ROLLING CONTACT FATIGUE OF SURFACE DENSIFIED MATERIAL: MICROSTRUCTURAL ASPECTS

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ABSTRACT

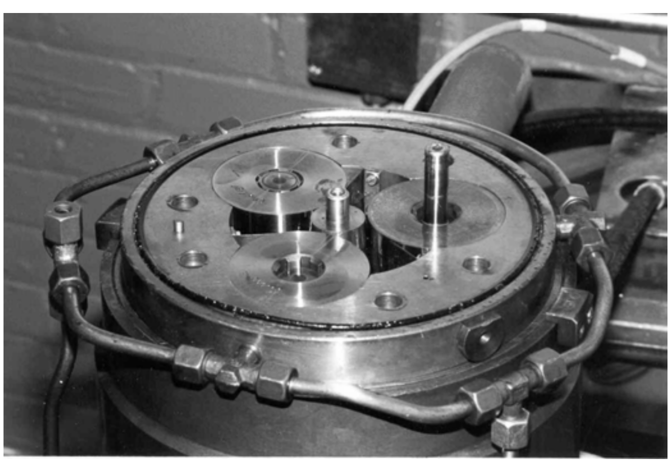
Automotive gearing applications have material requirements combining static strength, bending fatigue, and rolling contact fatigue durability. Advances in P/M alloys and processing can produce as-sintered densities greater than 7.4 g/cm³ in complex gearing geometries. This high sintered density results in high static and fatigue resistance. However, at less than full density rolling contact fatigue performance is compromised. For high duty cycle gearing, pore free density is needed in the tooth contact region and in the area where the tooth flank intersects with the gear tooth root radius. This paper will investigate the effects of part processing and surface densification on the rolling contact fatigue properties of a high density FLN2-4405 material. Variables studied include: depth of densification, sintering conditions, surface microstructure, and post densification heat treatment practices. The results will demonstrate effects of residual porosity, case microstructure, and soft-nickel rich regions on rolling contact fatigue. Metallographic analysis will illustrated the cause of the failures associated with these variables.

INTRODUCTION

P/M processing is capable of producing dimensionally accurate components that have successfully replaced many high strength components [1]. Advances in both powder production and P/M part manufacturing technologies facilitate part densities greater than 7.4 g/cm³ via single press / single sinter processing. This high sintered density promotes greater uniformity of density throughout the part minimizing low-density neutral zones, often the region of highest loading in gearing applications [2]. Despite the many successes of P/M, property requirements of automatic transmission pinion gears exceed the current capabilities of conventional P/M processing [3]. Presently, these gears are produced from low alloy wrought steel wire that is hot shaped, machined, gear cut, carburized, and hard finished [4]. Performance requirements of these gears dictate that good rolling contact fatigue life is necessary to guarantee long-life power train reliability.

A comprehensive study performed by the Center for Powder Metal Technology (CPMT) demonstrated that rolling contact fatigue of P/M components is a function of surface density and heat treat condition [5,6]. Once near full density is achieved on the surface, rolling contact fatigue life proved to be equivalent to wrought steel. The lubrication regime of the CPMT study was type 2 (mixed mode), with this lubrication mode the failure mode was predominantly surface pitting. This study did not investigate the depth of densification, carburizing variables, etc. Additionally, the surfaced densified samples utilized in this study were double pressed and double sintered (DP/DS) to core densities approaching 7.5 g/cm³. This processing is impractical for the manufacture of helical gearing. Ensuing work by Slattery etal, demonstrated that a 22° helical gear could be single pressed to green densities $\geq$7.3 g/cm³ [7]. Following sintering, these high-density pinions were successfully surface densified to nearly pore free density to depths approaching 1 mm, while still maintaining the demanding dimensional requirements for test radius, involute profile, helix, and tooth surface finish. Another significant finding of this study demonstrated crowning of the flank and lead was possible during the surface densification process [7].

Ultimately, the suitability of a P/M alternative for the production of high performance gearing will be determined after extensive dynamometer and vehicle testing [8]. However, during the preliminary evaluation stage actual gear testing is time consuming and costly. To evaluate P/M materials and processing alternatives, a ranking test is desirable. Although gears operate in the type 2 mixed mode lubrication regime where the typical failure mode is surface pitting, P/M gear candidates must demonstrate comparable material performance to wrought steel. The ZF-RCF Test Bench (Figure 1) assesses material gear characteristics via a cylindrical test specimen. The original ZF-Test Bench was modified to evaluate candidate powder metal materials and processing schemes; these modifications facilitated testing of as processed rings thus eliminating machining of the P/M surface. This testing utilizes the native surface of the P/M part evaluating materials in full elastic-hydrodynamic lubrication regime (type 3) and similar to actual gears utilizes line contact. Previous studies utilizing the ZF-RCF Test Bench demonstrated its effectiveness in ranking materials and heat-treat conditions in accordance with the expected life of gears. Despite some differences in the absolute magnitude of the endured contact stress, test results mirrored the actual gear performance [9].



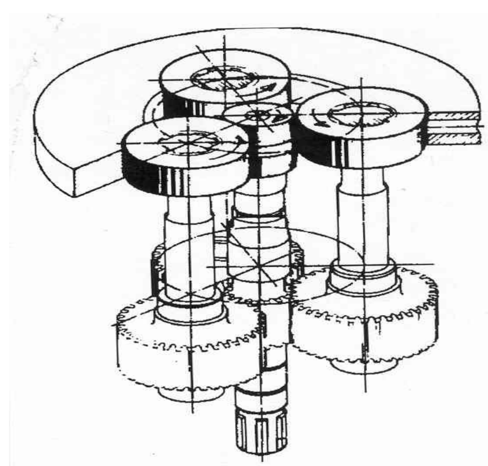


Figure1: ZF-Rolling contact fatigue Test Bench

This study was initiated to qualify microstructural effects produced by various P/M processing on rolling contact fatigue properties of a high density FLN2-4405 material. Microstructural features investigated were residual porosity, case microstructure, and soft nickel rich regions. Processing parameters affecting these microstructural details were sintering temperature, depth of densification, surface microstructure, and post densification thermal treatment. The ultimate objective was to define processing parameters required for this material such that pinion gears could be produced with rolling contact fatigue life equivalent to current wrought steel gears. These results were deemed important for reducing actual engineering test time and accelerating acceptance of P/M in the marketplace.

