A SUPERIOR SINTER-HARDENABLE MATERIAL

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ABSTRACT

Sinter-hardening technology has been assisting the P/M parts fabricator by improving processing efficiencies and reducing costs. Furthermore, the barriers to attaining good sinter-hardenability and part performance have been reduced through improvements in materials and equipment developments. Recent material advances have focused on new alloys with increased hardenability and compressibility.

A new sinter-hardenable alloy has been introduced which provides improvements in hardenability and compressibility over the well-established FLC-4608 composition. These improvements will allow fabricators to reach higher densities and mechanical performance under typical compaction and sintering conditions. Mechanical performance and material capabilities are investigated as a function of density and admixed composition. Additional processing to achieve higher green densities and mechanical performance will also be reviewed.

BACKGROUND

Sinter-hardening usually refers to the process of cooling a part from the sintering temperature at a rate sufficient to transform a significant portion of the material matrix to martensite. Interest in sinter-hardening has grown because it offers good manufacturing economy by providing a one step process and a unique combination of strength, toughness, and hardness.

A variety of microstructures and properties can be obtained by varying the post sintering cooling rate. By controlling the cooling rate, the microstructure can be manipulated to produce the required proportion of martensite necessary to meet or exceed property targets. By understanding how the sintering conditions affect the microstructure, materials can be modeled to produce the final properties that are desired.
The characteristic isothermal transformation (I -T) diagram provides a graphical means of examining the effects of alloying elements on the microstructure of an as-sintered steel. This diagram indicates the time necessary for the isothermal transformation to start and end as well as the cooling time \ temperature combinations required to produce the final microstructure.

Alloying elements are used in P/M materials to promote hardenability and increase the mechanical strength of the parts. Typical alloying elements such as molybdenum, nickel, and copper move the continuous cooling transformation curves to the right, allowing phase transformations to occur at slower cooling rates. By alloying the materials, the hardenability increases and more martensite can be produced at sintering furnace cooling rates.

In addition to cooling rate, the hardenability of a material is a critical factor in defining the type of structure that will be produced upon cooling. Hardenability is the property that determines the depth and distribution of hardness induced by quenching from the austenitic condition. A material with high hardenability has the ability to transform to martensite without forming secondary phases such as bainite, even at slower cooling rates. Optimum sinter-hardening materials should have a high hardenability, such that the cooling rates needed to produce large proportions of martensite will be attainable.

INTRODUCTION

Continued growth of the P/M industry is very much dependent upon meeting ever increasing performance requirements. The key to continually meeting and surpassing increasing performance targets is to thoroughly understand the density, composition, and microstructure relationships of a given P/M system.

Density

The role of density in P/M performance is well understood. The benefit of increasing density on P/M performance has been thoroughly investigated over the years. The combination of existing technologies such as double press/ double sinter, and new processes like warm compaction with ANCORDENSE® technology have been shown to have a considerable effect on density. Using ANCORDENSE technology, it has been demonstrated that a density increase of 3.0% resulted in a 30% increase in transverse rupture strength (TRS) of a Distaloy 4800A based material [1]. Further densification through high temperature sintering resulted in an additional increase of 1.2% in density, and an additional 14% increase in TRS. The effect of increased density on ductility measurements such as tensile elongation and impact properties was even more pronounced. Understanding how to maximize the density of P/M components is an important step toward producing parts for high performance applications.

Composition and Microstructure

Material composition plays an equally important role in P/M performance. At a given density level, alloying elements that aid hardenability of an alloy system generally improve the mechanical performance of the system. Such alloying elements can be added to the melt prior to atomization, thereby creating a prealloyed material. The primary benefit of prealloyed P/M materials is uniform chemistry within each powder particle and throughout the P/M compact following compaction and sintering. Ideally, this uniformity allows for consistent hardenability throughout the part, providing excellent response to accelerated cooling and / or heat treatment. On the other hand, increasing prealloy content generally decreases a powder’s compressibility and makes it more difficult to reach higher density levels.

Nickel and molybdenum have been used in the development of prealloy powders such as Ancorsteel® 2000 and Ancorsteel 4600V. These prealloy powders have been employed for years in P/M and P/F applications, where high performance is required. Even at high compacting pressures, single press density levels are typically limited to 6.8 - 6.9 g/cm^3 due to the compressibility constraints of these materials. However, many automotive and lawn and garden applications requiring wear resistance (e.g. high hardness) have favorably applied these materials with the assistance of sinter-hardening or a secondary heat treatment. To further improve the hardenability of these alloys, copper is often admixed with the prealloyed base material. The resultant material is often referred to as a hybrid system. The FLC-4608 composition provides a benchmark material for sinter-hardening alloy development, targeting larger mass and increased section size P/M components. The investigation studied the relationship between post sintering cooling rates, mechanical performance, and microstructure.

The development of materials with lower prealloyed chemistry content and improved compressibility created additional avenues to improve material performance. The use of molybdenum as the primary alloying element was introduced with Ancorsteel 85 HP and Ancorsteel 150 HP. Despite its lower prealloy content, Ancorsteel 85 HP premix compacts exhibited a greater ultimate tensile strength than comparable Ancorsteel 4600V premix compacts under accelerated cooling conditions [2]. The more compressible Ancorsteel 85 HP material exhibited an increase in density when compacted at 45 tsi compared with the Ancorsteel 4600V. These important findings demonstrated the importance of understanding composition and density constraints when choosing an alloy and processing system. Development of the Ancorsteel 85 HP based system continued by increasing admixed copper and nickel contents to further improve material performance. Ultimate tensile strength and apparent hardness were seen to increase with increasing martensite content. Through this work, a strong understanding of materials, processing, microstructure and mechanical performance was established.

Controlling microstructure with proper material selection and processing conditions offers opportunities to improve mechanical performance. Specifically, accelerated cooling from sintering temperatures will produce for martensitic transformation and increase sintered strength and apparent hardness. As discussed above, the benefits of sinter-hardening have greatly expanded due to material developments. In addition, recent developments in accelerated cooling systems have made it possible to achieve higher cooling rates.

Material Design

The aim of alloy design is to increase hardenability by delaying the austenite to ferrite plus carbide transition so that martensite forms during cooling. As hardenability increases, martensite is capable of forming at progressively lower cooling rates. In ferrous metallurgy, several predictors exist that foretell the effect of individual elements and combinations of elements upon hardenability. Unfortunately, a qualitative ranking of alloying element effects, as presented in Table I, indicates that, to a large degree, the alloys that are efficient in improving hardenability tend to reduce compressibility and increase the oxygen content of the sintered part.

Table I: Qualitative Ranking of Alloying Elements in Prealloyed Materials

	Hardenability Factor	Effect on Compressibility	Affinity for Oxygen
Higher	Manganese	Copper	Manganese
	Chromium	Nickel	Chromium
	Molybdenum	Chromium	Nickel
	Copper	Manganese	Molybdenum
Lower	Nickel	Molybdenum	Copper

The table indicates that, if alloy design principles established for wrought alloys are employed, efficient sinter-hardening alloys require significant chromium and manganese contents. However, the stability of chromium and manganese oxides under conventional powder processing and sintering conditions dictates that a high proportion of the alloy addition will not remain in solution in the alloy matrix. Under these conditions, chromium and manganese will not contribute to hardenability and their presence as particle and grain boundary oxides may reduce performance.

