PERFORMANCE IMPROVEMENTS IN SURFACE-DENSIFIED FLN2-4405 GEARS MADE WITH EXTRA-FINE NI POWDER

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ABSTRACT

Automotive gears require high bending strength combined with rolling contact fatigue (RCF) endurance. While P/M gear surfaces can be densified by roll compaction techniques, high core density is also needed in order to provide sufficient bending strength and to reduce the rolling pressure needed to densify the surface to a depth greater than the maximum subsurface stress. Low alloy steel powders contemplated for complex geometry gear applications therefore need to be highly compressible and readily processed in order to achieve core densities approaching 7.5 g/cm^3.

The RCF behaviour of high temperature sintered FLN2-4405 (2% Ni admixed, 0.85% Mo prealloyed Fe powder, 0.5% C) steels has been previously studied. At high contact pressure, failure was thought to initiate in Ni-rich phases. In this study, an equivalent testing program was carried out with the substitution of extra-fine Ni (XF-Ni) powder in the FLN2-4405 steel. Extra-fine Ni powder has been previously shown to increase hardenability and uniformity of the microstructure in P/M steels. RCF samples were high temperature sintered to nominal 7.4 g/cm^3 density, roll compacted and case carburised. RCF performance was superior to baseline case carburised 5120 wrought steel at low contact pressure. Slope of the S-N curve, an indication of tolerance of the material to overloads, was similar to the baseline wrought steel and a significant improvement over previously tested P/M materials. Performance at high contact pressure had approximately twice the number of cycles to failure as FLN2-4405 made with standard Ni powder, however this result is still inferior to wrought steel. Data at high contact pressure had higher than normal scatter, which the authors believe can be reduced through improved processing procedures.

INTRODUCTION

The automotive transmission gear market is without doubt the most attractive emerging P/M market in terms of growth potential. Estimates of this potential in North America alone could increase the average P/M content by several kg per vehicle. P/M parts manufacturers have been working intensively in this area for several years and with recent advances in high density processing are now able to offer P/M gears that can compete with machined wrought steel gears. The key to being able to compete in this market is not only to meet the formidable performance challenges, but also to do this with cost competitive materials and processing.

Powder metallurgy steel gears need to meet the following criteria:

- High core density to provide sufficient bending strength
- Able to be surface hardened, which typically means carburised in automotive gears
- Hold dimensional tolerances
- Good rolling contact fatigue resistance

In Lipp and Hoffmann's overview of the design requirements for P/M automotive gears, the importance of surface treatments to increase density and surface hardness was clearly established [1]. Automotive gears and camshaft lobes are highly loaded under rolling contact conditions. Gear teeth meet in line contact, with the maximum contact pressure being subsurface. Failure of a material subject to contact pressure is typically initiated in the region of maximum subsurface stress, which can be determined using the von Mises yield criterion for a given material. At very high contact pressure, surface stress may exceed the maximum subsurface stress and cracks can initiate at the surface and grow into the material. Surface densification to near full density followed by surface hardening by treatments such as carburising are therefore critical to the fatigue performance of P/M gear materials.

Prealloyed grade Fe powders containing high Ni, Mn and Cr content have little chance of meeting the high core density requirements for complex geometry parts using reasonable compaction pressures. In the end, the parts manufacturer has to be able to make the part and eject it from the die without overly stressing the press or the green part. Cr steels have the additional disadvantage of being susceptible to oxidation at the typical temperatures and oxygen partial pressures in carburising cycles. This is particularly of concern for P/M materials that may contain open porosity at the gear surface. Large pores left behind in sintered Cu steels are also not desirable for fatigue performance. The choice of materials therefore has focussed on compressible Fe powders containing little alloy content or prealloyed Fe-Mo powders exhibiting good compressibility, with admixed alloying additions of principally Ni, but also fine ferroalloy powders. Ni-Mo steels have the advantage of being easily processed and forgiving in their response to sintering and any subsequent heat treatment. However admixed Ni powder results in an inhomogeneous microstructure after sintering containing Ni-rich phases due to the slow diffusion rate of Ni at conventional sintering temperatures and short time at temperature.

