**Application of Sinter-Hardenable Materials for Advanced Automotive Applications such as Gears, Cams, and Sprockets**

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ABSTRACT

Recent demands within the automotive industry have been for applications requiring high hardness, high hardenability, and increased mechanical performance. These often conflicting requirements necessitated the development of new materials that offer high as-sintered hardness and good static/dynamic mechanical properties without the added expense of a secondary heat treatment. Traditionally, sinter-hardening materials have offered acceptable hardness but at the expense of mechanical properties and sintered density. This paper will document a series of sinter hardening materials that offer good compressibility, high hardness and enhanced mechanical properties. The discussion will focus on utilization of these materials in automotive applications (within both the engine and transmission) such as gears, cams and sprockets that are currently produced by either the press, sinter, and heat treat process or by conventional machining of a casting or wrought material.

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.

**Select Part Performance Requirements**

Many automotive production parts / materials have been identified as candidates for replacement with P/M [5,6].  These candidates include, but are not limited to, sun gears, pinion gears, ring gears, connecting rods, sprockets, camshaft pulleys, crankshaft pulleys, timing gears, and balancing gears.  Applications that currently employ nodular iron castings or ferritic and pearlitic malleable iron casting are of particular interest.  The physical property requirements for such castings are presented in Table 1 [5].  In addition, stress requirements for typical sun gears, pinion gears, and ring gears, as calculated using von Mises yield criterion, are shown in Table 2.  Other prerequisites, such as adequate fatigue properties, also exist for these applications.

Physical Property Requirements for Materials Targeted for P/M Conversion

| **Material** | **UTS (MPa / psi)** | **YS (MPa / psi)** |
|---|---|---|
| Nodular Iron Casting | 400 / 58,000 MIN<br>690 / 100,000 MAX | 260 / 38,000 MIN<br>550 / 80,000 MAX |
| Ferritic / Pearlitic Malleable Iron Casting | 690 / 100,000 MIN | 550 / 80,000 MIN |

Calculated Yield Requirements for Gear Applications

| Gear Type | $\sigma_1$* (MPa / psi) | $\sigma_2$* (MPa / psi) | Yield Requirement (MPa / psi) |
|---|---|---|---|
| Sun | 414 / 60,000 | -896 / -130,000 | 779 / 113,000 |
| Pinion | 517 / 75,000 | -1034 / -150,000 | 668 / 97,000 |
| Ring | 310 / 45,000 | -827 / -120,000 | 724 / 105,000 |

* $\sigma_1$ **=** bending stress in gear ; $\sigma_2$ **=** compressive stress in gear

The cost savings realized in converting castings to P/M in engine and transmission applications can be augmented by choosing sinter-hardening over traditional quenched and tempered P/M parts in many instances. In addition to its economic benefit, sinter-hardening can offer the ability to tailor a part's microstructure for a particular application by varying admixed additions and effective furnace cooling rates. To date, sinter-hardened parts have been embraced in every industry from automotive to small business machines to lawn and garden.

In order to meet the requirements of high strength part conversions, it became necessary to develop new sinter-hardening grades. In the evolution of such P/M materials, a series of powder grades have been introduced and utilized in a sinter-hardening capacity. These materials have included Ancorsteel 2000, Ancorsteel 4600V, Ancorsteel 85 HP, and Ancorsteel 150 HP. Numerous publications exist on the properties of these materials.

The most recent innovation in sinter-hardening powders, Ancorsteel 737 SH, was introduced in 1998. This new alloy 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. The work below illustrates the performance capabilities of Ancorsteel 737 SH.

## EXPERIMENTAL PROCEDURE

### 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 |

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.

**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.

### 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 |

## RESULTS AND DISCUSSION

### Effect of Copper and Graphite Additions

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
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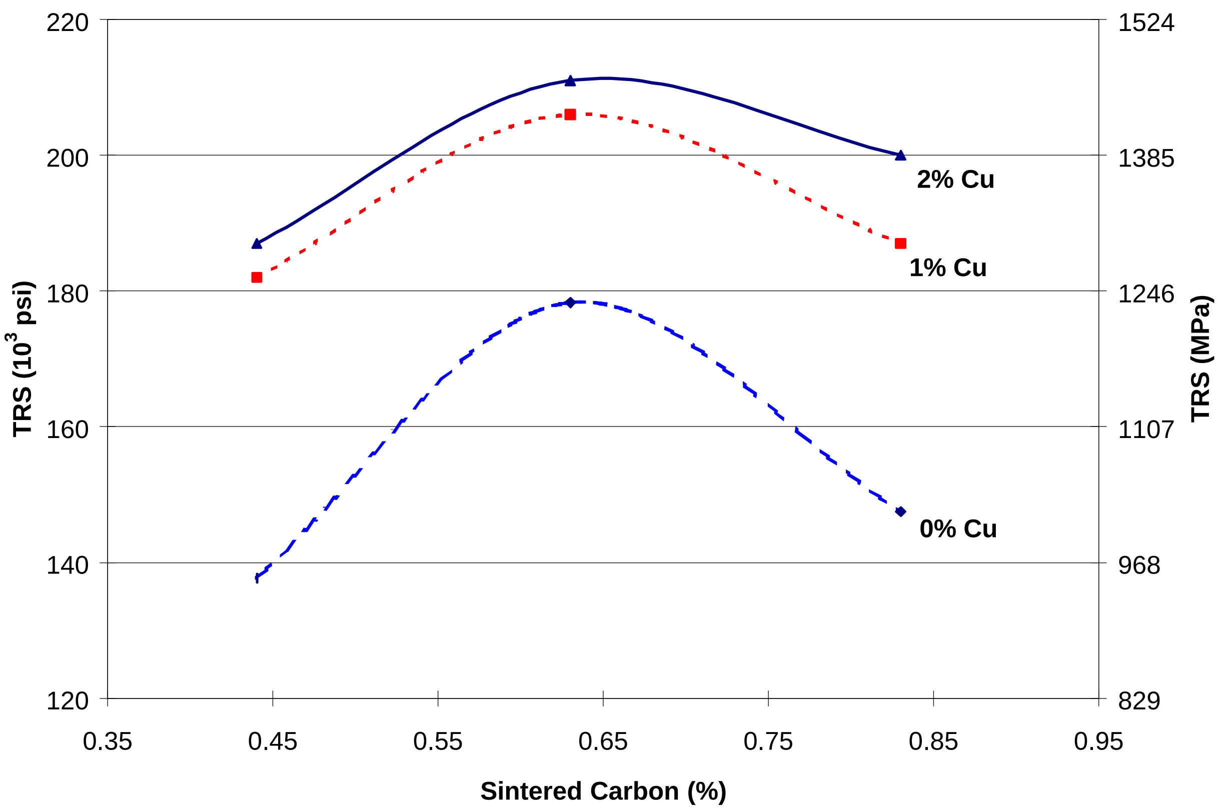