Overall Alloying Effects Study

In an effort to discern the effects of individual alloying additions and combinations, a matrix study was performed on over thirty prealloys with varying chromium, nickel, molybdenum, and manganese contents and processed in straight graphite and copper-graphite mixes [3,4].

Overall, apparent hardness was seen to increase with alloy content. However, the most effective alloying additions were found to be manganese and the combination of nickel and molybdenum. Although chromium aided hardenability in straight graphite mixes when present in concentrations less than 0.5 w/o, it had little effect in copper-graphite mixes.

Higher alloy contents generally led to lower compressibilities. Nickel tended to decrease compressibility slightly, while manganese and molybdenum were very similar in their behavior and caused moderate drops in compressibility. The sharpest decrease in compressibility was seen with increasing chromium content.

Based on this analysis, an optimized alloy combination was developed into the following chemistry of a new sinter-hardenable material, Ancorsteel 737 SH : 0.42 w/o Mn, 1.25 w/o Mo, 1.40 w/o Ni. The work below illustrates the performance of Ancorsteel 737 SH premixes.

EXPERIMENTAL PROCEDURE

Part I - Effect of Copper and Graphite Additions

It is generally well known that copper and graphite additions have a dramatic effect on the properties of sinter-hardenable materials. Therefore, it becomes extremely important to fully characterize any sinter-hardening base material by investigating a range of premix compositions. Due to the alloy content's tendency to shift the eutectoid carbon content of a system, each base powder is likely to have its own 'optimum' premix composition(s) [5].

In an effort to gauge the effect of copper and carbon content on the properties of Ancorsteel 737 SH, nine premix compositions were chosen for investigation. These compositions are presented below in Table II. A 2200 gram premix was made for each composition. The copper used was ACuPowder 8081 and the graphite was Asbury 3203. In all cases, 0.75 w/o Lonza Acrawax was added to the mixes.

Table II: Premix Compositions for Part I

Premix	Copper (w/o)	Graphite (w/o)
1-1	--	0.5
1-2	--	0.7
1-3	--	0.9
1-4	1.0	0.5
1-5	1.0	0.7
1-6	1.0	0.9
1-7	2.0	0.5
1-8	2.0	0.7
1-9	2.0	0.9

Green density, green expansion, sintered density, and dimensional change were determined from the average of five compacted transverse rupture strength (TRS) specimens with a nominal size of 0.25 inches x 0.5 inches x 1.25 inches (6.35 mm x 12.7 mm x 31.75 mm). Tensile tests were conducted on machined threaded tensile specimens with a gauge length of 1.0 inches (25.4 mm) and a nominal diameter of 0.20 inches (5.08 mm). Due to the apparent hardness of the material, tensile specimens were machined by grinding. All specimens were compacted at 30 tsi (415 MPa), 40 tsi (560 MPa), and 50 tsi (690 MPa).

All test pieces were sintered under production conditions. The Abbott furnace used in this study was equipped with a VARICOOL post sintering cooling system which combines radiant and convection cooling to accelerate the cooling capabilities of the continuous belt furnace. The production sintering cycle was as follows:

Sintering Temperature:	2080ºF (1140ºC)
Atmosphere:	90 v/o N_2 , 10 v/o H_2
Belt Speed:	5.0 in/min
VARICOOL Setting:	60 Hz

The parts were at sintering temperature for 30 minutes. The sintered parts were tempered at 400ºF (205ºC) in air for 1 hour prior to testing or machining.

Apparent hardness measurements were performed on the surface of the specimens using a Rockwell hardness tester. All measurements were conducted on the Rockwell C scale (HRC) for ease of comparison. Transverse rupture strength and dimensional change from die size were measured according to ASTM B 528 and B 610. Tensile testing was performed on a 60,000 pound (267,000 newton) Tinius Olsen universal testing machine at a crosshead speed of 0.025 inches/minute (0.635 milimeters/minute). Elongation values were determined by utilizing an extensometer with a range of 0 to 20%. The extensometer was left on until failure.

Part II - Premix Refinement

Upon completion of Part I, the general effects of copper and carbon on the properties of Ancorsteel 737 SH were becoming clearer. The next phase represented an effort to further refine premix compositions in order to increase mechanical properties under the same production conditions. The premixes considered in phase II are listed in Table III.

Table III: Premix Compositions for Part II

Premix	Copper (w/o)	Graphite (w/o)
2-1	--	0.8
2-2	1.0	0.7
2-3	1.5	0.8
2-4	2.0	0.9

All sintering, testing, and specimen preparation was done in accordance with the procedures listed under Part I.

Part III - Impact / Temper Study

A tempering study was conducted to gain a more complete understanding of the tempering response of Ancorsteel 737 SH premixes and how the impact properties / apparent hardnesses of these materials can be affected. The premixes from Part II, as seen in Table III, were the premixes studied.

Charpy impact specimens were pressed from each mix to a 7.0 g/cm^3 density. Bars were sintered per the production sintering cycle designated in Phase I. A set of five bars per mix were then tempered at each of the following temperature / conditions for 1 hour: no temper, 200ºF (95ºC), 300ºF (150ºC), 350ºF (175ºC), 400ºF (205ºC), 500ºF (260ºC), 600ºF (315ºC), and 800ºF (425ºC). Sintered density, dimensional change from die size, and Rockwell apparent hardness were determined prior to impact testing.

Part IV - ANCORDENSE Processing

A concurrent development project employed ANCORDENSE processing in an effort to increase the density and properties of select Ancorsteel 737 SH premixes. These premixes are listed in Table IV. In all cases, 0.6 w/o lubricant was added.

Table IV: ANCORDENSE Premix Compositions

Premix	Copper (w/o)	Nickel (w/o)	Graphite (w/o)
AD 1	--	--	1.0
AD 2	2.0	--	0.9
AD 3	--	2.0	0.9

Metallography

Metallographic evaluation was performed on sections prepared from machined tensile, TRS, and charpy impact bars. Photomicrographs showing typical microstructures were taken following a 1% nital / 4% picral etch at an original magnification of 500X. The relative martensite content was determined utilizing a point count method. Pores were subtracted for purposes of reporting the percentages of microstructural constituents.

RESULTS AND DISCUSSION

Part I - Effect of Copper and Graphite Additions

Data collected while testing Ancorsteel 737 SH premixes with varied copper and graphite additions are presented in Table V. Sintered carbon levels for premixes which contained 0.5 w/o, 0.7 w/o, and 0.9 w/o admixed graphite averaged 0.44 w/o, 0.63 w/o, and 0.83 w/o, respectively.