EXPERIMENTAL PROCEDURE

Processing variables evaluated in this study are summarized in Table 1.

Table 1
Material Test Conditions
Material Utilized was MPIF FLN2-4405*

Sintering Temperature	Depth of Densified Layer, mm	Post Densification Thermal Treatment**	Carburized Surface Carbon, %
2050 °F (1120 °C)	0.38	No	0.90 / 1.0
	0.76	No	0.90 / 1.0
	0.76	No	~0.80
2300 °F (1260 °C)	0.76	No	0.90 / 1.0
	0.76	Yes	0.90 / 1.0
	0.76	No	0.90 / 1.0

* (7.30 g/cm³ green density, $\geq$ 7.35 g/cm³ [94% pore free] after sintering)
** Prior to carburizing a high temperature treatment to promote sintering of collapse porosity.

Details of the processing are as follows:

- High-density P/M cylinders (45 mm diameter by 19 mm height) were compacted via heated die techniques to a green density of ~7.3 g/cm³ [10].
- Sintering was done either at 2050 °F (1120 °C) or 2300 °F (1260 °C) in a continuous belt sintering furnace using a 90 v/o nitrogen and 10 v/o hydrogen atmosphere with sintering times of ~40 minutes at temperature.
- Pressed and sintered samples were machined to the OD size required for the densification treatment. The additional stock left on the outer diameter (OD) was varied to provide the depth of densification desired. Locating on the virgin densified surface OD and machining the ID to the correct diameter achieved concentricity requirements.
- Samples were surface densified to a depth of 0.38 mm or 0.75 mm.
- All samples were carburized at 1700 °F (925 °C) in a vacuum furnace for 90 minutes at temperature to a surface carbon of ~0.90 to 1.0% carbon. The carburizing cycle consisted of 45 minutes for the boost phase and 45 minutes for the diffuse phase. One group of samples was carburized to a ~0.80% surface

carbon to evaluate the effects of surface martensitic microstructure: acicular vs. lathe martensite.

- One test group was given a thermal treatment prior to carburizing to evaluate potential sintering of the collapsed pores after surface densification. This will be described later.

All test samples were evaluated in the densified and heat-treated condition; no post heat-treating machining was performed. Test conditions for the ZF rolling contact fatigue test bench were as follows:

- Test speed of 3000 RPM with three load wheels, 9000 load cycles per minute
- Two load levels: 1900 MPa and 2500 MPa, assuming a Young's Modulus of 30 million psi (206,000 MPa), loading constant. See Figure 2 for the sub-surface stress distribution for various loading conditions.
- Sliding of –24% between the test sample and load wheels.
- Type 3 lubricant regime, implying complete elasto-hydrodynamic lubrication. Lubricant: Dextron III, automatic gear box oil provided by General Motors Corporation, the oil was held at 80 °C ± 2 °C.
- Failure during the test was detected using an accelerometer, which terminated the test once vibrations from surface spalling were detected. Five samples were evaluated at each Hertzian stress level.

All test conditions were metallographically analyzed for depth of densification plus the carburized case and core microstructure. Failure analysis was performed to determine the cause of sub-surface failure.

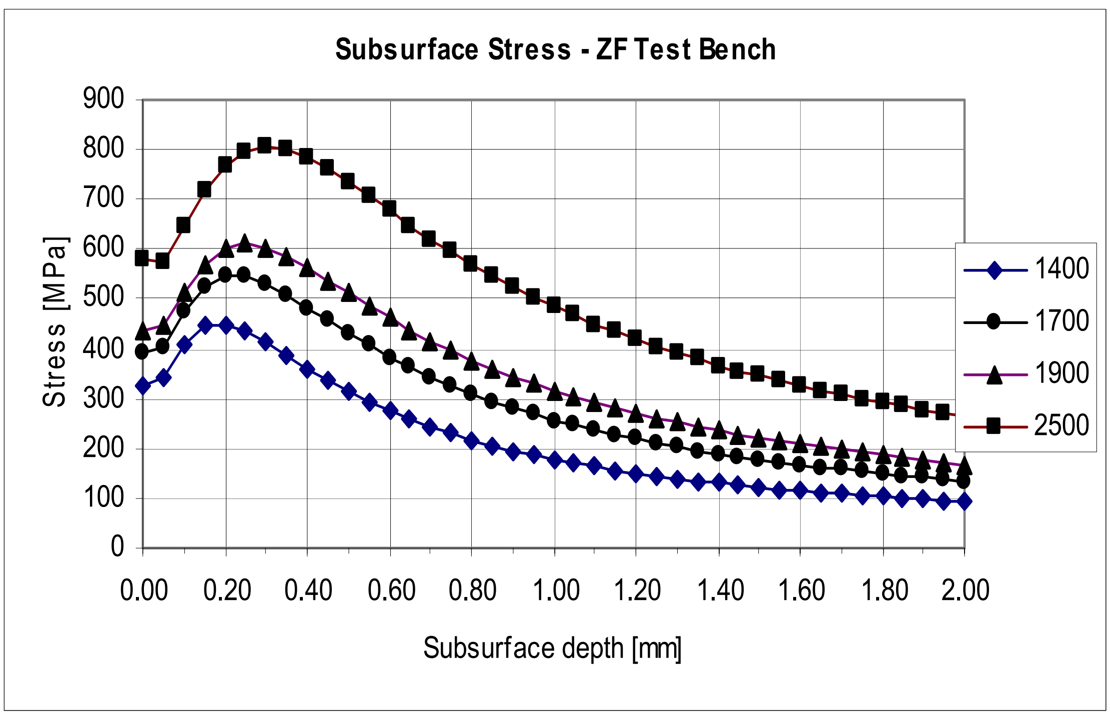


Figure 2: Sub-surface stress distribution for the applied loads calculated using von-Mises yield criterion and assuming fully dense material.

RESULTS AND DISCUSSION

Results from this study will be presented by discussing the primary variables investigated.

