

# Surface Densification Coupled with Higher Density Processes Targeting High-Performance Gearing

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## Abstract:

This paper will describe a powder and processing method that facilitates single press-single sintered densities approaching 7.5 g/cm<sup>3</sup>. At this sintered density, mechanical properties of the powder metal (P/M) component are significantly improved over current P/M technologies and begin to approach the performance of wrought steels. High performance gears have the added requirement of rolling contact fatigue durability that is dependent upon localized density and thermal processing. Combining high density processing of engineered P/M materials with selective surface densification enables powder metal components to achieve rolling contact fatigue durability and mechanical property performance that satisfy the performance requirements of many high strength automotive transmission gears. Data will be presented that document P/M part performance in comparison to conventional wrought steel grades.

## Introduction

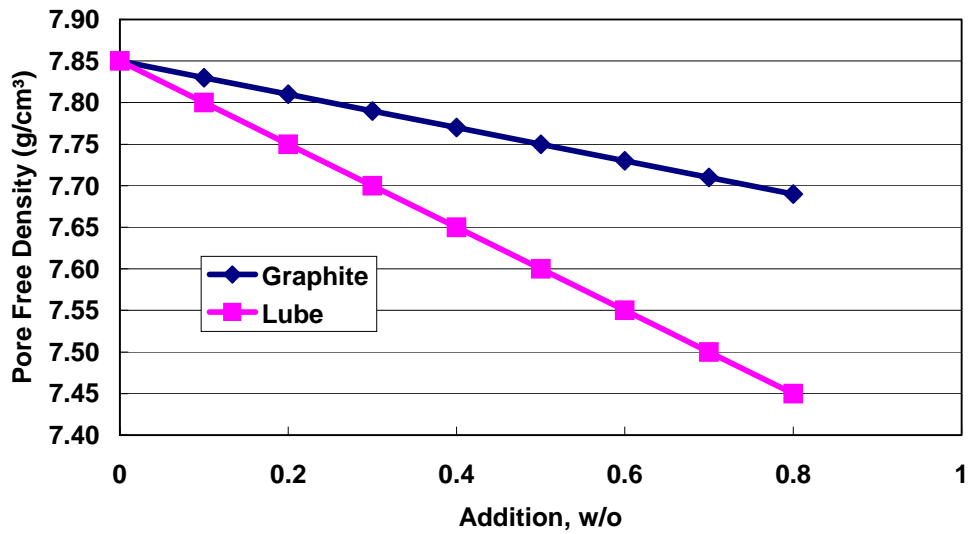
Mechanical property performance of ferrous P/M components is dependent upon density, microstructure, and composition. Alloy composition affects heat treat response; additionally, alloyed ferrous materials have improved static and dynamic properties response relative to unalloyed iron components. [1] Mechanical properties such as impact toughness and rolling contact fatigue are more susceptible to sintered density relative to static properties such as yield or tensile strengths. [2] Well-established techniques that increase sintered density of P/M components are as follows:

- Warm compaction technology
- Double press / double sinter (DP/DS)

Warm compaction techniques are two-fold; one is heated die combined with heated powder and the second is simply heated tooling. DP/DS techniques require the use of two distinct compaction and sintering operations. Limitations of DP/DS include additional processing steps in the manufacture of parts and an inability to effectively produce complex shapes such as helical gearing.

Warm compaction techniques are limited to producing a green part that is a maximum of 98% of the pore free density (PFD) of the starting premix material. [3] Low-density premix additives such as graphite and lubricant dramatically reduce PFD thus lowering attainable green and sintered densities. Figure 1 illustrates the reduction in PFD with additions of graphite and powder lubricant; for premixes containing both graphite and lubricant the reduction in PFD is the summation of the individual effect of lubricant and graphite. Thus to achieve high single press / single sinter densities without having excessive shrinkage during sintering, it is necessary to limit both the amount of lubricant and graphite present in the starting premix. Limiting internal