In the scope of this investigation, only minor increases in apparent hardness were observed at admixed graphite levels beyond 0.7 w/o. This lack of apparent hardness gains seemed to show the robustness of Ancorsteel 737 SH and the presence of an ‘apparent hardness plateau’ under the production conditions considered. The effect of carbon content on mechanical properties was especially evident in the TRS data trend shown in Figure 1. Irrespective of copper content, transverse rupture strength was seen to peak at the 0.7 w/o admixed graphite level (0.63 w/o sintered carbon).

Beyond the peak at 0.7 w/o graphite content, transverse rupture strength was thought to decrease due to lower M_s temperatures (with increasing graphite content) and more retained austenite content. Although a similar peak was seen in yield strength data, ultimate tensile strength values did not follow this trend.

The effect of copper can clearly be seen in Figure 1. A 1 w/o copper addition produced a marked increase in transverse rupture strength values over the entire range of carbon contents. However, when copper was increased to 2 w/o, no appreciable increases in transverse rupture strengths were observed. A similar effect was seen in yield strengths. This result seemed to suggest that, for strength and economy, a 1 w/o copper addition was optimum under the production conditions studied. Data presented in the next section also covers premixes of different copper contents.

When all premixes were compared, the 1 w/o copper - 0.7 w/o graphite composition presented the most interesting combination of apparent hardness, strength, and ductility. The mechanical properties attainable with premix #1-5 were seen to closely mirror those achieved by the commonly used 2 w/o copper - 0.9 w/o graphite (premix #1-9) composition. In fact, the yield and tensile strengths of premix #1-5 tended to be 10-15% higher than those seen for #1-9

Table V: Ancorsteel 737 SH Premix Compositions with Varied Copper and Graphite Additions

Premix	Cu (w/o)	Gr (w/o)	Comp Press (tsi)	Green Density (g/cm^3)	Green Exp. (%)	Sintered Density (g/cm^3)	Dim. Change (%)	App Hard (HRC)	TRS (10^3 psi)	YS (10^3 psi)	UTS (10^3 psi)	Elong. (%)
1-1		0.5	30	6.55	0.13	6.51	+0.08	0	111	58	69	1.0
			40	6.86	0.16	6.82	+0.10	2	138	69	83	1.1
			50	7.05	0.20	7.03	+0.12	8	166	71	87	1.2
1-2	--	0.7	30	6.55	0.13	6.49	+0.19	22	137	84	88	0.7
			40	6.85	0.16	6.79	+0.22	32	179	88	97	0.6
			50	7.03	0.20	6.98	+0.25	37	199	114	118	0.7
1-3	--	0.9	30	6.56	0.16	6.50	+0.21	27	117	68	72	0.6
			40	6.85	0.17	6.79	+0.26	34	148	77	80	0.5
			50	7.02	0.21	6.97	+0.28	39	165	90	95	0.6
1-4	1.0	0.5	30	6.58	0.14	6.58	+0.24	19	153	97	106	0.9
			40	6.88	0.14	6.80	+0.27	26	182	115	135	1.3
			50	7.07	0.17	6.99	+0.30	30	227	121	148	1.4
1-5	1.0	0.7	30	6.58	0.14	6.51	+0.22	26	156	103	106	0.9
			40	6.87	0.15	6.80	+0.26	32	206	114	119	1.0
			50	7.06	0.19	6.99	+0.30	37	238	134	151	1.3
1-6	1.0	0.9	30	6.58	0.13	6.53	+0.12	29	140	80	82	0.8
			40	6.87	0.16	6.81	+0.18	35	187	99	100	0.8
			50	7.03	0.19	6.99	+0.22	39	202	107	114	0.9
1-7	2.0	0.5	30	6.59	0.12	6.45	+0.52	17	151	99	101	0.8
			40	6.89	0.18	6.74	+0.57	25	187	116	130	1.0
			50	7.07	0.18	6.93	+0.58	28	233	133	151	1.2
1-8	2.0	0.7	30	6.59	0.13	6.51	+0.29	26	167	101	102	0.8
			40	6.88	0.17	6.78	+0.38	31	211	119	124	0.9
			50	7.04	0.19	6.96	+0.41	35	258	141	146	1.0
1-9	2.0	0.9	30	6.60	0.13	6.57	+0.03	27	166	86	94	0.9
			40	6.88	0.16	6.83	+0.10	34	200	105	122	1.0
			50	7.04	0.19	7.01	+0.15	38	234	114	132	0.9

*Note - All sintered and mechanical properties reported for tempered specimens

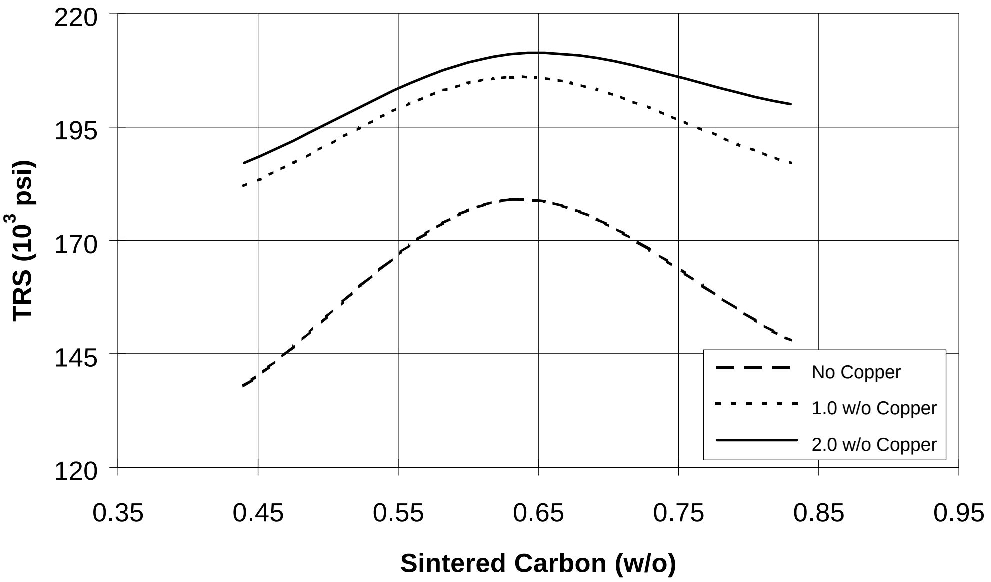

Figure 1 : Transverse Rupture Strength as Function of Sintered Carbon Content for Specimens Compacted at 40 tsi

Part II - Premix Refinement

Sintered carbon levels above the 0.65 - 0.75 w/o range were previously shown to adversely affect the mechanical properties of Ancorsteel 737 SH without substantially boosting properties in other key areas (i.e. apparent hardness). In an effort to further resolve the range of interest, a premix refinement effort was undertaken. The results of this study are presented in Tables VI and VII.