While the role of soft, Ni-rich phases in axial and bending fatigue of P/M steels has traditionally been regarded as beneficial, more recently this belief has been called into question. However in rolling contact fatigue (RCF) testing of P/M steels, there appears to be a consensus that Ni-rich phases have little benefit or indeed are detrimental to RCF life [2-4]. The low compressive yield stress of soft, Ni-rich austenite creates regions subject to plastic deformation under high Hertzian contact stress [3]. As Ni-rich regions tend to be associated with residual porosity in P/M Ni steels as a result of localization of Ni at original Fe particle surfaces, stress concentration in the vicinity of pores leads to the initiation of cracks as shown by Jandeska et al [4].

The RCF work by Slattery and more recently by Jandeska on carburised FLN2-4405 (0.85% prealloyed Mo-Fe powder; 2% Ni, 0.5% C both admixed) with standard Ni (STD-Ni) powder (Inco® T123 PM) was the catalyst for initiating the collaborative effort by the authors that lead to this work [4,5]. An extra-fine (XF-Ni) grade of Ni powder has been developed recently for the P/M market [6-8]. The shorter diffusion time of Ni and more uniform microstructure obtained with XF-Ni powder could be potentially beneficial for RCF applications of P/M Ni steels.

MATERIALS AND PROCESSING

Samples for mechanical property data were made by two different processes: conventional admixed and AnchorMax D (Hoeganaes Corp.). Admixed samples were blended in a laboratory scale mixer (Turbula T2F) with 0.6% lubricant (Lonza Acrawax C), pressed at 450 to 680 MPa (30 to 50 tsi), delubricated at 500 – 600 °C for 10 minutes and then sintered in a laboratory tube furnace for 30 minutes at 1120 °C in a 95/5 N_2/H_2 atmosphere.

Other mechanical property samples and all samples for RCF testing were processed using the AncorMax D lube system, utilizing 0.55% total lube and 0.85% prealloyed Mo Fe powder (Ancorsteel 85HP) to which 2% XF-Ni (Inco ® T110 D) powder was admixed. Sample blanks in the form of 45 mm diameter by 19 mm height discs were compacted using a Dorst 80 ton mechanical press at a stroke rate of 8 parts/min. Compaction pressure ranged from 53 to 60 tsi and were identified as separate lots. Average green density was 7.25 g/cm^3.

Samples were sintered at either 1120 or 1260 °C (2050 or 2300 °F) in a ceramic belt furnace (Abbott / Hoeganaes Corp.) using a 90/10 N_2/H_2 atmosphere at a belt speed of 3 to 5 cm/min. (1.2 - 2.0 in./min. Sintering time was approximately 30 minutes at temperature. Average sinter densities were 7.40 or 7.45 g/cm^3 for the samples sintered at 1120 and 1250 °C respectively. Slugs were then machined to (1.188 in.) OD and then roll-densified to (1.180 in.) (Capstan Atlantic). The additional stock left on the outer diameter provided a surface-densified layer thickness on the order of 0.38 mm, similar to the previous study by Jandeska et al [3].

RCF samples in this study were carburised for 3 h at 1700 °F (CI Hayes) using a single 90 minute boost followed by 90 minute diffuse carburising cycle to achieve a nominal 1.0% surface carbon content. Carburised samples were then machined to give the 5 mm flat and the correct concentricity of ID to OD for the RCF tests.

Tests were carried out with a ZF-RCF test rig, described elsewhere [9]. Of the various methods for measuring rolling contact fatigue endurance, the ZF test rig is considered to best approximate the line contact and fully elasto-hydrodynamic conditions of actual gears [1]. The test conditions were as follows:

- Speed = 3000 rpm = 540,000 load cycles per hour
- Constant load levels at 1900, 2000 and 2500 MPa
- Sliding = -24% between test sample and load wheels
- Lubricant: Dextron III automatic gear box oil (General Motors)
- Temperature of oil = 80 ± 2 °C

Load levels were chosen based on previous experience with P/M samples to give approximately 1 x 10^6 and 10 x 10^6 cycles to failure. These loads also correspond to approximately 130 to 170% of the maximum design compressive stress for planetary gear sets based on a torque of 1500 N-m at the ring gear [10]. As a run-out (defined as 5 x 10^7 cycles without failure) was measured at 1900 MPa, the lower load level was increased to 2000 MPa (see Results section). Six samples were tested at each Hertzian stress level. Failure during the test was detected using an accelerometer, which terminated the test once vibrations from surface pitting occurred. Evaluation of the statistical data was based on the assumption of a log-normal distribution of the individual test data. Probability of survival of the individual test specimen was calculated by:

$$P_S = \frac{3m-1}{3n+1} * 100\%$$

where m = sample number in order of increasing cycles to failure
n = total number of samples at given load

Probability of survival T_N = 50%, T_N=10% and T_N=90% can be determined from a log-normal plot of the data, for which the scatter of the data can be calculated by $T_N = 1{:}T_{10}/T_{90}$.