nded to be 10-15% higher than those seen for #1-9

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

**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 yield and ultimate tensile strengths of Ancorsteel 737SH specimens and comparisons with sun gear yield strength requirements (the most demanding of those considered in this paper) are presented in Figure 2.

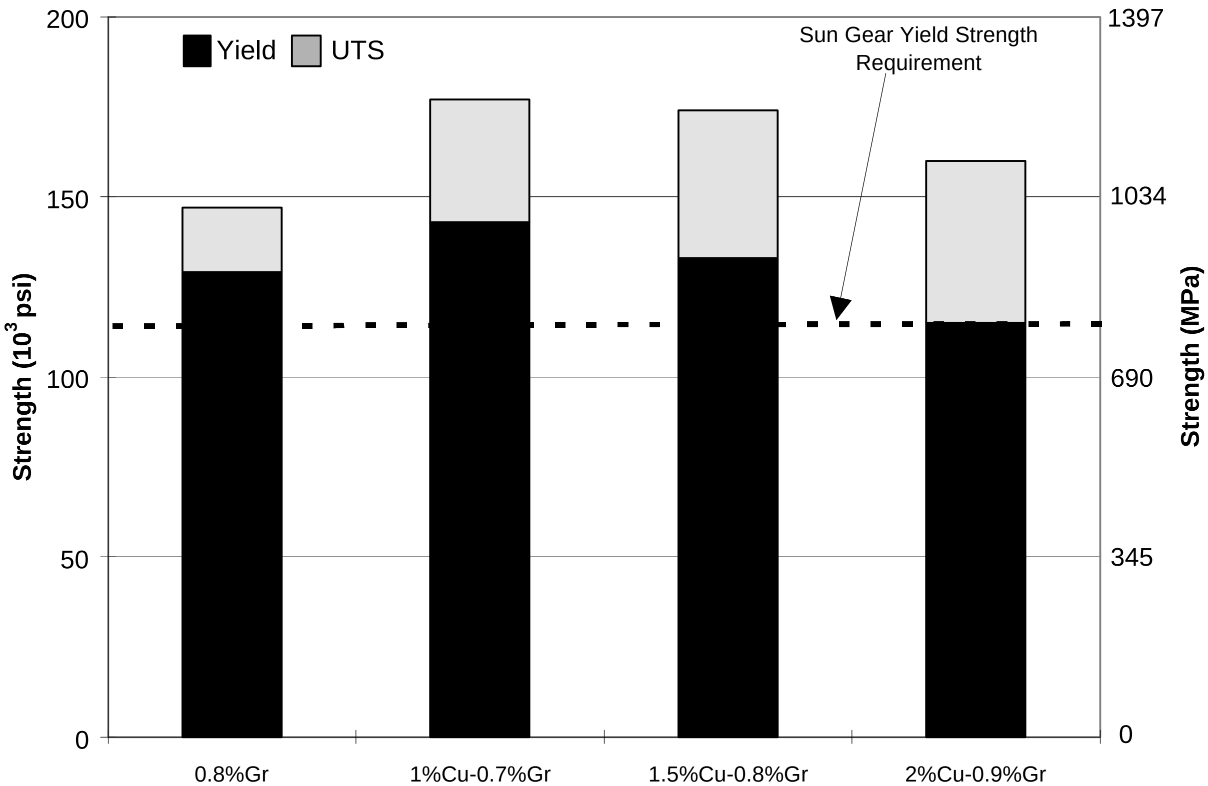


Figure 2: Strengths of Ancorsteel 737SH specimens and comparison with sun gear yield strength, one of the many requirements.

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. Further work is in progress on rotating bending fatigue and rolling contact fatigue of these materials.

**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%. Yield strengths for these materials were as high as 122,000 psi (841 MPa). 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.

**Case Studies**

Case study testing and preparation is currently underway and will be presented during the conference.

## 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.

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.

Based on the data presented in the preceding paper, sinter-hardening represents a viable alternative to select casting materials and/or quenched and tempered P/M materials. Further development of Ancorsteel 737SH premixes and related products may be capable of approaching wrought property benchmarks.

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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. Kim, Young S., “Powder Metal Challenges for Current and Future Automatic Transmission Applications”, *1999 International Conference on Powder Metallurgy & Particulate Materials*, June 20 - 24, Vancouver, BC.

6. Hall, D.W., Mocarski, S. “Update on P/M Automotive Applications”, *The International Journal of Powder Metallurgy & Powder Technology*, Vol. 21, No.2 , American Powder Metallurgy Institute, 1985.

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