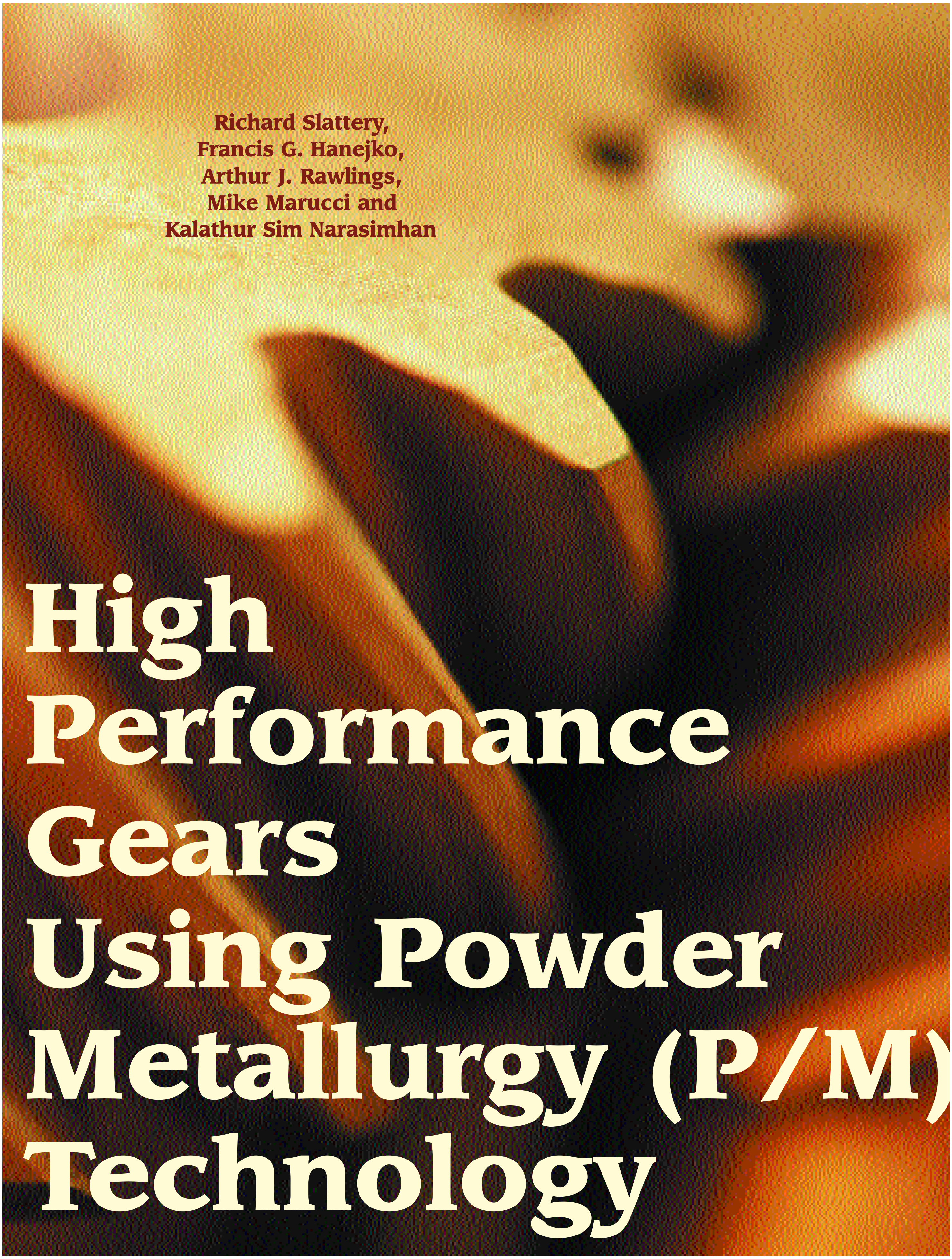

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High Performance Gears Using Powder Metallurgy (P/M) Technology

Management Summary

Powder metallurgy (P/M) techniques have proven successful in displacing many components within the automobile drive train, such as: connecting rods, carriers, main bearing caps, etc. (Ref. 1). The reason for P/M's success is its ability to offer the design engineer the required mechanical properties with reduced component cost.

Powder metallurgy is also a proven technology to produce high strength gears for the automotive market. P/M techniques can manufacture spur gears with overall part densities up to 7.5 g/cm^3 via today's powder production, compaction and sintering processes—combined with double pressing. However, helical gears are more difficult to produce to these same densities because the geometry does not lend itself to the double press/double sinter process.

But advances in powder production, compaction, and sintering—combined with secondary operations—have enabled core part densities up to 7.4 g/cm^3 and fully dense tooth flanks in helical gears.