Tested samples representing the load levels at 2000 and 2500 MPa were examined metallographically to document the failure and analyse the microstructure of the carburised case and core including sites of crack initiation and propagation.

RESULTS AND DISCUSSION

Mechanical property data for FLN2-4405 containing STD-Ni and XF-Ni were generated by two different laboratories. The first set of data represent the materials processed by conventional admixed processing. Sintering was performed in a laboratory tube furnace at a constant sintering temperature of 1120 °C for 30 min (Table 1). Data are reported in the as-sintered condition. The second set of data were obtained from materials using the AncorMax D process. Sintering was done in a ceramic belt furnace at both 1120 and 1260 °C with 30 minute residence time. Data are reported in the tempered condition (Table 2).

Table 1. Mechanical properties of FLN2-4405 steels made by conventional admixing (0.6% Acrawax, T_s = 1120 °C, t_s = 30 min)

FLN2-4405	**Comp. Pressure MPa (tsi)**	**Density (g/cm^3)**		**UTS MPa (10^{3}psi)**	**TRS MPa (10^{3}psi)**	**Apparent Hardness**		**Elongation (%)**
		Green	**Sinter**			**HRB (HRA)**	**HRC (HRA)**	
STD-Ni	410	6.99	7.02	520 (76)	810 (120)	81 (50)		1.7
	550	7.05	7.16	610 (89)	1050 (150)	89 (55)		2.5
	680	7.19	7.28	640 (93)	1200 (170)	90 (56)		1.8
XF-Ni	410	6.99	7.16	640 (93)	930 (135)		20 (61)	1.8
	550	7.10	7.22	670 (97)	1200 (170)		22 (62)	2.7
	680	7.23	7.36	850 (120)	1450 (210)		22 (62)	2.9

XF-Ni resulted in increased green and sinter density compared to STD-Ni FLN2-4405. Sinter density approaching 7.5 g/cm^3 was achieved when compacted at 830 tsi and sintered at 1260 °C. Elongation was also generally improved with XF-Ni, with elongations up to 4 % achieved when sintered at 1260 °C. Apparent hardness values in Table 1 are converted to HRA in parentheses for comparison to data in Table 2. There is very good agreement in apparent hardness at similar compaction pressure.

Table 2. Properties of FLN2-4405 AncorMax D process (T_s = 1120 and 1260 °C, t_s = 30 min) (tempered)

FLN2-4405	**Compaction Pressure (MPa)**	**Density (g/cm^3)**		**UTS MPa (10^{3}psi)**	**TRS MPa (10^{3}psi)**	**Apparent Hardness (HRA)**	**Elongation (%)**
		Green	**Sinter**				
STD-Ni 1120 C	550	7.08	7.14	660 (96)	1305 (189)	53	2.3
	690	7.27	7.31	730 (106)	1540 (224)	56	3.1
	830	7.36	7.40	750 (109)	1650(239)	57	3.1
XF-Ni 1120 C	550	7.20	7.23	680 (99)	1405 (204)	59	1.7
	690	7.33	7.31	705 (102)	1550 (225)	61	1.5
	830	7.37	7.40	740 (107)	1630 (237)	61	1.5
STD Ni 1260 C	550	7.08	7.13	680 (99)	1420 (206)	53	2.1
	690	7.27	7.23	745 (108)	1500 (218)	54	2.3
	830	7.36	7.30	765 (111)	1630 (237)	57	2.7
XF-Ni 1260 C	550	7.20	7.28	690 (100)	1460 (212)	56	3.0
	690	7.33	7.37	750 (109)	1580 (229)	57	4.1
	830	7.37	7.46	780 (113)	1620 (235)	59	4.0

When comparing the results, the difference in processing must be taken into account. As shown in Tables 1 and 2, there was greater difference in mechanical properties between admixed STD-Ni and XF-Ni FLN2-4405 than in the equivalent materials processed by AncorMax D. This observation is consistent with other bonded materials that have been tested to date, which have exhibited smaller differences in mechanical properties between alloys with similar composition containing STD-Ni and XF-Ni [11]. UTS of admixed XF-Ni in Table 1 at the maximum compaction pressure of 680 MPa (50 tsi) appears high relative to the data in Table 2. On the other hand, the strength data in Table 2 at maximum compaction pressure of 830 MPa (60 tsi) appears low, as the STD-Ni alloys have slightly higher strength sintered at both temperatures, which is not consistent with other test data.