Table VI: Comparison of the Green and Sintered Properties of Premixes

Premix	Cu (w/o)	Gr (w/o)	Comp Press (tsi)	Green Density (g/cm^3)	Green Exp (%)	Sint. Density (g/cm^3)	D.C. (%)	App Hard (HRC)	TRS (10^3 psi)
2-1	--	0.8	30	6.58	0.13	6.54	+0.14	28	144
			40	6.87	0.17	6.83	+0.18	34	193
			50	7.04	0.19	7.01	+0.22	39	227
2-2	1.0	0.7	30	6.60	0.12	6.54	+0.16	27	154
			40	6.90	0.15	6.84	+0.22	33	212
			50	7.05	0.18	7.02	+0.27	37	242
2-3	1.5	0.8	30	6.62	0.13	6.56	+0.14	27	152
			40	6.90	0.15	6.84	+0.21	34	211
			50	7.06	0.18	7.01	+0.26	39	235
2-4	2.0	0.9	30	6.62	0.13	6.59	+0.05	30	141
			40	6.90	0.16	6.87	+0.10	36	204
			50	7.06	0.19	7.03	+0.15	39	240

*Note - All properties reported for tempered specimens

Table VII: Mechanical Properties of Select Ancorsteel 737 SH Premixes

Premix	Cu (w/o)	Gr (w/o)	Comp Press (tsi)	YS (10^3 psi)	UTS (10^3 psi)	Elong. (%)
2-1	--	0.8	30	104	113	1.0
			40	121	134	1.1
			50	129	145	1.1
2-2	1.0	0.7	30	107	121	1.2
			40	130	153	1.4
			50	143	176	1.6
2-3	1.5	0.8	30	110	122	0.9
			40	126	155	1.3
			50	133	173	1.4
2-4	2.0	0.9	30	94	124	1.3
			40	107	150	1.4
			50	115	160	1.4

*Note - Properties reported for tempered specimens

Once again, it was observed that increasing copper and graphite additions beyond 1.0 w/o and 0.7 w/o, respectively, led to only minor changes in apparent hardness values. Furthermore, mixes 2-2 and 2-3 exhibited nearly identical mechanical properties while higher graphite additions in mix 2-4, a commonly used sinter-hardening composition, caused a decline in mechanical performance. Based upon these results, small (~1.0 w/o) copper additions were found to be extremely beneficial for strength, but such additions had little effect on hardenability.

Part III - Impact / Temper Study

The effect of tempering temperature on the apparent hardness and impact properties of several Ancorsteel 737 SH premixes is presented in Table VIII. These data are also graphed in
Figures 2 and 3.

It was found that tempering at or below 300ºF (150ºC) had no appreciable effect on apparent hardness. However, upon reaching 350ºF (175ºC), a very definite softening was noted in all mixes. This softening trend continued over the range of tempering temperatures studied. Tempering temperatures at or around 350ºF (175ºC) to 400ºF (205ºC) were found to be quite effective, without causing excessive softening of the matrix.

A very defined peak in impact energy was noted for all mixes in the region of 350 to 400ºF. In the proximity of this peak, tempering temperatures appeared sufficient to increase toughness without sacrificing a great deal of apparent hardness. When impact energy and apparent hardness curves were overlaid, a region of interest was easily identified as lying between 350ºF (175ºC) and 400ºF (205ºC). Beyond this region, impact energy was seen to decline and apparent hardness was sacrificed.

Table VIII: Apparent Hardness and Impact Energy at Various Tempering Temperatures for Select Ancorsteel 737 SH Premixes

Premix	Cu (w/o)	Graphite (w/o)	Tempering Temp. (ºF / ºC)	Apparent Hardness (HRC)	Impact Energy (ft.lbf)
2-1	--	0.8	--	46	6
			200 / 95	46	6
			300 / 150	44	7
			350 / 175	41	7
			400 / 205	37	8
			500 / 260	34	6
			600 / 315	31	6
			800 / 425	30	6
2-2	1.0	0.7	--	42	8
			200 / 95	41	8
			300 / 150	41	9
			350 / 175	38	10
			400 / 205	36	10
			500 / 260	32	6
			600 / 315	31	6
			800 / 425	27	6
2-3	1.5	0.8	--	44	6
			200 / 95	45	6
			300 / 150	42	9
			350 / 175	39	9
			400 / 205	37	9
			500 / 260	33	6
			600 / 315	30	6
			800 / 425	29	5
2-4	2.0	0.9	--	46	6
			200 / 95	46	6
			300 / 150	43	9
			350 / 175	40	12
			400 / 205	39	11
			500 / 260	35	7
			600 / 315	33	6
			800 / 425	29	5