Abstract

To close the gap between conventional P/M and wrought steel, a process is needed that enables P/M gear producers to manufacture helical gears with sintered densities greater than 95% pore free via single press/single sinter processing. This higher density provides enhanced mechanical properties with a higher elastic modulus (Ref. 2). High density provides better mechanical properties, such as tensile strength, fatigue, and impact toughness. Still, even minor amounts of porosity can have a significant negative effect on certain characteristics. In particular, high performance gears require full density in the critical stress region to withstand the high Hertzian contact stresses.

Secondary processing, such as surface densification, enables the production of a highly engineered porous core component with full or near full density in the critical stress region of the gear (Ref. 3). What is needed is to merge the practice of surface densification with higher core densities to expand the potential applications for P/M.

Described in this paper is a P/M parts-making technology capable of producing single pressed and sintered helical gears with core densities approaching 7.4 g/cm^3. Description of a prototype run will be presented with the resulting sintered part densities and part-to-part variability. To further enhance the performance and geometry of these helical gears, they were subsequently surface densified via rolling. Improvements in the surface density and gear quality will be described.

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Introduction

At the present time, P/M is successful in two primary performance areas. The first is in density ranges of less than 7.1 g/cm^3 with low- to medium-strength requirements. The second main application area is fully dense P/M via powder forging. Here a sintered preform is hot forged to near pore-free density, maximizing the mechanical properties of the P/M component.

An example of a part family that offers significant volume opportunities for the P/M industry are helical gears used in the planetary gear sets of automatic transmissions. The requirements of these gears are high surface hardness, good core toughness, fatigue strength for tooth bending, rolling contact fatigue resistance, and high density to resist pitting and sub-surface spalling during service (Ref. 4). Currently, these gears are machined from either AISI 8620 steel or AISI 5120 steel carburized and machined to meet the dimensional specifications.

Conventional press and sinter technologies offer low production cost to produce these parts; however, the corresponding mechanical properties are inadequate. Powder forging a blank and then machining it will give the required mechanical properties but at a cost that is prohibitive. It is speculated that a technology enabling core densities ≥ 7.4 g/cm^3 with a fully dense surface will meet the mechanical property requirements of this application, yet be economically competitive.

In an effort to satisfy the diverse mechanical requirements of these helical pinion gears, Capstan Atlantic and Hoeganaes Corp. collaborated on the implementation of a new compaction technology (AncorMax D™) that enables the attainment of high core densities without the need to preheat the powder. The advantage of this process is its greater flexibility in the manufacture of high-density P/M parts. It will be demonstrated that this process can produce helical gears with sintered densities approaching 7.4 g/cm^3.

Following compaction and sintering, Capstan employed its proprietary surface densification technology to densify the high stressed region of the gear. This technology, coupled with the attainment of the proper heat-treated microstructure, can produce gears that approach the performance of wrought steel gears.

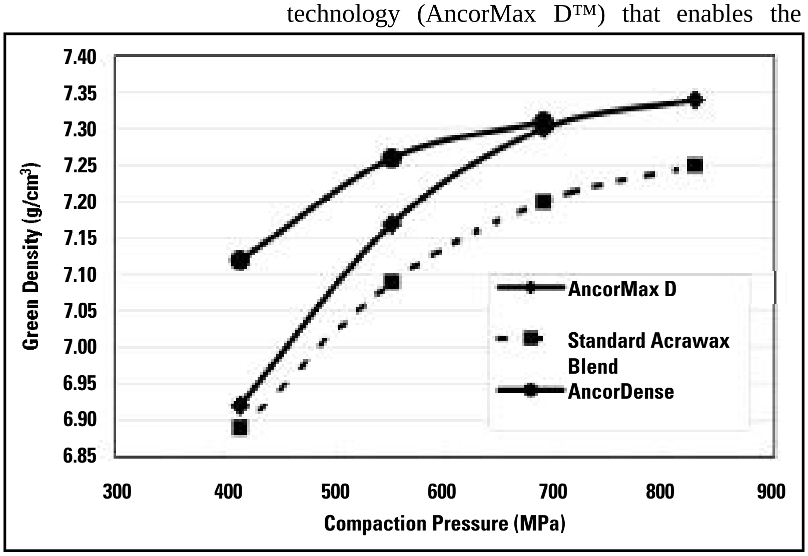

Figure 1—Comparison of the compressibility of a regular premix with AncorDense and AncorMax D.

The AncorMax D Process

The AncorMax D process is a patent pending premixing technology that optimizes both the lubricant and binder additions to achieve an increase of 0.05–0.15 g/cm^3 in density relative to a conventional premix (Refs. 5, 6).