Typical sintered microstructures of FLN2-4405 XF-Ni steels sintered at 1120 and 1260 °C are shown in Figures 1 and 2. Porosity of steels was noticeably lower when sintered at 1260 °C. Microstructures exhibited more rounded pore geometry and more isolated distribution. The microstructure of FLN2-4405 XF-Ni steels consisted of a mixture of bainite, martensite and a small amount of pearlite. Ni-rich martensite was present in steels sintered at 1120 °C, while no visible Ni-rich phases were detected in steels sintered at 1260 °C. The structure of FLN2-4405 XF-Ni steels sintered at 1260 °C was mainly martensite with much less bainite than the steel sintered at 1120 °C. In comparison, the microstructure of FLN2-4405 STD-Ni steel sintered at 1120 °C consists of similar phases with the addition of Ni-rich austenite (NRA). Martensite content is much lower and concentrated around the periphery of NRA. Although fewer NRA regions are found in the microstructure after high temperature sintering Ni steels, NRA persists in the microstructure even after sintering at 1260 °C for 30 minutes, which is consistent with observations by other researchers [4].

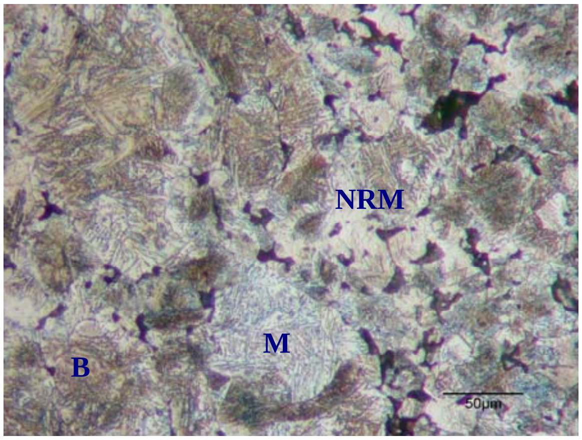


Figure 1. FLN2-4405 XF-Ni Ts = 1120 °C
NRM = Ni-rich martensite; B = Bainite,
M = martensite

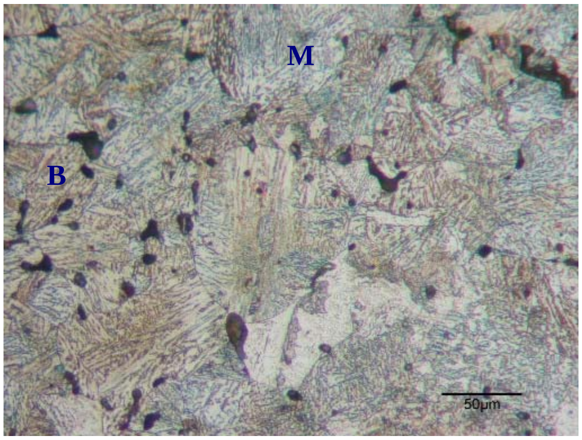


Figure 2 FLN2-4405 XF-Ni Ts = 1260 °C

Ni distribution in FLN2-4405 containing both XF-Ni and STD-Ni was mapped using Energy Dispersive Spectrometry (EDS) in the Scanning Electron Microscope (SEM). The improved uniformity of Ni distribution obtained with XF-Ni is clearly shown in Figures 3 and 4. No Ni-rich regions were present in the FLN2-4405 XF-Ni steel. Analysis of the bulk composition by EDS confirmed uniform distribution of Ni throughout the microstructure.