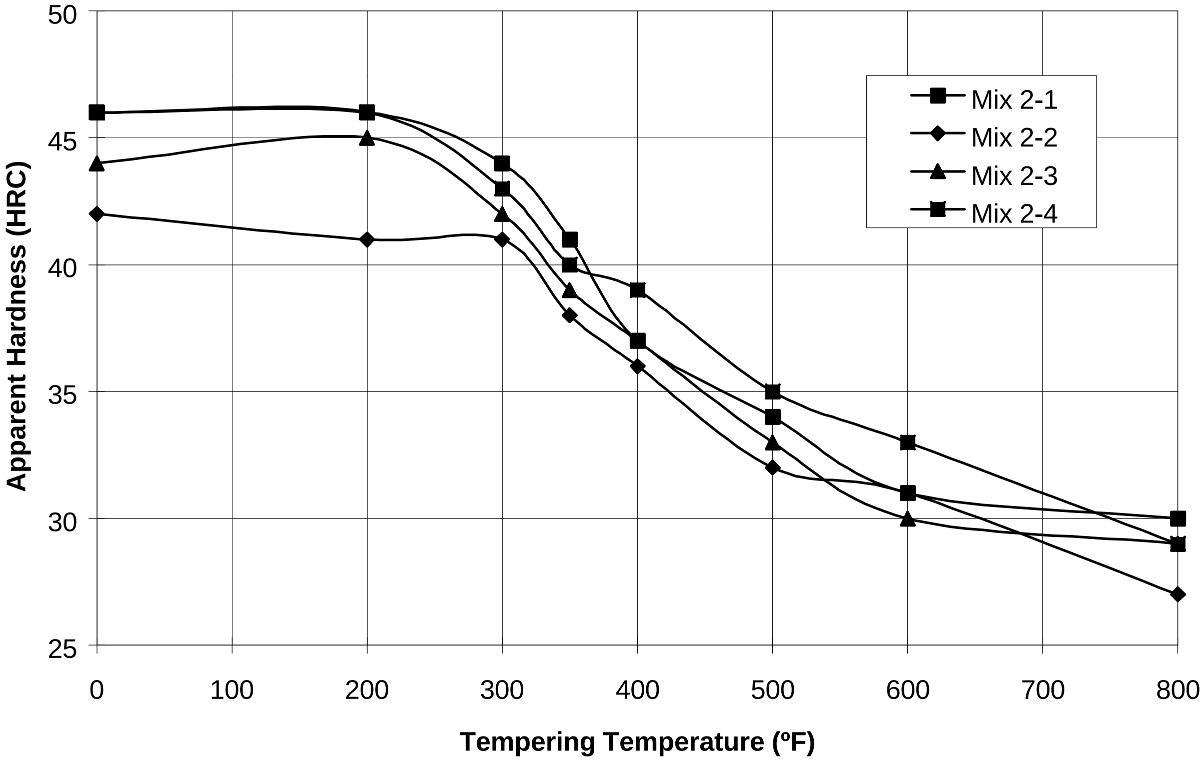

Figure 2: The Effect of Tempering Temperature on Apparent Hardness

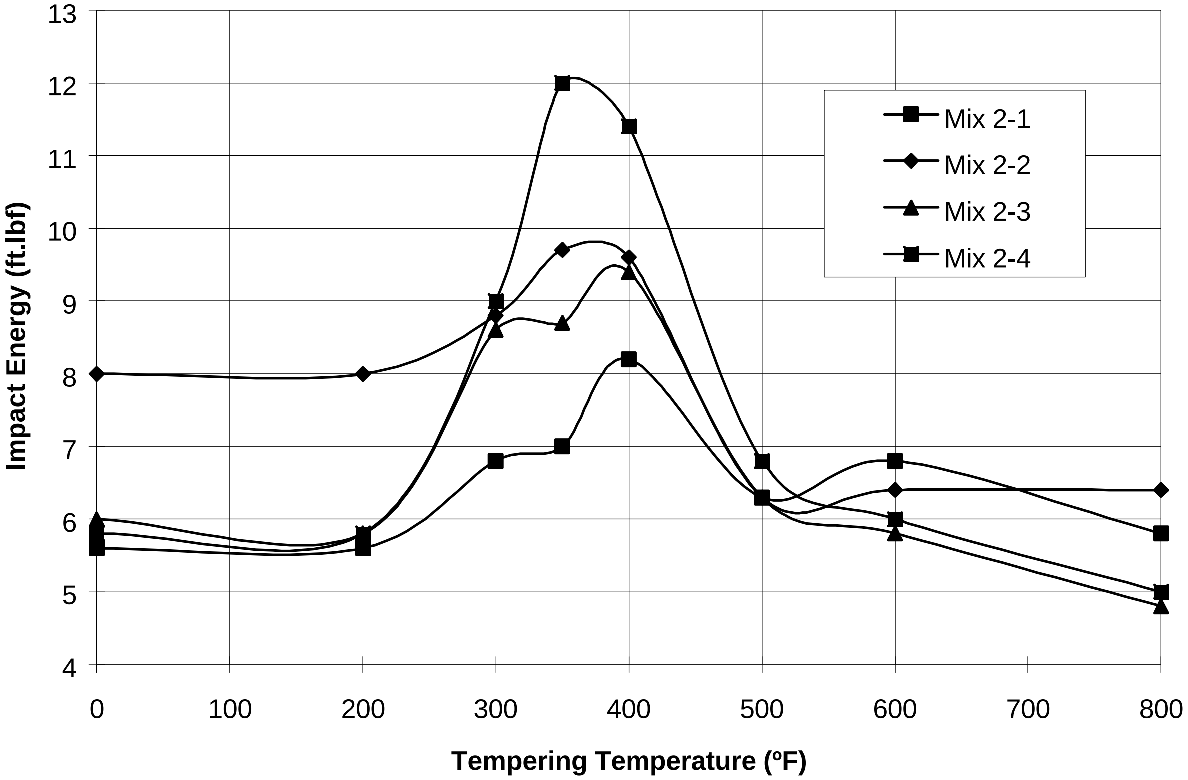

Figure 3: The Effect of Tempering Temperature on Impact Energy

Part IV - ANCORDENSE Processing

The data collected as part of an effort to increase density and mechanical performance of Ancorsteel 737 SH premixes by warm compaction are presented in Table IV. Mechanical properties are reported for specimens that were tempered at 400ºF for 1 hour.

Perhaps no other material system has exhibited the benefits of warm compaction better than Ancorsteel 737 SH. The material's excellent compressibility coupled with ANCORDENSE processing's ability to increase sintered density by 0.10 - 0.20 g/cm^3 yielded parts with enhanced mechanical properties and apparent hardness values. As-tempered apparent hardnesses of 40-45 HRC were easily achieved at compaction pressures of 40-50 tsi. At 45 tsi with copper and graphite additions, ultimate tensile strengths on the order of 190,000 psi (1310 MPa) were realized and elongations were seen to exceed 2.0%. Upon consideration of previously presented data, extrapolation of warm compaction data to lower graphite levels indicated strengths in excess of 200,000 psi (1380 MPa) might be possible.

Metallography

Martensite contents were seen to exceed 95% in all mixes except those with 0.5 w/o admixed graphite contents. Those 0.5 w/o graphite mixes were observed to contain a combination of martensite, lower bainite, lamellar pearlite, and divorced pearlite. Typical microstructures for select straight graphite and copper / graphite mixes are shown in Figures 4-6.

Retained austenite was not observed in mix 2-1 (Figure 7) and only small amounts were found in mix 2-2 (Figure 8). However, more retained austenite was seen to appear in mix 2-3 (Figure 9) and became even more noticeable in mix 2-4 (Figure 10). Interestingly enough, retained austenite tended to occur in areas of copper diffusion, along grain boundaries and particle perimeters, but not within the particles / grains themselves. This retained austenite can be observed as white regions in Figure 8-10. The presence of this retained austenite was thought to be responsible for the strength decrease in mix 2-4, as well as previously presented high graphite mixes such as 1-3, 1-6, and 1-9.

The location of retained austenite in Figures 8-10 seemed to suggest that higher copper concentrations in these regions, potentially coupled with higher carbon contents, had depressed the M_f temperature such that complete martensitic transformation was not possible at room temperature. Previous work suggests that the presence of carbon retards copper penetration into the grain boundaries and generally reduces copper diffusion into iron [6,7]. Since carbon can almost completely combine prior to reaching the melting point of copper during sintering, the effect of carbon on copper diffusion can be a significant one. This effect can lead to higher degrees of shrinkage due to the occurrence of a dissolution - precipitation process. Interestingly enough, the 2 w/o copper - 0.9 w/o graphite mix, which had the most pronounced "copper-rich" regions, was found to have a lower dimensional change than other mixes investigated.