Coupled with this increase in green and sintered densities, the AncorMax D process offers reduced alloy segregation, reduced dusting, superior flow, and enhanced die fill (Ref. 7). These factors give the opportunity for greater consistency and higher quality P/M parts.

Attaining high-density, single press, single sinter P/M parts has been an objective of the P/M industry for many years. ANCORDENSE™ processing was introduced approximately eight years ago; it is a technology that requires preheating the die, punches, and powder to approximately 120–150°C (250–300°F) (Ref. 8).

The challenge of maintaining consistent temperature during the compaction process has prevented widespread acceptance of this processing technique. The AncorMax D system requires only die heating in the range of 60–70°C (140–160°F). The powder remains unheated until it enters the die cavity.

The advantages of this system include the aforementioned density gain of 0.05–0.15 g/cm^3, less ancillary equipment, and reduced powder waste. Limitations include a maximum part length of approximately 25 mm (1.0 in.) due to limited heat transfer in the powder and the continued need for a heated die. Also, compaction pressures greater than 550 MPa (40 tsi) are a prerequisite to attain the improvement in density.

Shown in Figure 1 is a comparison of the green density vs. compaction pressure for an FLN2-4405 material made via regular premixing, ANCORDENSE premixing, and AncorMax D premixing. General observations from this chart are as follows: the ANCORDENSE premix gives the highest green densities at the lowest compaction pressures, and the maximum green density achieved for ANCORDENSE and AncorMax D are nearly the same.

The benefit of the AncorMax D processing is observed at compaction pressures greater than 40 tsi (550 MPa). The maximum density achieved with either the ANCORDENSE or AncorMax D technology is dependent upon the pore-free density of the premix with a limiting value of 98% of the pore-free density (PFD).

Properties of AncorMax D FLN2-4405

To illustrate the potential benefits of using the AncorMax D process, a comparison of the mechanical properties of an FLN2-4405 premix processed via two routes was performed. Table 1 shows the test alloy matrix.

Reference is made to Figure 1 for the compressibility curve for the two materials. It is noted that compaction pressures greater than 550 MPa (40 tsi) show an increase in green density. However, with the compaction pressure at 415 MPa (30 tsi), the increase in density is minimal. In addition to compressibility samples, standard MPIF dog bone tensile samples were compacted with a die temperature of 63°C (140°F). Rotating bending fatigue (rbf) samples were produced by machining standard test samples from blanks also compacted at a die temperature of 63°C (140°F). All samples were sintered under the following conditions:

- Continuous Belt Furnace,
- Standard Water Jacket Cooling,
- Sintering Temperature: 1,120°C & 1,260°C (2,050°F & 2,300°F),
- Time at Temperature: 25 min., and
- Atmosphere: 75%N_2, 25%H_2 (by volume).

Increasing the density of a P/M component increases the tensile and fatigue strength of the finished part. Figures 2 and 3 demonstrate that the 0.10 g/cm^3 increase in density achieved with the AncorMax D processing results in a 10% increase in ultimate tensile strength (UTS) and yield strength (YS) at equivalent compaction pressures. Additional increases in strength can be achieved by increasing the sintering temperature from 1,120°C to 1,260°C (2,050°F to 2,300°F) by comparing the data presented in Figures 2 and 3.

The rbf data presented in Table 2 demonstrates the same beneficial effect of increasing density on the fatigue survival limits. The 0.10 g/cm^3 increase in density yields approximately a

Table 1—Alloy Test Matrix (FLN2-4405).

	Base Material	Nickel, % by weight	Graphite, % by weight	Lube, % by weight	Premix Technique
1	FL-4400	2.0	0.6	0.75	Standard Premix
2	FL-4400	2.0	0.6	0.55	AncorMax D

Table 2—RBF Data for AncorMax D Processed FLN2-4405.

Compaction Pressure, MPa	Sintering Temp., °C	90% Survival Limit, MPa	UTS, MPa	% of UTS (90%)	Density g/cm^3
690	1,120	266	759	34.4	7.34
830	1,120	292	745	38.2	7.41
690	1,260	252	759	32.5	7.38
830	1,260	273	841	31.8	7.44