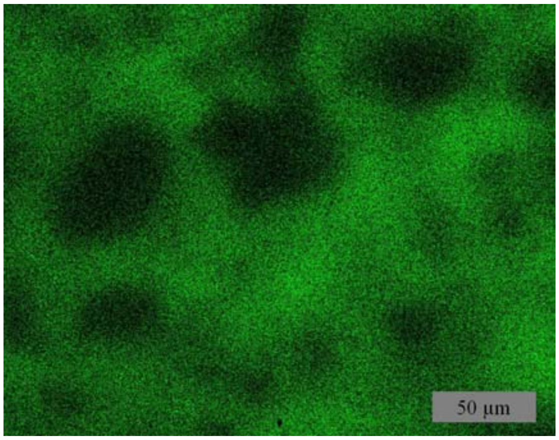


Figure 3 EDS Ni map FLN2-4405 (XF-Ni)

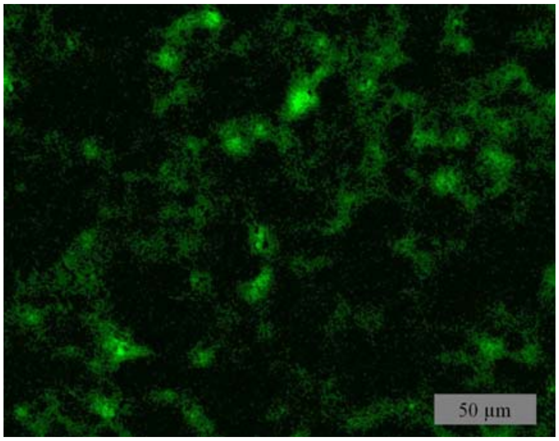


Figure 4 EDS Ni map FLN2-4405 (STD-Ni)

Based on recommendations in the Jandeska paper, only the high temperature sintered steel was RCF tested at this time. Microindentation hardness profiles were measured from the surface to a depth of 1.8 mm (Fig. 5). Average core hardness of all materials was between HV 500 and HV 600, sufficient to prevent core crushing. The XF-Ni steel had the highest surface hardness of all analyzed materials. The sample with the lowest number of load cycles at the highest contact stress (2500 MPa) also had a drop of HV 60 at the surface compared to other materials.

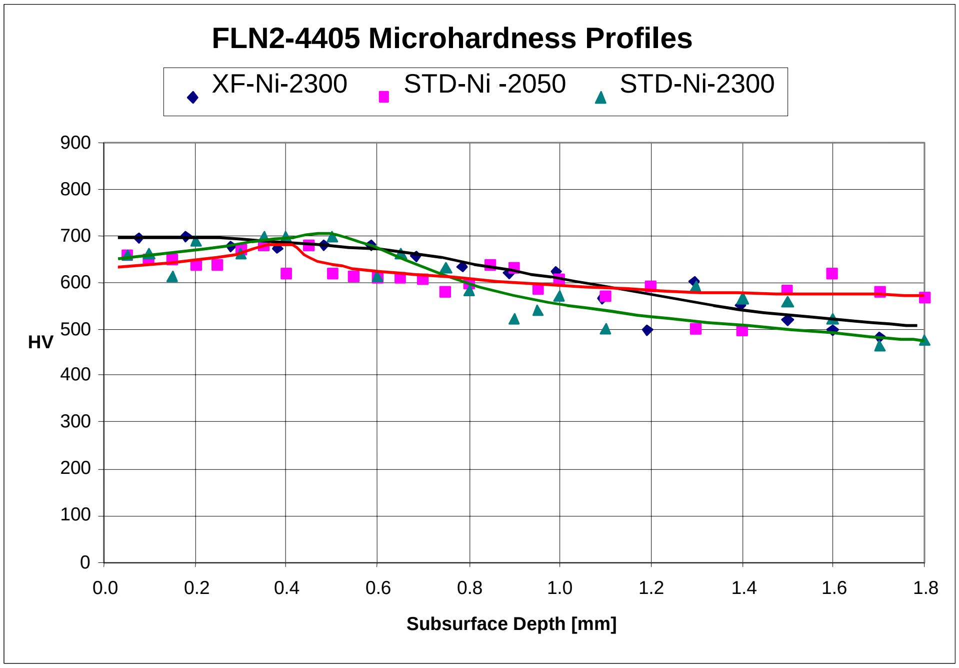


Figure 5 Microhardness profiles of case-carburised FLN2-4405 steels sintered at 1250 °C (“2300”) and 1120 °C (“2050”)

The RCF test results are summarized in Table 3 and compared to benchmark 5120 case-carburised wrought steel and previous test data for FLN2-4405 steels. The results include the 10, 50 and 90% probability of survival, the scatter in the data as measured by $T_N = 1{:}T_{10}/T_{90}$ and the slope of the S-N curve k. Low values of k are preferred as this is a measure of sensitivity of the material to overloads. Note that the slope (k = 4.2) of the FLN2-4405 XF-Ni steel is lower than the other P/M steels and that the number of cycles to failure at 2500 MPa load is much higher that the STD-Ni steel sintered at the same temperature.

