High performance sinter-hardenable P/M alloys for automotive applications

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Several grades of recently developed P/M materials have proven suitable, in varying degrees, for sinter-hardening applications. One such grade, Ancorsteel® 737SH, is a prealloyed product that takes advantage of hardenability elements such as Mn, Mo, and Ni. Despite its prealloy content and exceptional hardenability, Ancorsteel 737SH exhibits higher compressibility than other commercially available sinter-hardening grades.

Parole chiave: metallurgia delle polveri, sinterizzazione, acciaio

INTRODUCTION

The main focus of this paper is to present an alternate process that eliminates steps in the manufacture of Powder Metallurgy (P/M) parts. Applications of particular interest for P/M part conversion are gears and sprockets. This paper consists of two parts. The first deals with material development and properties, while the second discusses part-specific automotive applications. These two items are investigated concurrently, where applicable, in order to provide focus on application goals in material development and conversion.

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 620 MPa 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

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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. 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.

	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

Table I: Qualitative Ranking of Alloying Elements in Prealloyed Materials

Tabella 1: Classificazione qualitativa degli elementi alliganti nei materiali prelegati

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

A representative application for gears is a camshaft sprocket. The requirements and specifics for this part can be found in the Case Studies section at the end of this paper.

Many other automotive production parts / materials have been identified as candidates for replacement with P/M [5,6]. These applications include replacement of malleable iron castings and nodular iron castings. Table II lists the properties of these castings [5]. As will be made clear, Ancorsteel 737 SH can satisfy these property requirements. However, strength is not the only requirement, as ductility and density may also be an issue. The application of materials to a specific part requires close interaction with design engineers.

Further development of materials will lead to P/M parts replacing transmission gears such as pinion, sun, and ring gears. Stress requirements for typical sun gears, pinion gears, and ring gears, as calculated using von Mises yield criterion, are shown in Table III. Other prerequisites, such as adequate fatigue properties, also exist for these applications.

Material	UTS (MPa)	YS (MPa)
Nodular Iron Casting	400 MIN 690 MAX	260 MIN 550 MAX
Ferritic / Pearlitic Malleable Iron Casting	690 MIN	550 MIN

Table II: Physical Property Requirements for Materials Targeted for P/M Conversion

Tabella 2: Requisiti delle proprietà fisiche per materiali usati per la conversione P/M

Gear Type	σ_1* (MPa)	σ_2* (MPa)	Yield Requirement (MPa)
Sun	414	-896	779
Pinion	517	-1034	668
Ring	310	-827	724

* σ_1 = bending stress in gear ; σ_2 = compressive stress

Table III: Calculated Yield Requirements for Gear Applications

Tabella 3: Requisiti di rendimento per applicazioni come ingranaggi

By converting castings to sinter-hardened P/M in engine and transmission applications, some processing steps and much of the machining scrap can be eliminated. In addition to this 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.

Premix	Cu (w/o)	Gr (w/o)	Comp Press (MPa)	Green Density (g/cm³)	Green Exp. (%)	Sintered Density (g/cm³)	Dim. Change (%)	App Hard (HRC)	TRS (MPa)	YS (MPa)	UTS (MPa)	Elong. (%)
		415	6.55	0.13	6.51	+0.08	0	770	400	480	1.0	
I-1		0.5	550	6.86	0.16	6.82	+0.10	2	950	480	570	1.1
		690	7.05	0.20	7.03	+0.12	8	1140	490	600	1.2	
		415	6.55	0.13	6.49	+0.19	22	940	580	610	0.7	
I-2	--	0.7	550	6.85	0.16	6.79	+0.22	32	1230	610	670	0.6
		690	7.03	0.20	6.98	+0.25	37	1370	790	810	0.7	
		415	6.56	0.16	6.50	+0.21	27	810	470	500	0.6	
I-3	--	0.9	550	6.85	0.17	6.79	+0.26	34	1020	530	550	0.5
		690	7.02	0.21	6.97	+0.28	39	1140	620	660	0.6	
		415	6.58	0.14	6.58	+0.24	19	1050	670	730	0.9	
I-4	1.0	0.5	550	6.88	0.14	6.80	+0.27	26	1250	790	930	1.3
		690	7.07	0.17	6.99	+0.30	30	1570	830	1020	1.4	
		415	6.58	0.14	6.51	+0.22	26	1080	710	730	0.9	
I-5	1.0	0.7	550	6.87	0.15	6.80	+0.26	32	1420	790	820	1.0
		690	7.06	0.19	6.99	+0.30	37	1640	920	1040	1.3	
		415	6.58	0.13	6.53	+0.12	29	970	550	570	0.8	
I-6	1.0	0.9	550	6.87	0.16	6.81	+0.18	35	1290	680	690	0.8
		690	7.03	0.19	6.99	+0.22	39	1390	740	790	0.9	
		415	6.59	0.12	6.45	+0.52	17	1040	680	700	0.8	
I-7	2.0	0.5	550	6.89	0.18	6.74	+0.57	25	1290	800	900	1.0
		690	7.07	0.18	6.93	+0.58	28	1610	920	1040	1.2	
		415	6.59	0.13	6.51	+0.29	26	1150	700	700	0.8	
I-8	2.0	0.7	550	6.88	0.17	6.78	+0.38	31	1450	820	850	0.9
		690	7.04	0.19	6.96	+0.41	35	1780	970	1010	1.0	
		415	6.60	0.13	6.57	+0.03	27	1140	590	650	0.9	
I-9	2.0	0.9	550	6.88	0.16	6.83	+0.10	34	1380	720	840	1.0
		690	7.04	0.19	7.01	+0.15	38	1610	790	910	0.9	