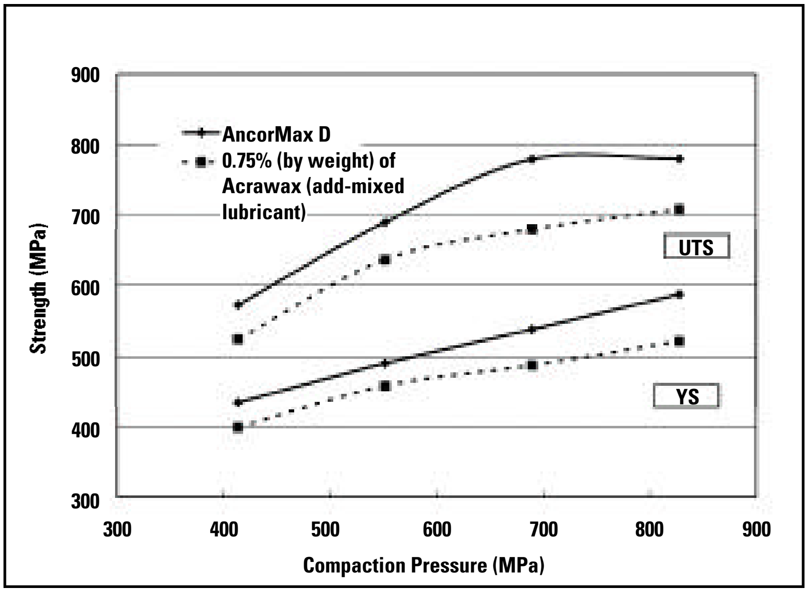

Figure 2—Strength of FLN2-4405 sintered at 1,120°C (2,050°F).

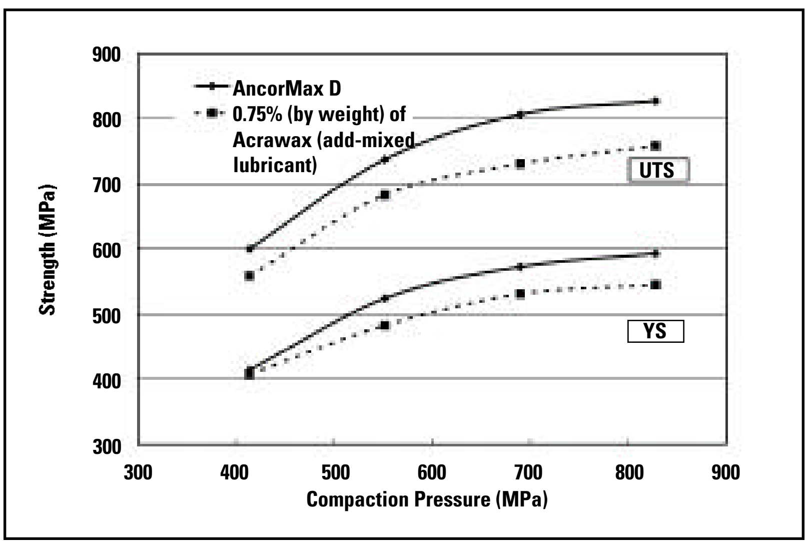

Figure 3—Strength of FLN2-4405 sintered at 1,260°C (2,300°F).

10% increase in fatigue life.

The rbf survival limits for the samples sintered at 1,260°C (2,300°F) are lower than the samples sintered at 1,120°C (2,050°F). This superior fatigue performance of the 1,120°C sintered material is related to the heterogeneous microstructure. At 1,120°C, the admixed nickel does not completely diffuse into the iron matrix, resulting in a nickel-rich second phase that acts to arrest crack propagation.

Conversely, the homogeneous microstructure of the high temperature sintered samples lack these crack-arresting particles with a resulting decrease in fatigue performance (Refs. 9, 10).

Prototype Production of a Helical Gear

To verify the production capability of the AncorMax D process, Capstan Atlantic and Hoeganaes Corp. collaborated in the compaction and sintering of the helical gear shown in Figure 4.

During this effort, a standard premix material consisting of FLN2-4405 composition (Table 1) was compacted as a reference at pressures ranging from 550–830 MPa (40–60 tsi) in non-heated tools at a press speed of ~8 strokes per minute.

Phase two of the trial involved compaction of an AncorMax D premix of the same FLN2-4405 composition (with the exception of the lubricant addition and type) utilizing the same helical gear tooling. Compaction pressures of 550–830 MPa (40–60 tsi) were utilized with a die temperature of 65°C (150°F). In both compaction trials, the part height was varied from 6 mm (0.25 in.) up to approximately 25 mm (1.0 in.).

Results from the compaction trial are summarized in Table 3. Similar to the results achieved with laboratory test samples, the AncorMax D gears exhibited an overall density increase of approximately 0.05–0.10 g/cm^3 compared to the standard premix at equivalent compaction pressures. One notable aspect of this work demonstrated that the AncorMax D with its reduced lubricant level gave satisfactory compaction and ejection up to a part height of 22.5 mm.