The results for FLN2-4405 XF-Ni are plotted as an S-N curve in Figure 6. The heavy black line represents 50% probability of survival, which is used to estimate the fatigue endurance limit. The lighter black lines show the 10% and 90% probability of survival and give an indication of the scatter in the data. Note that at the original low load level of 1900 MPa, there was a run-out at 5 x 10^7 cycles, whereas previous materials including the 5120 baseline wrought steel failed at much lower number of cycles. These results need to be confirmed by developing a full S-N curve using the staircase method in order to more accurately determine where the knee of the S-N curve occurs. The low load level was increased for subsequent tests to 2000 MPa. At high load level of 2500 MPa, the scatter in the data was relatively high. The high scatter in the RCF data at high contact stress could be related to the difference in surface hardness between samples with high and low cycles to failure as mentioned earlier, which in turn could be processing related, for example inconsistent case carbon content or case depth.

Table 3. Comparison of RCF test results for case-carburised steels: FLN2-4405 XF-Ni sintered at 1260 °C, Bench Mark 5120 wrought steel and FLN2-4405 STD-Ni steels sintered at 1260 and 1120 °C

Material / Ts (°C)	Contact Pressure (MPa)	T_N=50%	T_N=10%	T_N=90%	T_N=1:T_{10}/T_{90}	k
FLN2-4405 XF-Ni / 1260	2000	$1.0*10^7$	$1.9*10^7$	$5.1*10^6$	1 : 3.7	4.2
	2500	$3.9*10^6$	$9*10^6$	$1.6*10^6$	1 : 5.6	
5120 Bench Mark	1900	$1.6 *10^7$	$2.0 *10^7$	$1.1 *10^7$	1 : 1.8	3.5
	2500	$6.1 *10^6$	$8.0 *10^6$	$4.8 *10^6$	1 : 1.7	
FLN2-4405 STD-Ni / 1120	1900	$1.7*10^7$	$5.5*10^7$	$5.5*10^6$	1 : 10	6.9
	2500	$2.6*10^6$	$5.8*10^6$	$1.2*10^6$	1 : 4.8	
FLN2-4405 STD-Ni / 1260	1900	$1.0*10^7$	$1.5*10^7$	$7.8*10^6$	1 : 2.0	4.6
	2500	$2.8*10^6$	$5.0*10^6$	$1.6*10^6$	1 : 3.2	