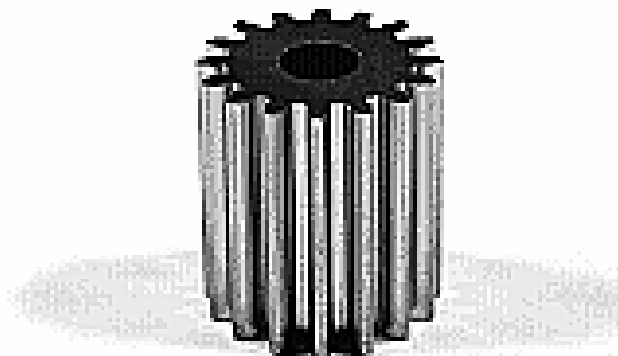
lubrication will potentially result in problems ejecting parts from the die while limiting graphite additions may negatively affect mechanical properties of the final component.



**Figure 1:** Effect of graphite and lubricant additions on pore free density of P/M components

### Process Details

To achieve a  $\sim 7.5$  g/cm<sup>3</sup>-sintered density, it is necessary to compact green parts to a density of  $\sim 7.4$  g/cm<sup>3</sup> and then via sintering gain an additional 0.10 g/cm<sup>3</sup>. Recognizing that 98% of PFD of a premix can be achieved via compaction, a 7.4 g/cm<sup>3</sup> green density denotes a PFD of the powder premix of approximately 7.55 g/cm<sup>3</sup>. From Figure 1, this requirement limits both lubricant and graphite additions to  $\sim 0.40\%$  maximum. Prior part production experience at this low lubricant level demonstrated extreme difficulty in ejecting compacted parts, these compacted parts showed both excessive surface scoring coupled with high ejection pressures. A recent development in powder lubrication technology facilitated the use of 0.40% total internal lubricant. This reduced lubricant level coupled with compaction die temperatures of  $\sim 85$  °C and compaction pressures up to 760 MPa produced green densities  $\geq 7.4$  g/cm<sup>3</sup>. Parts lengths up to 30 mm have been compacted with excellent surface finish.



**Figure 2** Test Gear

Shown as Figure 2 is a prototype gear utilized to evaluate compaction processes and powder lubrication. This gear is compacted on a mechanical compaction press at speed of 10 parts per minute. Details of this 16 tooth gear are as follows: major diameter of 28.3 mm, ID of 9.45 mm, module of 1.66, pressure angle of 20°, and a pitch diameter of 24.5 mm. This gear has a high surface area to volume ratio, which demonstrates effectiveness of lubrication particularly as the height and density increases. For example using a standard FLN2-4405 with

0.75% Acrawax and 0.35% graphite, a maximum green density of  $\sim 7.2$  is achieved at an overall part height of 25 mm and compaction pressures of 760 MPa. Increasing the part height above 25mm, scoring of the part was observed after ejection. With the newly developed lubrication system, part heights up to 30 mm have been achieved with green densities  $\geq 7.4$  at compaction pressures of 760 MPa utilizing a die heating to 85 °C.

Presented in Table 1 are mechanical properties of an FLN2-4405 material (with 0.35% graphite). As sintered densities increase, yield and tensile strengths approach the strength values established for AISI 8620 wrought steel. Elongation and impact toughness of P/M steels are less than wrought steel. The Q&T values listed in Table 1 were determined following austenitizing at 925 °C for 1 hour, oil quenching, and tempering at 205 °C for 1 hour.

**Table 1**  
**Mechanical Property of FLN2-4405 (0.35% Graphite)**  
**Sintered at 1120 °C for 20 minutes (90 v/o nitrogen and 10 v/o hydrogen)**

Condition	Density, g/cm <sup>3</sup>	0.2% Offset YS, MPa	UTS, MPa	Elongation, %	HRA	Impact, Joules (unnotched)
FLN2-4405 As-sintered	7.36	392	578	4.0	49	31
	7.41	397	602	4.2	51	35
	7.46	423	626	4.6	52	48
FLN2-4405 Q&T	7.33	828	951	1.4	59	16
	7.37	896	1027	1.5	62	18
	7.43	917	1075	1.8	62	21
AISI 8620, Q&T	7.86	1075	1355	8.0	71	312