Table IV: ANCORDENSE Properties of Ancorsteel 737 SH Premixes

Premix	Cu (w/o)	Ni (w/o)	Gr (w/o)	Comp Press (tsi)	Green Density (g/cm^3)	Green Exp (%)	Green Strength (psi)	Sint Density (g/cm^3)	App Hard (HRC)	YS (10^3 psi)	TS (10^3 psi)	Elong. (%)	Impact Energy (ft.lbf)
AD 1	--	--	1.0	30	6.93	0.21	2130	6.89	37	--	--	--	7
				40	7.13	0.29	2420	7.11	42	--	--	--	10
				45	--	--	--	7.18	44	none	140	0.9	12
				50	7.19	0.35	2275	7.21	45	--	--	--	11
AD 2	2.0	--	0.9	30	6.96	0.20	2120	6.90	37	--	--	--	11
				40	7.17	0.24	2565	7.10	40	--	--	--	14
				45	--	--	--	7.17	41	122	188	2.0	15
				50	7.24	0.30	2730	7.20	42	--	--	--	16
AD 3	--	2.0	0.9	30	6.98	0.21	2205	6.99	36	--	--	--	10
				40	7.19	0.27	2590	7.20	40	--	--	--	13
				45	--	--	--	7.25	41	117	162	1.6	14
				50	7.24	0.32	2670	7.28	42	--	--	--	15

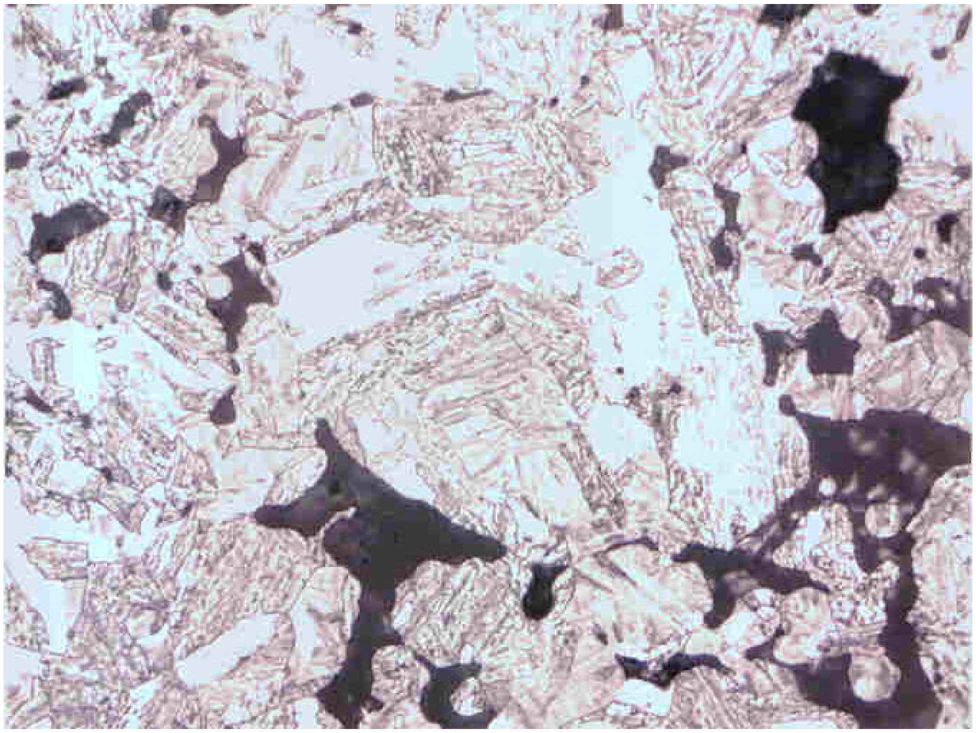

Figure 4: Microstructure of a Sample Produced from Premix #1-1 (0.5 w/o Graphite). Etched with 1% Nital / 4% Picral. Original Magnification 500X.

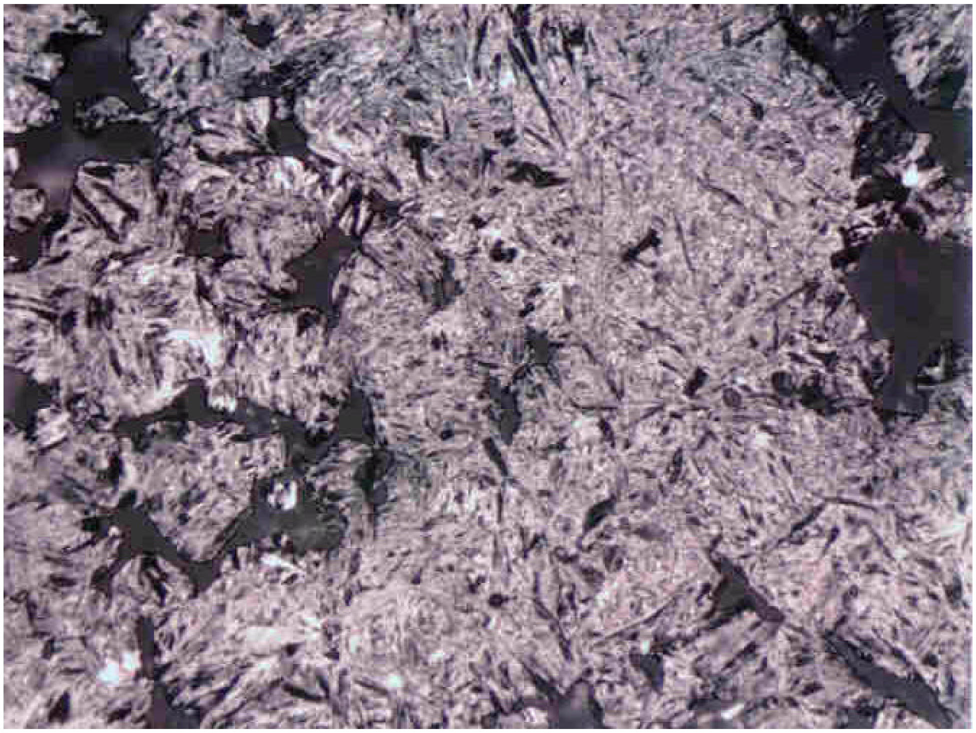

Figure 5: Microstructure of a Sample Produced from Premix #1-5 (1 w/o Copper - 0.7 w/o Graphite). Etched with 1% Nital / 4% Picral. Original Magnification 500X.