Compacting gears with overall lengths (OAL) greater than 22.5 mm resulted in high die ejection forces with corresponding poor surface finishes.

Part-to-part weight variability of the gears produced with the AncorMax D process showed reduced scatter relative to the standard material (Table 4). This reduced scatter will lead to reduced dimensional variation in the production of the actual component.

After compaction, the gears were sintered at 1,120°C (2,050°F) in a 90%N_2, 10%H_2 (by volume) sintering atmosphere for approximately 30 minutes at temperature. The sintered gears were evaluated for sintered density; the results are presented in Table 5. More than 3,000 gears were compacted during this pre-production effort. Twelve sectional densities were evaluated by sectioning a part into four quadrants around the diameter and into three height regions. The result of this analysis is shown in Table 6.

It is worth noting that the density gradient from top to bottom and around the circumference is uniform within +/– 0.03 g/cm^3. This uniformity of density is significant because uniform density throughout the part minimizes distortion during sintering.

Methods to Improve the Physical Properties of P/M Components

Achieving higher sintered density is perhaps the primary method to improve the performance of a P/M part. However, recent experimental work has shown that heat treat practice and secondary operations can also have a significant

Table 3—Green Density Results of Helical Gear Trial.

Premix	Gear OAL, mm	Green Density at 550 MPa, g/cm^3	Green Density at 690 MPa, g/cm^3	Green Density at 830 MPa, g/cm^3
Standard Premix	12	7.12	7.26	7.26
	19	7.13	7.25	7.28
	25	7.03	7.25	7.28
AncorMax D	12	7.24	7.34	7.38
	19	7.25	7.32	7.34
	22.5	7.05	7.28	7.34

Table 4—Part-to-Part Weight Variability @ 830 MPa.

Process	Var. 1σ gms	Range gms.
Standard Premix	0.48	1.66
AncorMax D	0.20	1.10

Table 5—Sintered Density of Helical Gears at 1,120°C (2,050°F).

Premix	Gear OAL, mm	@550 MPa g/cm^3	@690 MPa g/cm^3	@830 MPa g/cm^3
Standard Premix	12	7.12	7.24	7.28
	19	7.12	7.25	7.29
	25	6.99	7.18	7.23
AncorMax D	12	7.26	7.41	7.45
	19	7.28	7.43	7.45
	22.5	7.07	7.43	7.45

Table 6—Density Variations within a Sintered Helical Gear, g/cm^3.

Position	North (front of die)	South	East	West
Top	7.38	7.40	7.37	7.41
Middle	7.37	7.39	7.40	7.39
Bottom	7.41	7.39	7.40	7.40

effect on actual part performance. This section will review recent advancements in these processes and demonstrate how these advances can lead to improved gear performance.

It is well known that carburizing produces favorable compressive stresses on the surfaces of components. This phenomenon applies to P/M components as well. Several researchers have found a 15–20% improvement in rotating bending fatigue properties (Refs. 11, 12). In addition, the lower carbon core produces a material with greater impact toughness and core ductility.

Despite the positive effect of carburizing on mechanical properties, one key material characteristic in which P/M falls short of wrought steels is in the area of rolling contact fatigue resistance. In rolling contact fatigue, the high subsurface stresses resulting from the gear contact area and relative slip have shown the need for full density in the critical stress regions to withstand the Hertzian contact stress associated with rolling contact fatigue of high performance gears.

To improve the gear performance of P/M components, surface densification is sometimes used to densify the highly stressed region of the part, without affecting the core characteristics.

Benefits of surface densification can include:

- A composite structure with a pore-free case and a porous core,
- Potentially lower component cost because the high density region is only in the critical stress region of the part,
- Improved gear geometry and tolerance because the P/M gear is rolled against a precision roll die, and
- Potentially add the ability to crown the tooth of the densified P/M gear.

Surface densification is a process that locally densifies the surface of a pressed and sintered P/M preform. The concept of densifying only the surface is that maximum Hertzian stress in a gear is developed in the near surface region of the gear and diminishes with increasing distance from the surface. Thus, a gear with a surface densified case (to the appropriate depth) will give rolling contact fatigue properties equivalent to a wrought steel gear. Process development at Capstan Atlantic showed that the depth of the pore-free densified layer can range from a minimum of 0.38 mm to greater than 0.70 mm.

Figure 5 presents metallographic analysis of the porosity distribution for cylindrical test specimens that were densified via surface rolling to two distinct depths. Near full density was achieved at subsurface distances up to 0.75 mm (0.030 in.). Beyond the densified layer, the porosity level increases to the level of the as-sintered component.

