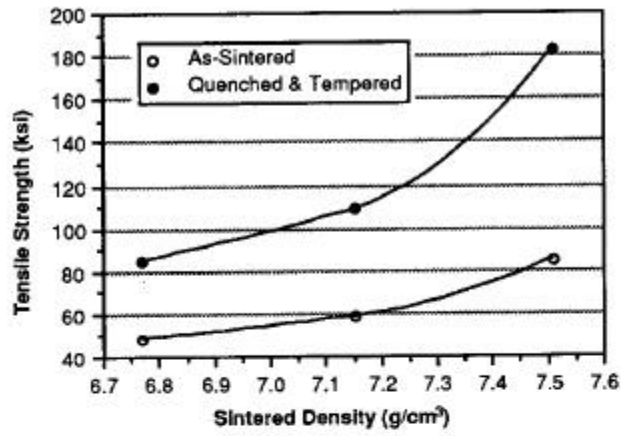


(a)

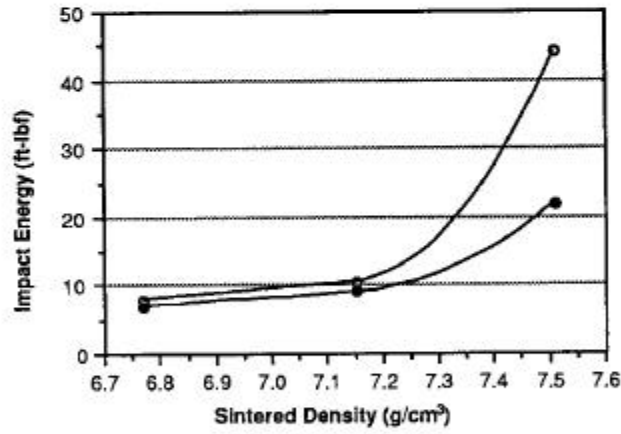


(b)

Figure 18 - Effect of tempering temperature on the quenched and tempered elongation and hardness of Ancorsteel 85 HP, Ancorsteel 2000 and Ancorsteel 4600V mixed with 0.6% graphite and 0.5% zinc stearate compacted at 40 tsi.

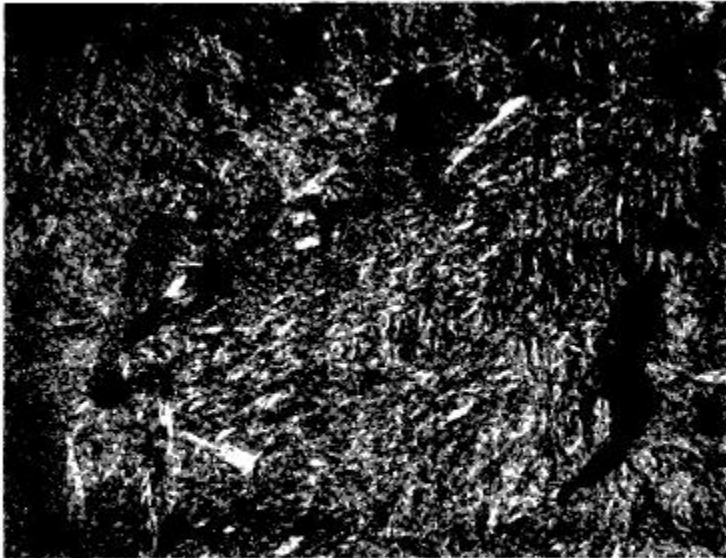


(a)



(b)

Figure 19 - Effect of density on the as-sintered and quenched and tempered tensile strength (a) and impact energy (b) of Ancorsteel 85 HP mixed with 0.6% graphite.



20µm

Figure 20 - Photomicrograph of quenched and tempered Ancorsteel 85 HP. The homogeneous microstructure is tempered martensite. The etchant was 2% nital, 4% picral.

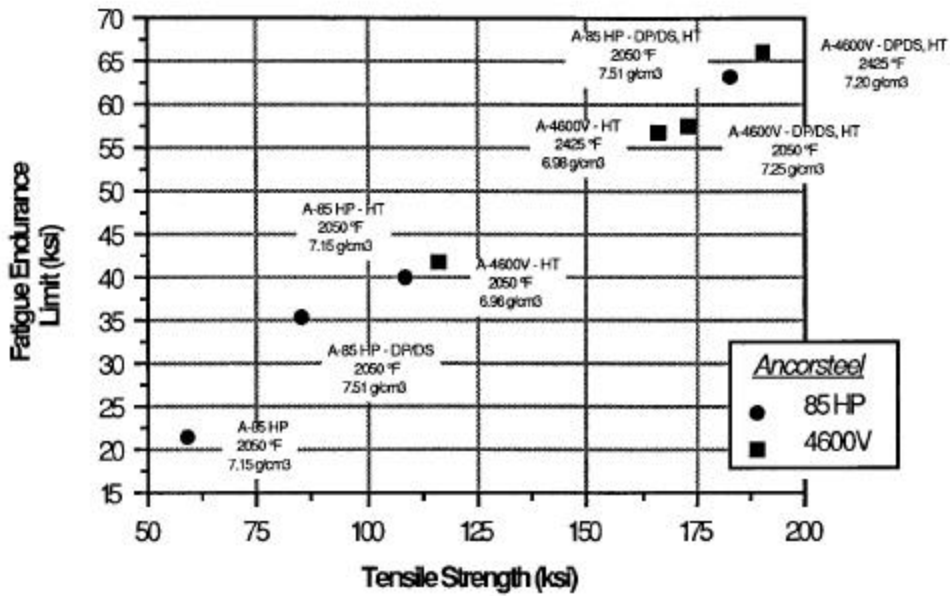


Figure 21 - Fatigue Endurance Limits of Ancorsteel 85 HP and Ancorsteel 4600V [Ref. 15] plotted with respect to tensile strength.