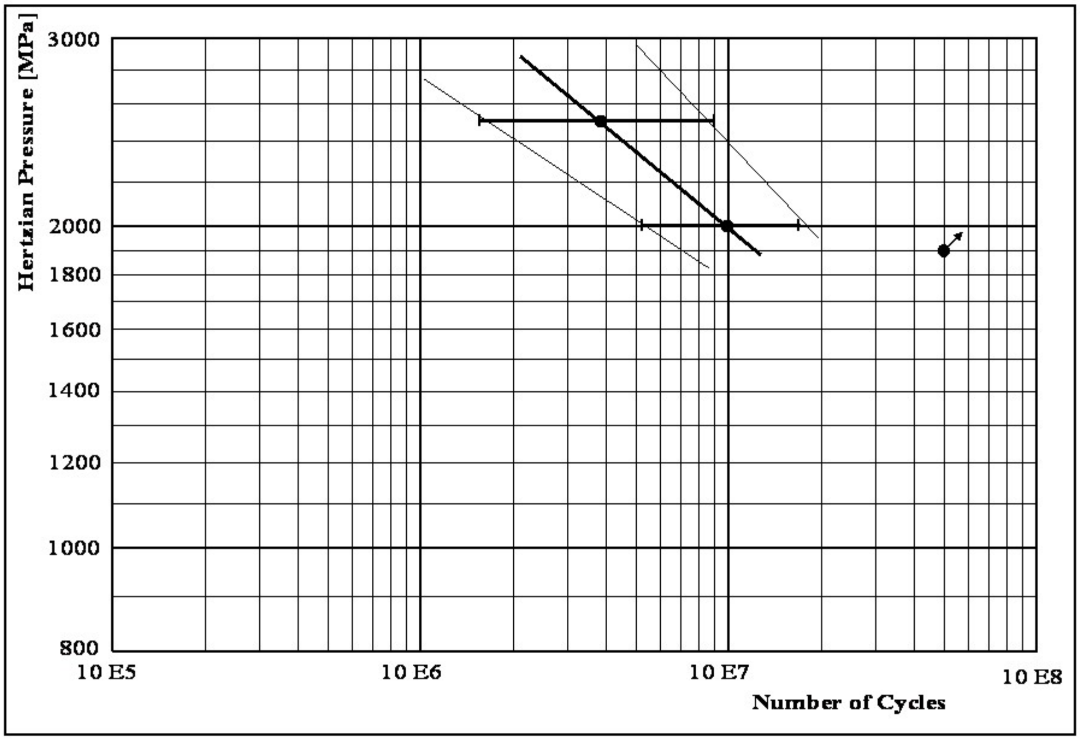


Figure 6. S-N curve from RCF testing of FLN2-4405 XF-Ni sintered at 1260 °C

The RCF results of Fig. 6 are compared to other tested materials below in Fig. 7. FLN2-4405 XF-Ni performed better than the baseline 5120 wrought steel at low load and had approximately twice as many cycles to failure at high load than the next best P/M material.

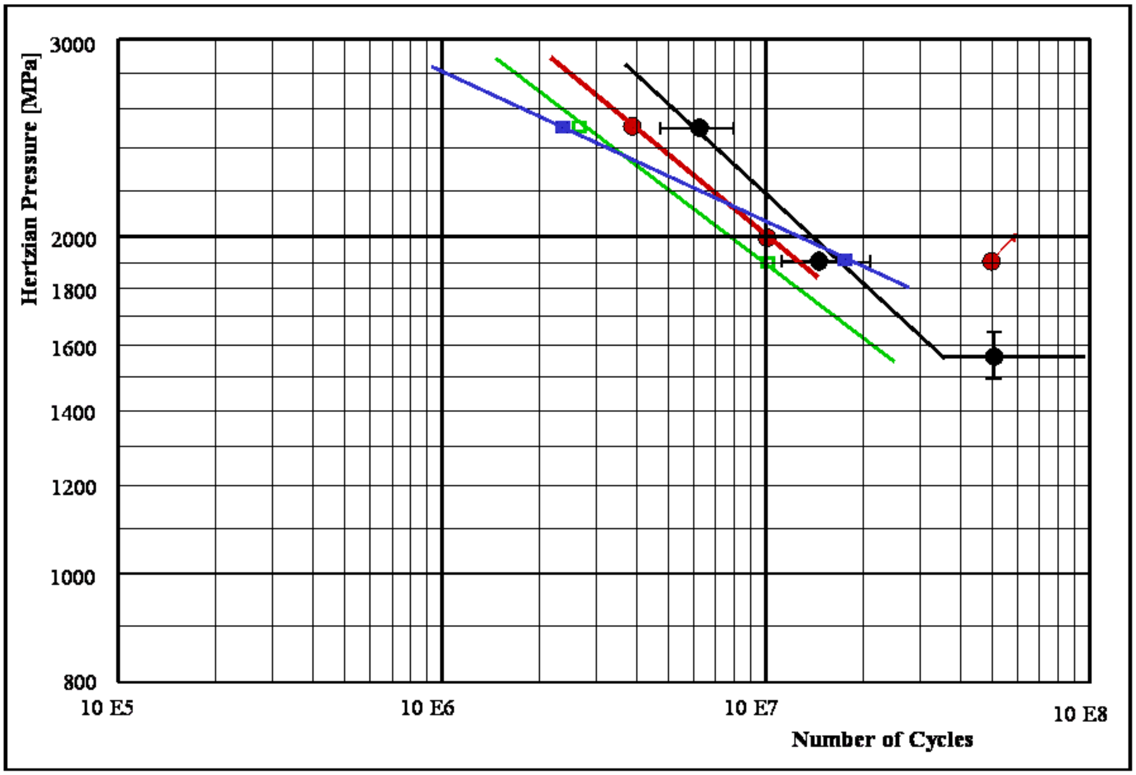


Figure 7. S-N curves of case-carburised FLN2-4405 steels compared to baseline 5120 wrought steel (red circle = XF-Ni 1260 °C; black circle = baseline 5120 wrought steel; green open square = STD-Ni 1260 °C, blue closed square = STD-Ni 1120 °C)