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

Tabella 7: Composizione della lega Ancorsteel 373 SH con diverse aggiunte di rame e grafite

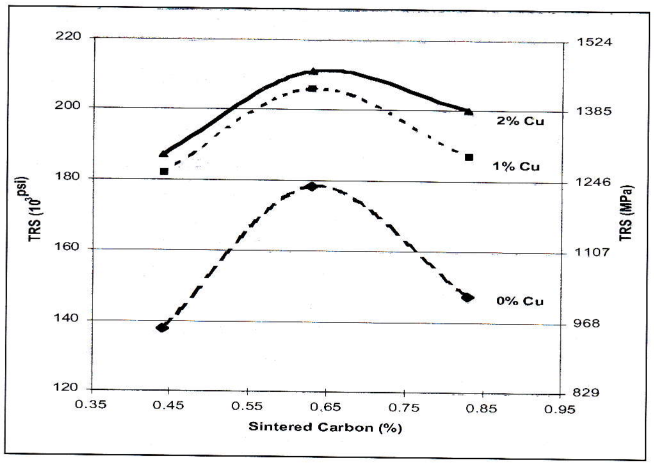

Figure 1: Transverse Rupture Strength as Function of Sintered Carbon Content for Specimens Compacted at 550 MPa.

Figura 1: Resistenza alla rottura trasversale in funzione del contenuto di carbonio sinterizzato per campioni compattati a 550 Mpa.

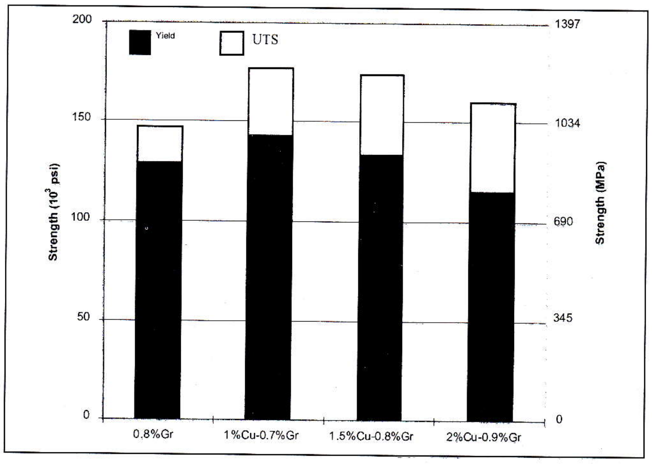

Figure 2: Strengths of Several Ancorsteel 737SH Premixes.

Figura 2: Resistenza di diverse miscele Ancorsteel 737SH

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 737 SH specimens are presented in Figure 2.

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.

Ancorsteel 737 SH specimens produced by the ANCORDENSE process exhibited as-tempered apparent hardnesses

MATERIALS SCREENING

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) [7].
In an effort to screen premix compositions of Ancorsteel 737 SH for automotive applications, nine premix compositions were chosen for investigation. These compositions are presented below in Table IV. 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.
Tensile tests were conducted on machined threaded tensile specimens with a gauge length of 25.4 mm and a nominal diameter of 5.08 mm. Due to the apparent hardness of the material, tensile specimens were machined by grinding. All specimens were compacted at 415 MPa, 550 MPa, and 690 MPa.