Effects of Surface Densification Depth

A key aspect of this effort was to establish what effect depth of densified layer had on rolling contact fatigue properties. Although surface densified layers greater than 1 mm are possible, increased amounts of cold work result in a greater potential for sub-surface cracking, increased die wear, and possible roll die damage. As shown in Figure 2, maximum sub-surface stresses in rolling contact fatigue occur at depths of 0.2 to 0.3 mm below the contact interface. Surface densifying to 0.38 mm was accomplished by machining sintered samples 0.15 mm oversize on the OD. Whereas, densifying to 0.75 mm densified condition was accomplished by machining samples 0.20 mm oversize. The final OD after rolling in both instances was 30 mm as required by the ZF Test bench. Porosity for the two conditions as a function of depth below the surface shown in Figure 3 was determined by quantitative image analysis. Percent porosity was determined on polished metallographic samples at a magnification of 500X at the mid-height of representative samples. Each data point represents the average of three adjacent fields, with a total measured area of 500 microns by 100 microns. Figure 4 shows the metallographic appearance of both densified layers.

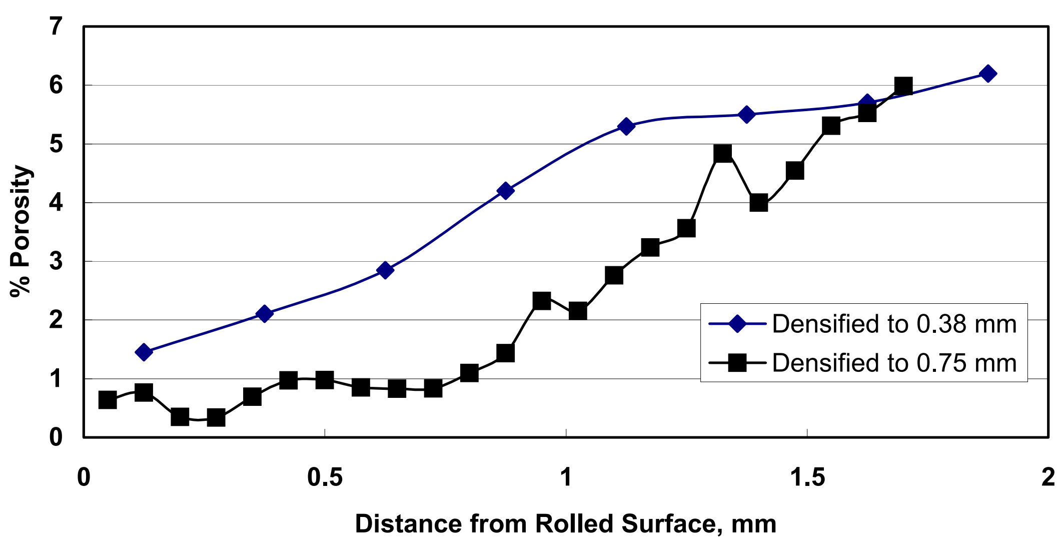
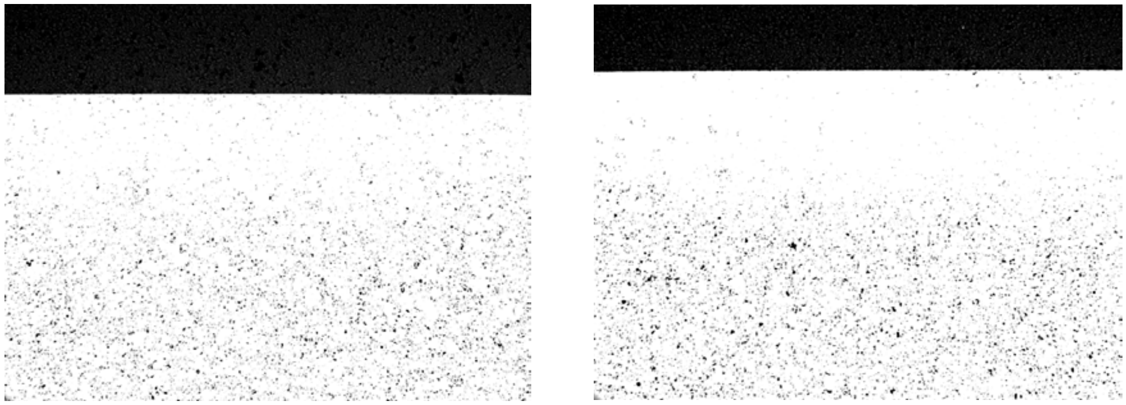


Figure 3: Density gradient as measured from surface of roll densified ring.



(4a) (4b)

Figure 4: Photomicrographs of densified surface
4a) 0.38 mm densified condition, original magnification 20X
4b) 0.75 mm densified condition, original magnification 20X

Rolling contact fatigue results of the two conditions are shown in Table 2. Data presented in Table 2 utilizes probability of survival at the two stress levels and a measure of the scatter of the data at each stress level. Definitions of the various terms are summarized below:

- Tn=50% Life at which statistically 50% of the samples will survive
- Tn=10% Life at which statistically 10% of the samples will survive
- Tn =90% Life at which statistically 90% of the samples will survive
- Tn=1: Tn=10/Tn=90 Relative measure of life to failure scatter
- k Slope of S-N curve; lower values are preferred

Samples densified to 0.38 mm exhibited rolling contact fatigue life at 1900 MPa greater than the wrought steel baseline, AISI 5120. Contrary to initial expectations, the 0.38-mm condition gave both superior life and reduced scatter in the data relative to the 0.75-mm condition. Both P/M materials showed increased scatter in life to failure compared to the AISI 5120 wrought steel baseline as evaluated by Tn=1:T10/T90. Also, the slope of the S-N curve (k) is greater for the P/M material because of reduced performance at higher contact stresses.