The data shown in Figure 5 demonstrate the versatility of the rolling process in producing densified layers as well as the ability to densify to specific depths depending upon the requirements of the final application. This densified layer produces improvements in the rolling contact fatigue results as shown by Sanderow (Ref. 13).

In addition to the benefits of improved rolling contact fatigue, the surface densification has the added benefit of improved gear geometry and the possibility of incorporating crowning on the surface of the gear.

Production of Surface Densified Gears

This section of the paper will describe the actual production of a surface densified helical gear shown in Figure 4. The intent of this section is to outline the steps necessary to achieve surface densification and the resultant gear geometries and densification profile.

Machining. P/M is often considered a net

Figure 4—Photograph of helical gear pressed in the collaborative effort. Note gear has a 22° helix angle with an OAL of 22.5 mm. The major diameter of the gear is 42.5 mm and the ID of the gear is 23.5 mm.

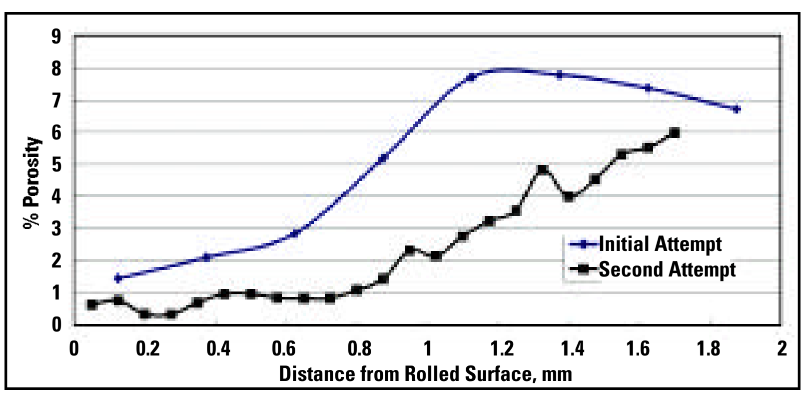

Figure 5—Porosity profiles of roll densified test samples.

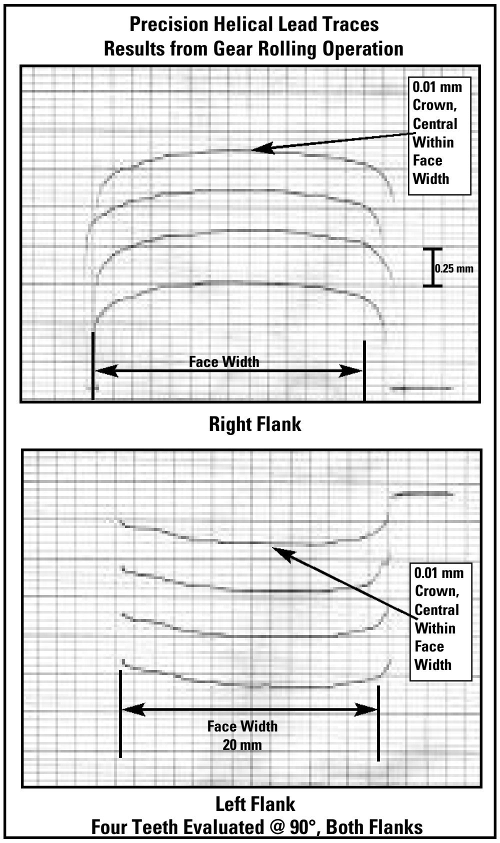

Figure 6—Gear tooth lead error traces on rolled densified helical gears taken at 90° intervals on the gears.

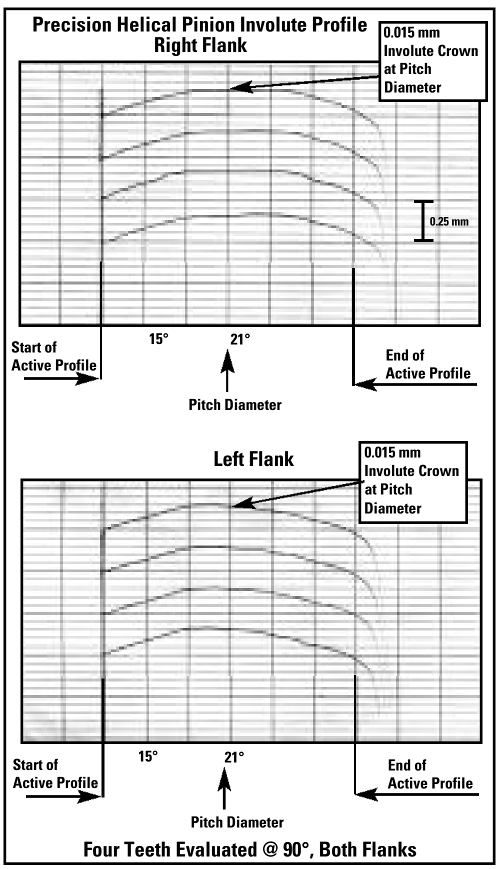

Figure 7—Involute gear traces on rolled densified helical gears taken at 90° intervals on the gears.