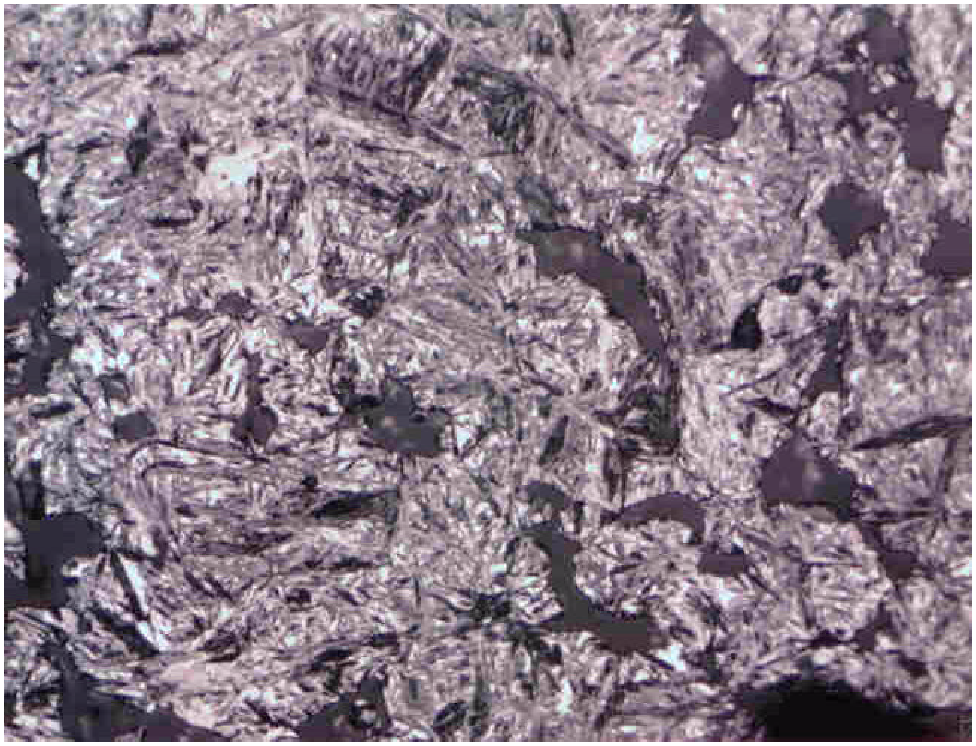

Figure 6: Microstructure of a Sample Produced from Premix #1-9 (2 w/o Copper - 0.9 w/o Graphite). Etched with 1% Nital / 4% Picral. Original Magnification 500X.

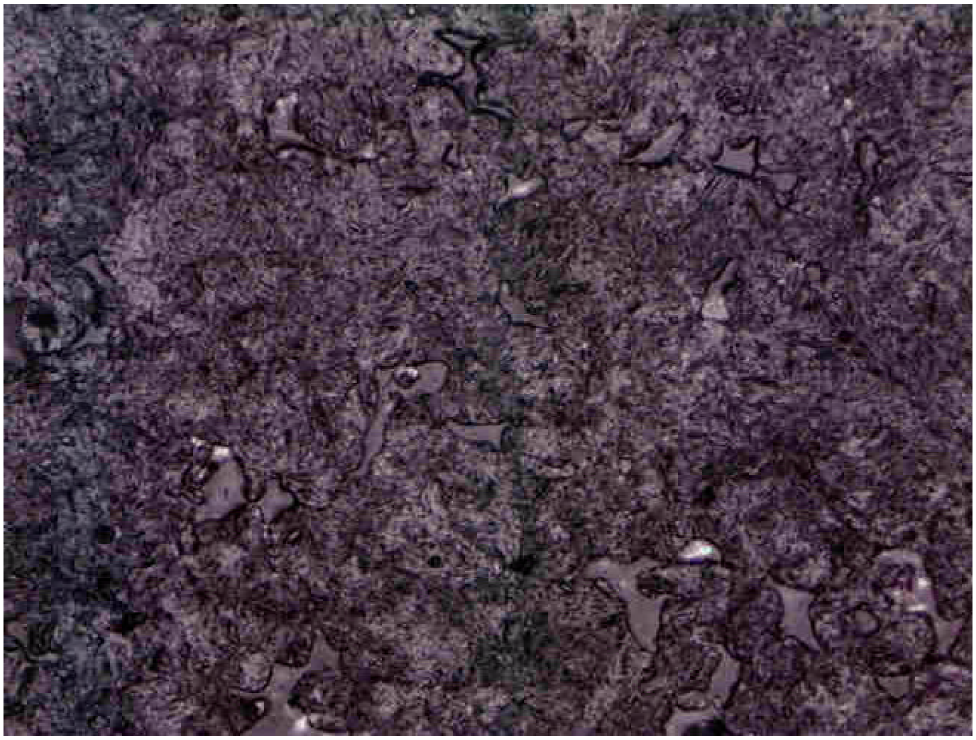

Figure 7: Microstructure of Premix #2-1 (0.8 w/o Graphite). Original Magnification 500X. No Retained Austenite Present.

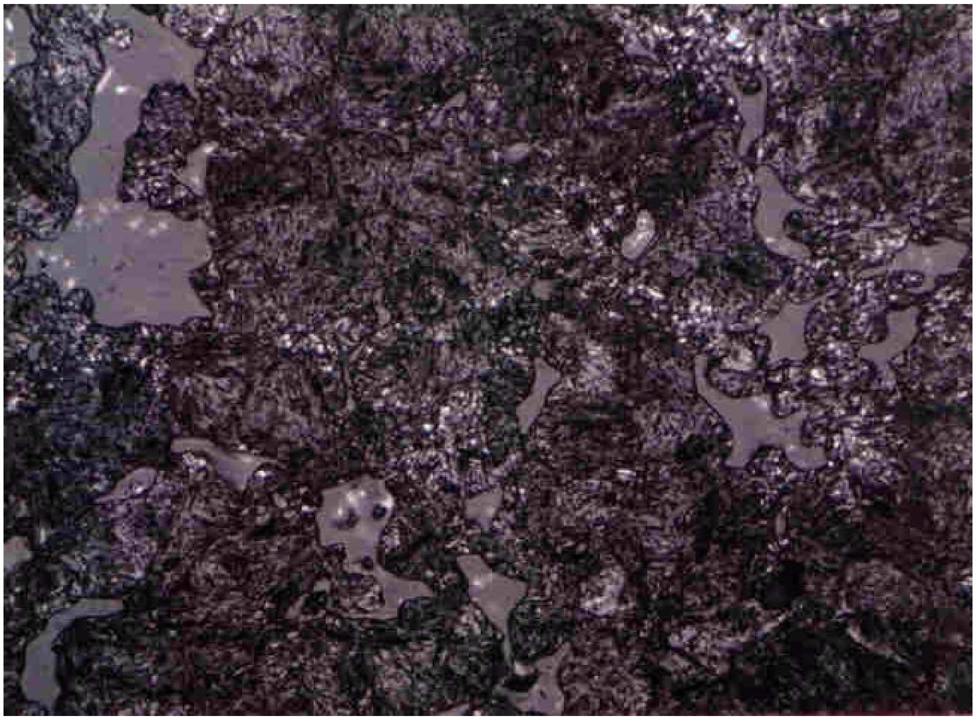

Figure 8: Microstructure of Premix #2-2 (1 w/o Copper - 0.7 w/o Graphite). Original Magnification 500X. Very Little Retained Austenite Present (White Regions).