Table 2
Effects of Depth of Densification on Rolling Contact Fatigue Life

Depth of Densification, mm	Contact Pressure, MPa	Tn = 50%	Tn = 10%	Tn = 90%	Tn = 1 : T10/T90	K
0.38	1900	2.6*E7	5.0*E7	1.5*E7	1 :3.3	8.0
	2500	2.8*E6	5.1*E6	1.6*E6	1 :3.2	
0.75	1900	1.7*E7	5.5*E7	5.5*E6	1 :10	6.5
	2500	2.6*E6	5.8*E6	1.2*E6	1 :4.8	
AISI 5120*	1900	1.6*E7	2.0*E7	1.1*E7	1 :1.8	3.5
	2500	6.1*E6	8.0*E6	4.8*E6	1 :1.7	

* Carburized to 1 mm total case depth.

During the planning stage of this program, it was assumed that deeper densification would improve rolling contact fatigue life. Failure analysis of these two conditions revealed that the 0.38 mm densified condition showed crack initiation at depths greater than predicted by the sub-surface stress calculation. Cracking initiated beneath the densified layer in the transition zone between the case and core (Figure 5). Whereas, sub-surface cracking in the 0.76 mm densified condition initiated in the densified zone at depths predicted by the calculated sub-surface stress (Figure 6).

This suggests that the shallowness of the densified case and the corresponding decrease in mechanical properties is inadequate to support the magnitude of the sub-surface stresses. The lower density has several deleterious effects. Not only are mechanical properties degraded but the reduced Modulus increase the magnitude of the applied stress. For example, an increase in porosity from full density to 6% porosity decreases the modulus from 206,000 MPa (30 million psi) to about 165,000 MPa (24 million psi). This results in 12% increase in the magnitude of the sub-surface stresses [8]. This implies that increased depth of densification will benefit rolling contact fatigue durability. Since the surface densified P/M has acceptable rolling contact fatigue life at 1900 MPa, from Figure 2 the maximum sub-surface stress is ~600 MPa. To achieve similar success at 2500 MPa, the depth of densification must be at least equal to or beyond where the maximum stress is 600 MPa. From Figure 2, the depth of sub-surface stress at 600 MPa is 0.22 mm at 1900 MPa and ~0.75 mm at 2500 MPa. Assuming a safety margin of 0.15 mm, then the critical densified layer to achieve equivalent life to wrought steel will be ~0.90 mm for the maximum stress of 2500 MPa.

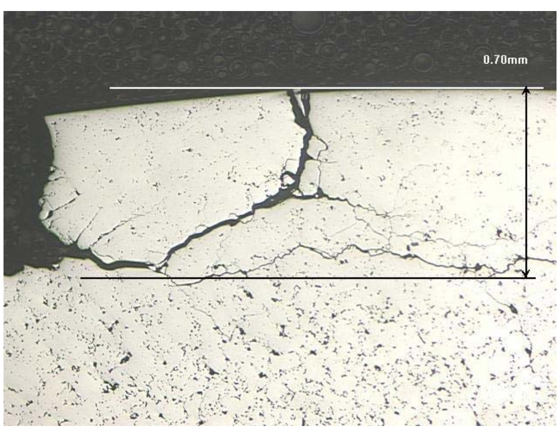


Figure 5: Crack initiation in 0.38 mm sample illustrating cracking in transition zone between densified case and core.

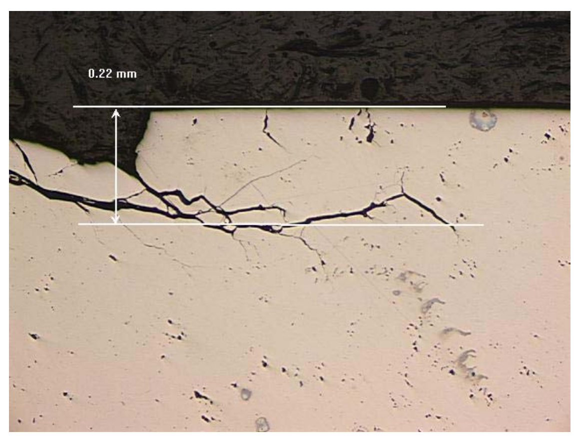
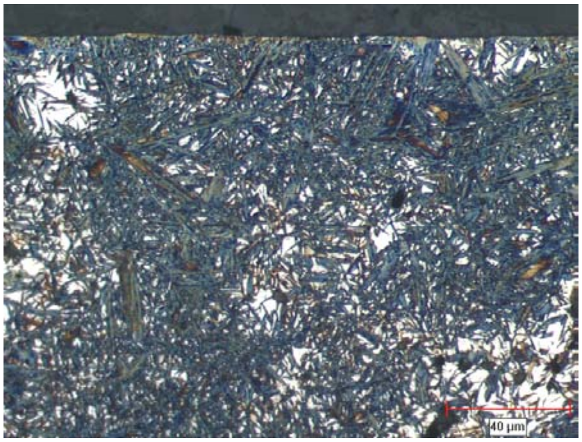


Figure 6: Crack initiation in 0.75 mm sample illustrating cracking in densified zone

Effect of Surface Microstructure

Photomicrographs illustrating the differences in the case microstructure as a function of surface carbon content are presented as Figure 7 and Figure 8. At 0.9/1.0 % surface carbon (Figure 7), the martensite formed is acicular (plate) with approximately 10% to 20% retained austenite. Whereas at 0.8% surface carbon content (represented in

Figure 8), the martensitic case is predominantly lathe type with less than 5% retained austenite.   The light etching regions in both photomicrographs are nickel rich areas resulting from incomplete homogenization of the nickel following sintering at 2050 °F (1120 °C). Shown as Figure 9 is the core microstructure associated with both carburizing conditions. The structure consists of lathe type martensite as expected with 0.50% sintered carbon.