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

Table IV: Premix Compositions Considered for Evaluation of Copper and Graphite Effects

Tabella 4: Composizione della pre-miscela considerata per la valutazione degli effetti di rame e grafite

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:	1140°C
Atmosphere:	90 v/o N_2 , 10 v/o H_2
Belt Speed:	127 mm/min
VARICOOL Setting:	60 Hz

The parts were at sintering temperature for 30 minutes. The sintered parts were tempered at 205°C 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 267 kN Tinius Olsen universal testing machine at a crosshead speed of 0.635 millimeters/minute. Elongation values were determined by utilizing an extensometer with a range of 0 to 20%. The extensometer was left on until failure.
The next phase was an effort to further refine premix compositions in order to increase mechanical properties under the same production conditions. The premixes considered are listed in Table V. All sintering, testing, and specimen preparation was done in accordance with the procedures listed previously stated.
A concurrent study of ANCORDENSE processing was undertaken to increase the density and properties of select Ancorsteel 737 SH premixes for use in more demanding automotive applications. These premixes are listed in Table VI. In all cases, 0.6 w/o lubricant was added.

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

Table V: Premix Compositions Considered for Premix Refinement

Tabella 5: Composizione della pre-miscela considerata per la raffinazione

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

Table VI: Premix Compositions Considered for ANCORDENSE Processing

Tabella 6: Composizione della pre-miscela considerata per il processo ANCORDENSE

CANDIDATES FOR AUTOMOTIVE APPLICATIONS

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 entirety of data collected in the first stage of this study is presented in Table VII.
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 Ms 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 optimal under the production conditions studied.
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 us[illegible] 2 w/o copper - 0.9 w/o graphite (premix #1-9) composi[illegible]
In fact, the yield and tensile strengths of premix #1-5 [illegible] to be 10-15% higher than those seen for #1-9.

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of 40-45HRC at compaction pressures of 550-690 MPa. At 620 MPa with copper and graphite additions, ultimate tensile strengths on the order of 1310 MPa were realized and elongations were seen to exceed 2.0%. Yield strengths for the materials were as high as 840 MPa. Upon consideration of previously presented data, extrapolation of warm compaction data to lower graphite levels indicated strengths in excess of 1380 MPa might be possible. The ANCORDENSE data is presented in Table VIII.

	Premix AD1	Premix AD2	Premix AD3
Copper (w/o)	--	2.0	--
Nickel (w/o)	--	--	2.0
Graphite (w/o)	1.0	0.9	0.9
Compaction Pressure (MPa)	690	690	690
Green Density (g/cm^3)	7.19	7.24	7.24
Sintered Density (g/cm^3)	7.21	7.20	7.28
Apparent Hardness (HRC)	45	42	42
UTS (MPa)	965	1296	1117

Table VIII: Properties of Ancorsteel 737SH Compacted by the ANCORDENSE Process

Tabella 8: Propietà della lega Ancorsteel 737SH compattata mediante processo ANCORDENSE

CASE STUDY

One success story for sinter-hardening involves the crankshaft sprocket used in a high volume passenger car engine. The sprocket weighed 170 grams and had a pitch diameter of 61 mm. The minimum density requirement for the sprocket was 6.80 g/cm^3, with 7.0 g/cm^3 required at the teeth. Additional requirements included wear resistance (35 HRC min) and high strength (1170 MPa min). Previously, the sprockets were produced by forging and additional secondary operations to machine and induction harden. In this case, sinter-hardening provided a substantial cost reduction as well as better dimensional accuracy and wear resistance than the induction hardened part.

CONCLUSIONS

Although application-specific work would be required for conversion, it has been demonstrated that sinter-hardening materials will have the inherent capability to meet many automotive engine and transmission part requirements. In that regard, Ancorsteel 737 SH premixes have been shown to exceed several key property targets for such applications. Further development of Ancorsteel 737 SH and related products may be capable of approaching wrought property benchmarks.
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/cm3 in straight graphite, copper / graphite, and nickel / graphite mixes. This density increase was seen to produce strength over 1275 MPa and an elongation exceeding 2.0%. Extrapolation of ANCORDENSE data indicated that lower graphite levels might attain strengths in excess of 1380 MPa.

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.

ABSTRACT

LEGHE P/M DA SINTEROTEMPRA AD ELEVATE PRESTAZIONI PER APPLICAZIONI NELL'INDUSTRIA AUTOMOBILISTICA

Diverse classi di materiali P/M recentemente sviluppati si sono dimostrati adatti per le applicazioni che richiedono sinterotempra.
L'acciaio Ancorsteel® 737SH, è un materiale prelegato che sfrutta le capacità di indurimento degli elementi quali Mg, Mo ed Ni.
Nonostante la sua composizione e la sua capacità di indurimento eccezionale, Ancorsteel 737SH mostra una compressibilità maggiore rispetto ad altri materiali induriti per sinterizzazione disponibili in commercio.
E' stato dimostrato che i materiali induriti per sinterizzazione possono soddisfare i requisiti relativi alle parti di trasmissioni e dei motori per autoveicoli. A questo proposito, Ancorsteel 737 SH ha superato diversi degli obiettivi di proprietà per tali applicazioni.