shape process that requires little or no machining. However, machining is sometimes required to incorporate undercuts, cross-holes, etc. Machining is also used to improve the dimensional accuracy of some P/M components. Machining of P/M gears, unlike their wrought steel counterparts, is limited to the inside diameter. The benefits from this single machining operation are: precise inside diameter tolerances and near perfect alignment of the gear teeth to the central axis of the gear.

Gear rolling. As briefly described earlier, another potential operation for the enhancement of gear geometry, as well as tooth fatigue endurance is gear rolling. With the incorporation of a specifically engineered rolling process, one has the ability to achieve optimum tooth alignment while surface densifying the gear teeth to depths in excess of 0.7 mm. An additional benefit of this operation is a "mirror-like" surface finish achieved on the tooth flanks, resulting in a much quieter running gear, which is critical in satisfying ever-increasing NVH requirements among our customer base.

Shown as Figures 6 and 7 are the gear traces evaluating gear tooth lead error and involute profile. Beyond the necessity to densify the surface and improve gear quality, another challenge presented by this application is the requirement of a "crown" central within the face width of the gear (shown in the lead traces) along with a peak involute at the pitch diameter of the gear (shown in the involute traces).

First, looking at the lead traces (Fig. 6), notice that the start and stop points of the trace are at the same level, while there is a positive crown in the middle of the trace. Typically with P/M gears, we would see a hollow in the central region of the face width of the tooth caused by the low dense region at or about the middle of the gear's face width.

We call this the "density dip" effect. The compaction of a high density gear preform with uniform density top to bottom, minimized this "density dip." Thus in combination with a specifically engineered rolling process, a 0.01 mm crown was created on both gear flanks.

The involute profile of the gear, or the "tooth shape," is a function of not only the rolling operation, but also the as-pressed tooth shape. To yield a specific involute profile, one must utilize more of a systems approach. Note on the involute traces that the peak positive involute is at the theoretical pitch line of the gear.

In addition to the dimensional and surface finish benefits realized by rolling, surface densification can also occur. Typically, where required, gear tooth flanks are densified to a depth of 0.3–0.7 mm. The primary benefits of this surface densification are increased fatigue life by inducing compressive stresses on the tooth surfaces and wear resistance.

Shown in Figure 8 is the photomicrograph of the surface densified helical pinion. The gear was sectioned at a 22° angle to the vertical to show the uniformity of densification on the leading and trailing sides of the gear tooth.

Figure 9 shows the depth of densification on the gear. This first attempt at densifying the helical pinion produced a less dense case than what was developed on the toroidal test samples. The reasoning for the more porous case is simple: The rolling conditions were not optimized. Prior experience at Capstan Atlantic has produced densified layers in gears equivalent to the test samples (data shown in Fig. 5). What made this particular effort more challenging was incorporating the crowing on the gears. Capstan Atlantic had not attempted to roll a P/M gear with a crown prior to this effort; thus the deformation behavior is not completely understood.

Additional trials with rolling this gear form are certain to produce the desired densified layer and form detail.

Summary

The sintered density distribution within a P/M component is paramount to obtaining good mechanical property performance. Described in this paper is a new parts-making process utilizing a unique binder/lubricant system (AncorMax D) that enables the production of high-density P/M parts through a combination of moderate die temperature 65°C (145°F) plus higher compaction pressures.

It was demonstrated that sintered densities up to 7.4 g/cm^3 are possible using laboratory test samples of an FLN2-4405 material. In addition to the high density, it was demonstrated that the density uniformity from top to bottom and around the circumference is quite consistent.

The laboratory testing was extended to the prototype production of a helical gear with a 22° helix angle. As observed in the laboratory production of test samples, the AncorMax D showed a similar density improvement in the helical gear of 0.05–0.10 g/cm^3 greater compared to a standard premix of FLN2-4405. The prototype production of the AncorMax D premix had reduced part-to-part weight variability, resulting in reduced finished part variability.

Beyond the development of the new binder/lubricant system, surface densification is a manufacturing technology capable of producing full density on the surface of the gear with full densification ranging from a minimum of 0.38 mm (0.015 in.) to a maximum of 0.70 mm (0.028 in.).

This surface densification creates a composite component giving the benefits of pore-free density in the critically stressed case region of the part with ~95% density in the core to provide for the required core properties. In addition to the densified case structure, the surface finish of the rolled part is better than that of a ground finish.