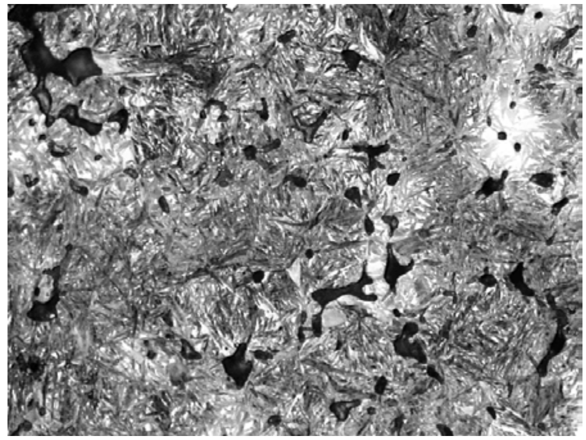


Figure 7: Etched microstructure of case with case carbon of 0.9/1.0%

Figure 8: Etched microstructure of case with case carbon of ~0.80%

Traditionally, carburizing grades of wrought steel have a carbon content less than 0.40%, to promote carburization and to increase surface compressive stresses produced during martensitic transformation. Because of the inherent porosity in P/M, low core carbon contents result in reduced mechanical properties. Thus, nominal sintered core carbons of 0.50% were chosen in this study to offset the negative effect of porosity.

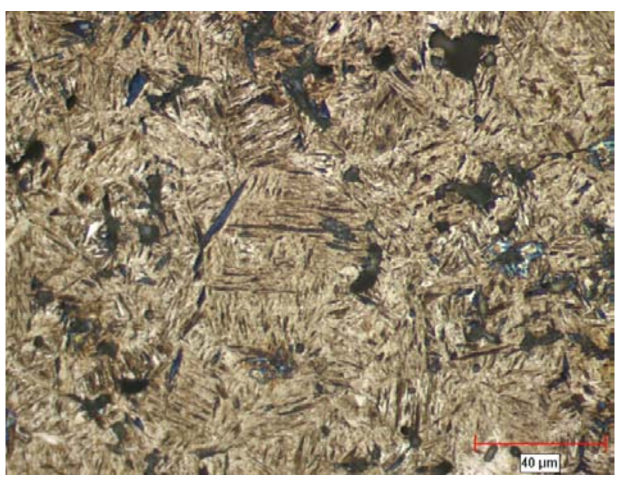


Figure 9: Core microstructure of 2050 °F (1120 °C) samples

Rolling contact fatigue results of these two conditions are presented in Table 4. Lower surface carbon and the corresponding difference in martensitic case microstructure result in an ~ 60% decrease in rolling contact fatigue life. This decrease is explained by a combination of reduced surface compressive stresses, insufficient surface retained austenite, and reduced strength of the material at critical sub-surface depths. Heat treat requirements for carburized gears specify that the amount of retained austenite be approximately 10% to 20% [3,4]. From results achieved in this study, this corresponds to a surface carbon content of 0.9/1.0% and the corresponding shift from lathe to nearly 100% acicular martensite. Micro-indentation hardness readings form both conditions showed similar test results, thus hardness alone is not a good indicator of material properties.

Table 4
Effects of Surface Carbon on Rolling Contact Fatigue

Surface Carbon, %*	Contact Pressure, MPa	Tn = 50%	Tn = 10%	Tn = 90%	Tn = 1 : T10/T90	k
~0.80	1900	7.5*E6	1.5*E7	3.8*E6	1 :4.0	6.5
	2500	1.3*E6	1.6*E6	1.1*E6	1 :1.5	
~0.90 / 1.0	1900	1.7*E7	5.5*E7	5.5*E6	1 :10	6.5
	2500	2.6*E6	5.8*E6	1.2*E6	1 :4.8	
AISI 5120	1900	1.6*E7	2.0*E7	1.1*E7	1 :1.8	3.5
	2500	6.1*E6	8.0*E6	4.8*E6	1 :1.7	

* Both P/M materials surface densified to 0.75 mm

Effect of Nickel Rich Regions

Traditional thinking within the P/M community considered nickel rich regions as beneficial in axial and bending fatigue because these soft regions act to blunt crack propagation [17]. However, recent research established crack propagation actually occurs through nickel rich regions in both axial fatigue and rolling contact fatigue [18,19]. In the as-sintered condition, nickel rich regions consist of high nickel / iron alloy, nickel rich martensite, and bainite. The nickel rich martensite and bainite regions have greater compressive yield strength than the ferrite / pearlite matrix. As such, deformation resulting from surface rolling does not eliminate all the porosity associated with these regions and this residual porosity can then act as crack initiation sites leading to failure. High temperature sintering homogenizes the FLN2-4405 microstructure virtually eliminating the nickel rich regions and the accompanying porosity. High temperature sintering has the added benefit of greater sinter densification, pore rounding, and reducing the overall porosity level (Figure 10).

To assess the effects of nickel rich regions, sample blanks were sintered at 2300 °F (1260 °C) and then surface densified to 0.75 mm. Depth of porosity after surface densification as a function of sintering temperature is shown in Figure 10. High temperature sintering promotes lower residual porosity in the critical high stress region of rolling contact fatigue samples. Shown in Table 5 are rolling contact fatigue test results comparing high temperature sintering to conventional sintering. Although there is a minor reduction in the T10 and T50 life at 1900 MPa with high temperature sintering; there is reduced scatter in the test data, approaching the scatter associated with the wrought steel baseline. This reduced scattering of the data is significant; it implies more consistent material properties. It also gives design engineers greater confidence in the P/M solution. This reduced scatter was observed at both 1900 MPa and 2500 MPa.

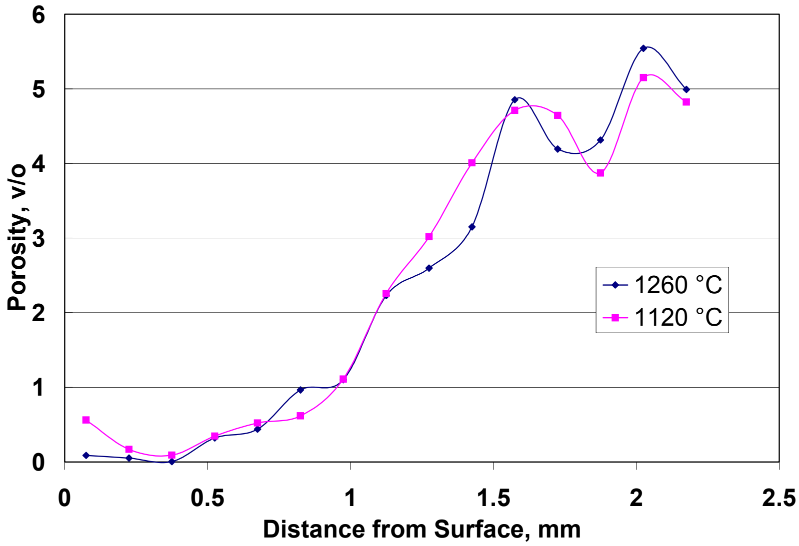


Figure 10: Porosity vs. distance from surface for two sintering conditions both surface densified to 0.75 mm.