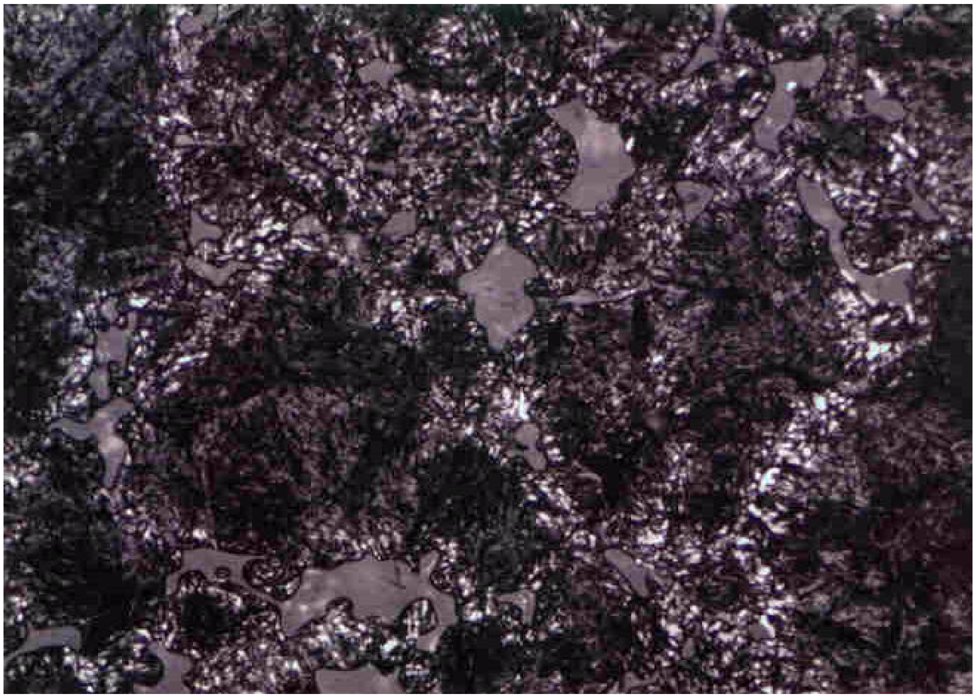

Figure 9: Microstructure of Premix #2-3 (1.5 w/o Copper - 0.8 w/o Graphite). Original Magnification 500X. Some Retained Austenite Present (White Regions).

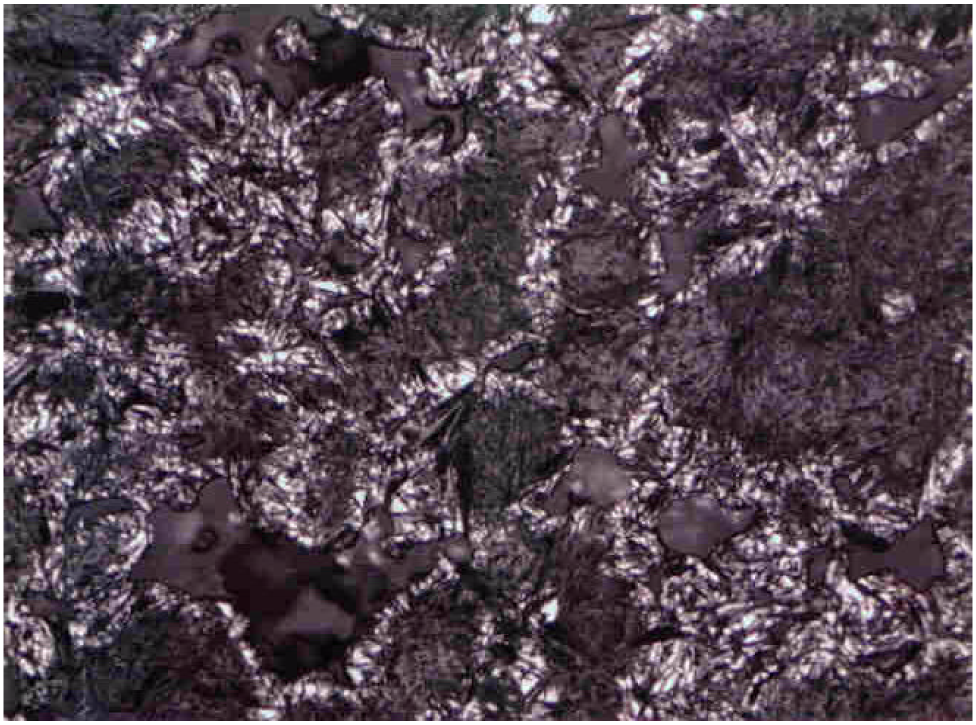

Figure 10: Microstructure of Premix #2-4 (2.0 w/o Copper - 0.9 w/o Graphite). Original Magnification 500X. Retained Austenite Present (White Regions).

CONCLUSIONS

Both copper and graphite additions were shown to greatly influence the properties of Ancorsteel 737 SH. Copper was found to dramatically increase mechanical properties when added in small amounts (~1 w/o), while further increases in copper content caused little or no change. The effects of graphite additions, however, were more complex. As graphite levels were increased from 0.5 to 0.7 w/o, the graphite served to increase martensitic transformation and to strengthen / harden the resultant martensitic microstructure. Upon reaching 0.8+ w/o graphite additions, the material began to show evidence of retained austenite. The presence of this phase caused a decrease in strength. Under the production conditions studied, the optimum graphite level in absence of copper was thought to be 0.8 w/o, while copper mixes were seen to peak with 0.7 w/o graphite. Metallographic evaluation suggested that diffusion of copper into the matrix at grain boundaries and/or particle boundaries lowers the M_f of the material and results in higher percentages of retained austenite in these regions.

The robust nature of Ancorsteel 737 SH allowed for the transformation of significant percentages of untempered martensite in a wide variety of copper / graphite mixes. Due to the brittle nature of any as-sintered martensitic microstructure, tempering was found to be very beneficial and was coupled with a 70-80% increase in strength over untempered values.

An initial trial indicated a distinct synergy between ANCORDENSE processing and Ancorsteel 737 SH. Use of ANCORDENSE processing, instead of conventional compaction, led to density increases of 0.10 - 0.20 g/cm^3 in straight graphite, copper / graphite, and nickel / graphite mixes. This density increase was seen to produce strength over 185,000 psi

(1275 MPa) and an elongation exceeding 2.0%. Extrapolation of ANCORDENSE data indicated strengths in excess of 200,000 psi (1380 MPa) might be attained by lowering graphite levels.

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REFERENCES

1. Rutz, H., Hanejko, F., “High Density Processing of High Performance Ferrous Materials”, *Advances in Powder Metallurgy & Particulate Materials*, Vol. 5, Metal Powder Industries Federation, Princeton, NJ, 1994, pp. 117-133.

2. Causton, R.J., James, W.B., Fulmer, J.J., “Performance Characteristics of a New Sinter-Hardening Low-Alloy Steel”, *Advances in Powder Metallurgy*, Vol. 5, Metal Powder Industries Federation, Princeton, NJ, 1991, p.91.

3. Davala, A.B., Graham, A.H., Causton, R.J., “Application of High Performance Materials and Processes - Alloy Systems”, *Advances in Powder Metallurgy & Particulate Materials*, Metal Powder Industries Federation, Princeton, NJ, 1998.

4. Baran, M., “Development of Sinter-Hardenable Ferrous Powders”, *Sinter-Hardening Seminar*, Metal Powder Industries Federation, Cleveland, OH, April 13-14, 1999.

5. Bain, E.C., Paxton, W., *Alloying Elements in Steel*, American Society for Metals, Metals Park, Ohio, 1966, pp. 97-113.

6. Hoeganaes Corporation, *Metallography of Sintered Ferrous Materials*, Internal Report, 1977.

7. German, R.M., *Liquid Phase Sintering*, Plenum Press, New York, NY, 1985, pp. 89-93.