Target applications for parts with sintered densities  $\geq 7.45$  g/cm<sup>3</sup> are high performance gears used in both automotive and non-automotive transmissions. In addition to high static and bending fatigue strength, high performance gears have the additional requirement of rolling contact fatigue durability (defined as resistance to surface spalling). [4] Previous experimental work demonstrated that rolling contact fatigue is dependent upon both the density of P/M parts in the highly stress sub-surface shear zone and heat-treat condition. [5] Presented in Table 3 is a summary of recently developed rolling contact fatigue data. This data presents a comparison of rolling contact fatigue life of high core density FLN2-4405 (0.30% sintered carbon) along with FLN2-4405 (at 0.50% core carbon) and two wrought steel materials. The data presented lists the material, type of carburizing employed, B50 life during rolling contact fatigue testing at two Hertzian stress levels, and a measure of the scatter defined as the ratio of B10 life to B90 (statistical determined as cycles to 10% failure and cycles to 90% failure). For all materials, the Hertzian stress was adjusted so as to achieve approximately the same B50 life. For the low carbon FLN2-4405 and the AISI 8620 steel, the B50 life was determined at 2100 MPa and 2000 MPa respectively. Testing these materials at 1900 MPa produced run-outs (defined at >50 million cycles) for both materials. The significance of this testing was that both FLN2-4405 low core carbon and AISI 8620 wrought steel would have superior B50 life compared to either AISI 5120 or FLN2-4405 (with 0.50% core carbon) if all testing was done at 1900 MPa.

Low core carbon contents promote higher surface compressive stresses because of differential in the martensite start temperature and volume expansion of martensite formation upon quenching. This is the primary reason high performance gear steels have core carbon contents of 0.15% to 0.30%. A similar effect was observed with FLN2-4405. Specifically, core carbons of ~ 0.30% gave a B50 life superior to the 0.50% core carbon FLN2-4405. The carburizing cycle employed also affected rolling contact fatigue performance. Utilizing a multiple boost-diffuse carburizing cycle as compared to a single boost-diffuse promoted higher rolling contact fatigue endurance. All samples were carburized for a total time of 3 hours at 925 °C. The case microstructure consisted of acicular martensite with retained austenite and the core was predominantly lath type martensite. Optimizing both the core carbon and carburizing method enabled the FLN2-4405 with a 0.30% core

carbon to give rolling contact fatigue performance equivalent to wrought steels at both testing conditions.

**Table 2**  
**Rolling Contact Fatigue Data of High Density P/M Materials**

Material	Processing Condition	Hertz Contact Stress, MPa	B50 Life, 10 <sup>6</sup> cycles	Scatter, Ratio B10 / B90
AISI 5120	Vacuum Carburized. Multiple boost/diffuse	1900	16.7	1.8
		2500	6.1	2.7
FLN2-4405, 0.5% C *	7.35 g/cm <sup>3</sup> core density 0.6mm surface densified	1900	19.0	3.0
		2500	2.6	2.5
FLN2-4405, 0.3% C **	7.4 g/cm <sup>3</sup> core density 0.6mm surface densified	2100	19.0	3.8
		2500	5.1	3.4
AISI 8620	Vacuum Carburized, Single boost / diffuse	2000	20.0	1.8
		2500	4.2	2.7

\* Carburized via single boost / single diffuse cycle

\*\* Carburized via multiple boost / diffuse cycle

### Conclusions:

1. Green densities of  $> 7.4 \text{ g/cm}^3$  are possible utilizing a new lubricant system enabling the use of 0.40% admixed lube. Compacted parts up to 30 mm in length are possible.
2. At sintered densities  $\sim 7.45 \text{ g/cm}^3$ , tensile and yield strengths are similar to wrought AISI 8620 material. Elongation and impact toughness of the P/M material are lower.
3. Rolling contact fatigue is critical in gearing. It is dependent upon the density of the P/M part in the critical sub-surface stress region. Surface densified P/M parts with  $7.4 \text{ g/cm}^3$  core density and 0.30% core carbon give rolling contact fatigue life equal to wrought steel..
4. With this high density processing combined with surface densification, P/M is now able to give static properties that are approximately equal to wrought with equal rolling contact fatigue properties.

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