Table 5
Effect of Sintering Conditions on Rolling Contact Fatigue

Sinter Temp.	Contact Pressure, MPa	Tn = 50%	Tn = 10%	Tn = 90%	Tn = 1 : T10/T90	k
2050 °F (1120 °C)	1900	1.7*E7	5.5*E7	5.5*E6	1 :10	6.9
	2500	2.6*E6	5.8*E6	1.2*E6	1 :4.8	
2300 °F (1260 °C)	1900	1.0*E7	1.5*E7	7.8*E6	1 :2.0	4.6
	2500	2.8*E6	5.0*E6	1.6*E6	1 :3.2	
AISI 5120	1900	1.6*E7	2.0*E7	1.1*E7	1 :1.8	3.5
	2500	6.1*E6	8.0*E6	4.8*E6	1 :1.7	

Failure analysis of samples processed at the two sintering temperatures, showed distinct differences in the failure mode. Sub-surface cracking in the samples sintered at 2050 °F (1120 °C) often initiated at porosity associated with nickel rich regions (Figure 11). Nickel rich regions have more porosity and less rounded pore morphology, these zones have a greater propensity for crack initiation and subsequent propagation. Also associated with nickel rich regions, SEM analysis of unetched samples using back scattered electron imaging (Figure 12) showed areas adjacent and ahead of the propagating crack as un-tempered martensite. The combination of repetitive stress cycles and local heating ahead of the cracks transform the retained austenite to un-tempered martensite thus providing a crack propagation path through brittle microstructure. This stress-induced transformation has often been observed in failures of roller bearing elements [17].

Failure analysis of the 2300 °F (1260 °C) sintered samples demonstrated surface initiated cracking, similar to carburized AISI 5120 wrought steel baseline. These surface micro-cracks were associated with sub-surface porosity as the cracks propagated through the matrix microstructure (Figure 13).

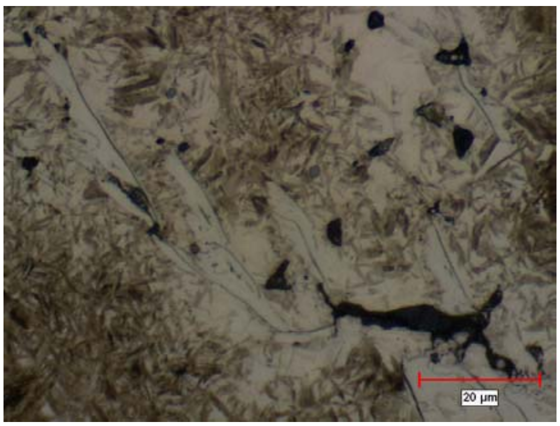


Figure 11: 2050 °F (1120 °C), 0.030-inch showing cracking initiating at pores and following nickel rich regions associated with elemental nickel additions

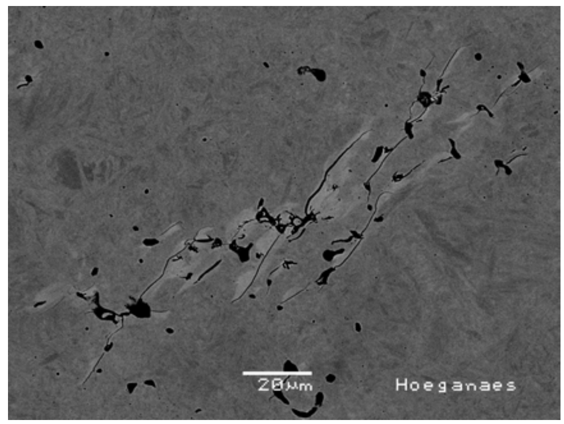


Figure 12: SEM backscatter electron image showing stress induced transformation to un-tempered martensite in nickel rich regions of the 1120 °C samples. Unetched

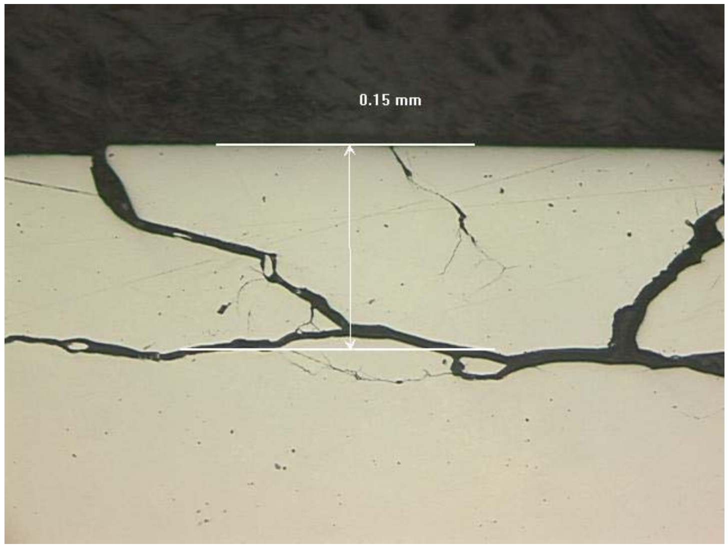
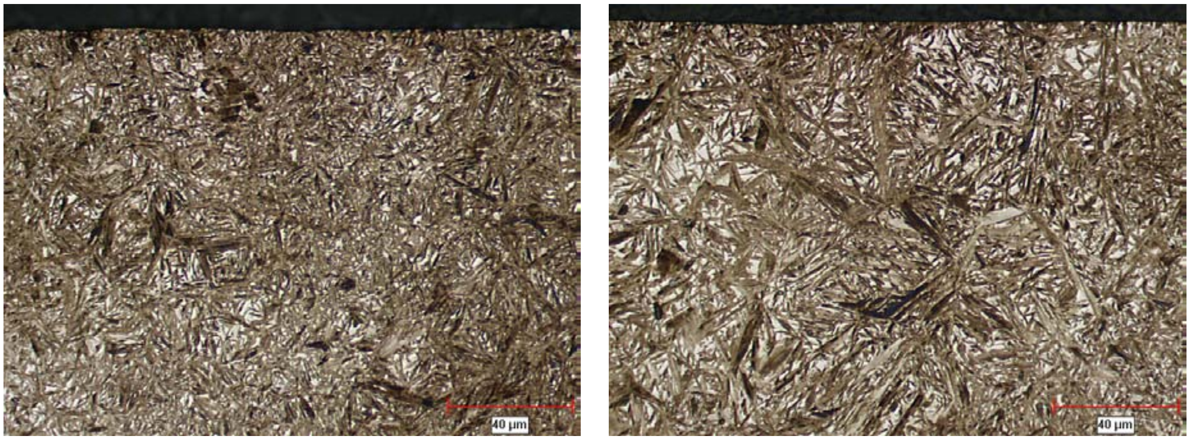