The processing route proposed for the high performance helical gear is as follows:

- Compact to 7.3+ g/cm^3 density using the AncorMax D processing,
- Sinter,
- Machine bore for concentricity (if necessary),
- Surface densify up to 0.70 mm (0.028 in.),
- Carburize, and

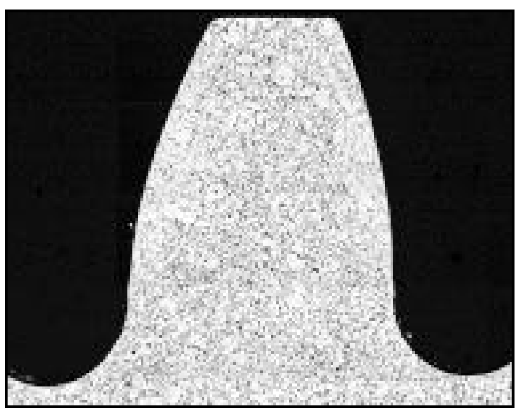

Figure 8—Photomicrograph of rolled densified helical gear tooth taken through crowned section.

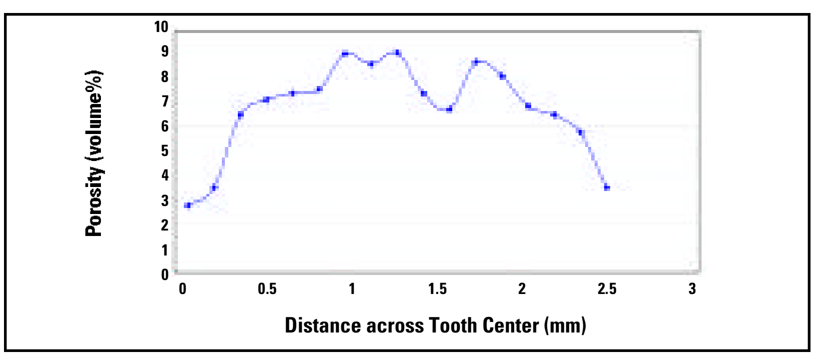

Figure 9—Density gradient of rolled densified helical gear tooth measured at crowned region.

High Performance Gears Using Powder Metallurgy (P/M) Technology

This paper was presented under the title "Powder Metallurgy of High Density Helical Gears" at the 2003 International Conference on Powder Metallurgy & Particulate Materials, held June 8–12, 2003, in Las Vegas, Nevada, and was published in the conference's proceedings, *Advances in Powder Metallurgy & Particulate Materials.* The paper is republished here with permission from the conference's sponsor, the Metal Powder Industries Federation.

- Finish machine as required.

This processing offers the mechanical properties of a high-density part, the surface fatigue resistance of a wrought part, and potentially the low cost inherent to P/M processing.

Surface densification gives the following advantages:

- Pore-free tooth surface,
- Excellent ("mirror-like") surface finish,
- Increased wear resistance,
- Reduced noise,
- Improved corrosion resistance,
- Minimal tooth-to-tooth & total composite error,
- Redirects helix angle to improve gear tooth lead while incorporating a tooth crown,
- Customized tooth profile, and
- Improved fatigue endurance.

It is worth noting that the carburizing step develops a hard, wear resistant surface layer plus produces desirable surface compressive stresses that give enhanced bending fatigue characteristics. Increases in the survival limit of rotating bending fatigue samples are on the order of 15–20%. Additionally, carburizing gives a desirable acicular martensitic microstructure in the case region (Ref. 14). The synergistic effect of surface densification and carburizing offers the end-user the potential for wrought steel gear performance with the low cost inherent with P/M processing.

Finally, and perhaps most significantly, surface densification has the added benefit of producing a part with high dimensional precision. Lead and involute gear checking of the as-rolled gear shows that the gear error is equivalent to a conventionally machined wrought steel gear.

Additionally, the roll densification process was able to produce a crown on the gear that further enhances the NVH performance of the gear. Gear crowning is impossible to achieve through P/M part compaction, but this feature—and its consistency—can be produced as a direct consequence of the uniformity of sintered density throughout the part and of the expert engineering of the rolling process.

Additional experimental work is required to produce the helical gear with the depth of densification achieved in the test samples. However, significant progress was made in the potential production of this component via P/M processing. The next steps include:

- Densifying the gears to 0.030 in. (0.70 mm),
- Carburizing the part to measure the potential distortion during heat treatment,
- Simulated gear testing to verify the performance of the proposed processing, and
- Actual gear testing of the finished gears to qualify the process. ⚙

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