Figure 13: Crack propagation exhibited in high temperature sintered test samples

Effect of Cold Working Induced by Surface Densification

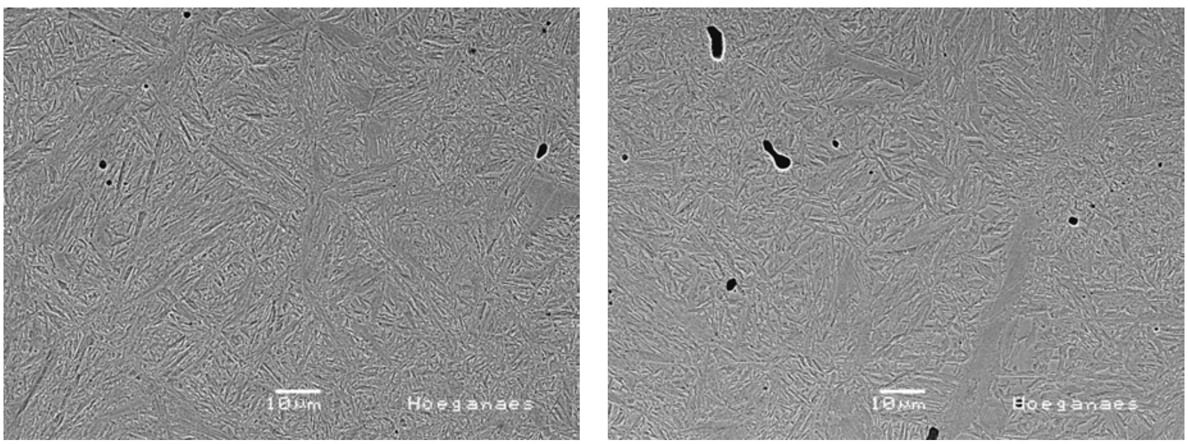
Surface densification is a cold working phenomena with the primary objective of eliminating residual porosity via pore closure. If these collapsed pores do not metallurgically bond during the carburizing cycle they may act as stress risers and preferential crack initiation and propagation sites. One way to promote sintering across the cold work interfaces is to use a high temper thermal treatment. In a prior study [18], the authors determined that heating damaged parts to 1700 °F (925 °C) for 7 hours eliminated micro-porosity resulting from cyclic fatigue. If collapsed pores within the samples behave similar to micro-porosity, then a thermal treatment that promotes micro-void coalescence will eliminate potential deleterious effects of these collapsed pores. In this study, a higher temperature was chosen to reduce the element of time [19,20]. Samples were sintered at 2300 °F (1260 °C), surface densified to 0.76 mm and then thermally treated at 1900 °F (1035 °C) for 30 minutes at temperature prior to carburizing.

Metallographic analysis of the two sample groups showed pronounced differences in the appearance of the carburized martensitic case and amount of micro porosity (Figure 14 and Figure 15). Thermally treated samples exhibited microstructural refinement: smaller martensite needle size and spacing with smaller retained austenite regions. SEM photomicrographs presented in Figure 15 show clearly the difference in micro porosity between the two samples. Thermally treated samples exhibit microstructural refinement and reduced porosity, both size and amount.



(14a) (14b)

Figure 14: Optical photomicrograph of martensitic case
14a Thermally treated
14b Non-treated



(15a) (15b)

Figure 15: SEM photomicrograph of martensitic case
15a Thermally treated
15b Non-treated

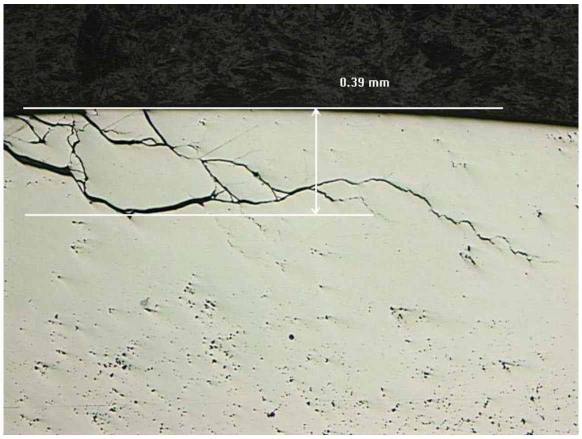
Rolling contact fatigue test data from the two conditions are presented in Table 6. The mean life to failure of thermally treated samples is equal to the AISI 5120 wrought steel at 1900 MPa. However, like other processing modification aimed at improving the rolling contact fatigue, this processing condition proved ineffective for the 2500 MPa test level.

Table 6
Effect of Thermal Processing

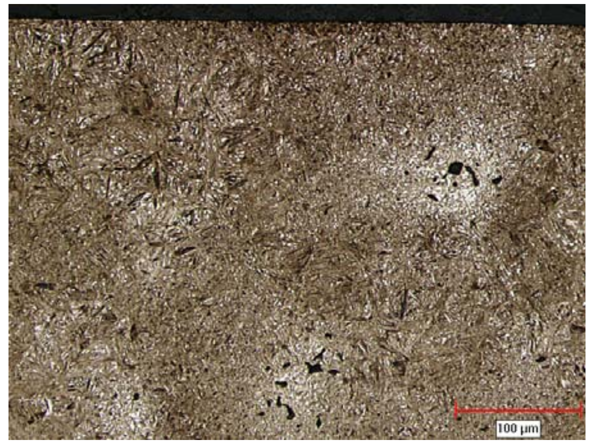
Sinter Temp.	Contact Pressure, Mpa	Tn = 50%	Tn = 10%	Tn = 90%	Tn = 1 : T10/T90	K
Non-treated	1900	1.0*E7	1.5*E7	7.8*E6	1 :2.0	4.6
	2500	2.8*E6	5.0*E6	1.6*E6	1 :3.0	
Thermally treated	1900	1.9*E7	3.3*E7	1.2*E7	1 :3.0	9.0
	2500	1.7*E6	2.7*E6	1.2*E6	1 :2.5	
AISI 5120	1900	1.6*E7	2.0*E7	1.1*E7	1 :2.0	3.5
	2500	6.1*E6	8.0*E6	4.8*E6	1 :1.5	

Failure analysis showed thermally treated samples exhibited cracking similar to wrought steel at 1900 MPa; depth of the sub-surface cracking corresponding to the depth of calculated maximum stress (see Figure 13). However at 2500 MPa, failure analysis showed cracks initiating at the depth of maximum stress but propagating toward the core (Figure 16). As seen in Figure 16a, the crack is propagating toward the core through the densified case region. This suggests that material in this region has insufficient strength (improper microstructure, Figure 16b) to support the higher stress profile associated with 2500 MPa (see Figure 2).

Increasing the carburized case depth will develop the preferential acicular martensitic microstructure and improve the mechanical properties of the material in the critical sub-surface stress region. All P/M samples were carburized at 1700 °F (925 °C) for 90 minutes resulting in a shallower carburized case depth (reviewing Figure 16b an acicular case depth of 0.25 mm to 0.30 mm) relative to the wrought steel evaluated. The wrought samples were carburized to a total case depth of 1 mm with acicular martensite to a depth of approximately 0.43 mm. Although 90 minutes is adequate for developing a 1 mm case at 7.3 g/cm³ density surface densified samples need times equivalent to wrought steel.



16 a



16 b

Figure 16: Optical Photomicrographs
16 a Crack propagation starting in critical stress region and propagating to core
16 b Carburized case depth of surface densified P/M samples with acicular case depth of 0.25 / 0.30 mm.

Concluding Remarks

Results have shown that successful gear material performance, similar to carburized AISI 5120 wrought material, requires surface carbon of 0.9 to 1.0 % with acicular martensite in the critical stress regions, and a case depth of $\geq$ 1 mm. However, surface densified P/M materials have additional requirements in the critical stress region: a homogeneous acicular martensite structure, free of nickel rich areas and full density. A summary of test results is as follows:

- Equivalent life at 1900 MPa for a P/M surface densified material compared to carburized AISI 5120 can be achieved with an acicular martensitic case of 0.38 mm and surface densified to a depth of 0.75 mm.
  - For the ZF test bench, based on the roll diameter and velocity, the densified depth of 0.38 mm is approximately 2X the maximum shear stress depth for an applied load of 1900 MPa. At this magnitude of Hertzian stress, the case and core conditions are adequate to support the developed stresses.
  - Carburizing conditions that promote acicular martensite rather than lathe martensite yield superior rolling contact fatigue performance. Even moderate amounts of lathe martensite in an acicular case results in an approximate 60% reduction in life.
- At 2500 MPa, neither the carburized case depth nor the densified layer was adequate to support the critical sub-surface stresses. Data suggests that an adequate rolling contact fatigue life could be obtained for test samples with a

densified layer of ~0.9 mm and with high enough carbon (0.9 to 1.0% carbon) to produce an acicular martensitic case of 0.43 mm depth.

- Nickel rich regions are associated with higher levels of residual porosity. This porosity acts as crack initiation sites with crack propagation through the stress induced martensitic transformed regions surrounding nickel rich areas.
    - Scattering in test results at the two stress levels is strongly influenced by the sintering conditions, with 2300 °F (1260 °C) sintering showing reduced scatter relative to 2050 °F (1120 °C) sintering.

This study showed that the performance of P/M processed rolling contact fatigue samples equaled or exceeded the performance of wrought steel at the lower stress level of 1900 MPa. However, at 2500 MPa, performance of P/M processed samples fell below the carburized wrought steel base line. At this time, speculation regarding the processing to produce acceptable performance over the range of test conditions should be as follows:

1.) Press to a minimum green density of 7.35 g/cm³.
2.) High temperature sinter (2300 °F (1260 °C)) to promote sinter densification and a homogeneous microstructure
3.) Surface densify to a depth $\geq$ 0.9 mm
4.) Thermally treat at 1900 °F (1035 °C) to heal the collapsed porosity produced during the cold working surface densification process.
5.) Carburize to a 0.9/1.0% surface carbon with a total case depth of 1 mm. Quench to produce acicular martensite at sub-surface depths where the maximum stress is equal to or greater than 600 MPa.

This processing scheme should give the required performance enabling P/M to be used in higher strength gear applications. These rolling contact fatigue tests results should be useful in ranking various process options and give definition for process risk assessment.

Future Work:

From this work, the following additional testing is necessary to further the understanding of P/M processing on rolling contact fatigue durability.

- Develop a full S-N curve for surface densified material. This will provide information concerning the slope segments over the entire time life curve.
- Study the effects of retained austenite while maintaining the acicular martensite condition.
- Consider carburizing to greater case depths. With the fully dense surface densified case, carburizing cycles must be similar to those used for wrought steel.
- Evaluate deeper depths of surface densification, up to 1.5 mm.
- Higher core densities may lessen the “full density case depth” requirement somewhat. Therefore core densities higher than 7.35 g/cm³ will be evaluated with various surface densified case depths, 0.38 mm and greater.

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