To help clarify possible reasons for the scatter in RCF data at high contact pressure, metallography was performed on a variety of samples to examine the relationship between microstructure and crack initiation and propagation. Previous FLN2-4405 samples in the Jandeska study were carburised for 90 minutes, using a 45 minute boost phase and 45 minute diffuse phase. One of the recommendations in this study was that longer carburising cycles would be beneficial. Therefore in the present work a 90 minute single boost phase and 90 minute diffuse phase cycle was employed. A typical case structure of an untested carburised FLN2-4405 XF-Ni RCF sample is shown in Fig. 8. The optical micrograph reveals a case structure consisting of acicular martensite and small areas of retained austenite (white phase). However examination of several tested samples revealed inconsistent case depth and likely variation in carbon content at the surface. In all samples, the case appeared to be much shallower than the 1.0 mm target depth, as evidenced by the microindentation hardness profiles in Figure 5. A multiple boost cycle used commercially for 5120 wrought steel would likely result in a more homogeneous case with potentially greater compressive stresses, favourable for RCF performance.

In Figure 9, the core microstructure consisted of a mixture of lathe and acicular martensite. Very little porosity was evident. No Ni-rich phases could be found in the microstructure, including regions around the small, isolated pores. In fact, there was poor delineation in the amount of porosity at the surface compared to the core. While a clearly densified surface layer was not obvious in the microstructure, this could be largely the result of little porosity in the material to start with. However with the higher martensite content of the as-sintered FLN2-4405 XF-Ni steel seen in Fig. 2, we suspect that surface densification may have induced some subsurface cracking prior to RCF testing. Although we could find no evidence for cracks in the un-tested samples examined, tempering of the samples prior to roll compaction is recommended to avoid this potential problem.

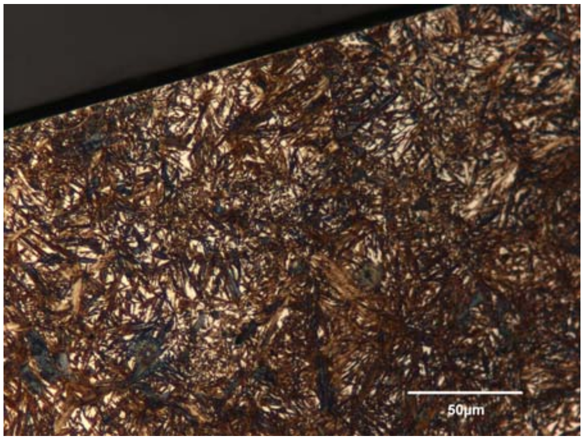


Figure 8. Untested RCF FLN2-4405 XF-Ni steel Ts = 1260 °C showing acicular martensite and retained austenite in carburised case

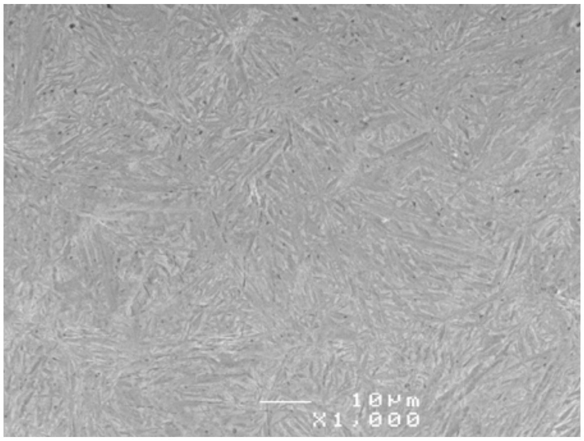
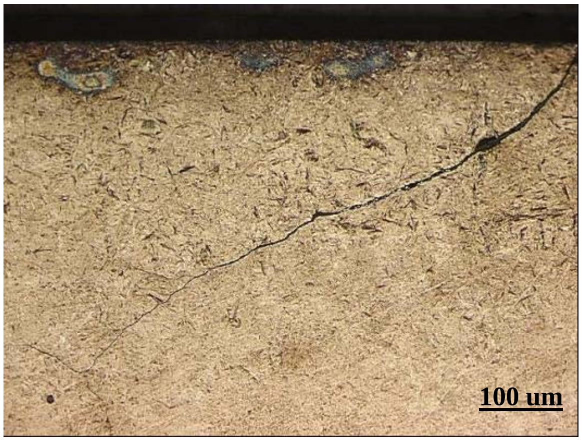


Figure 9 SEM microstructure of core region in FLN2-4405 XF-Ni steel Ts = 1260 °C consisting of 100% martensite with small, isolated porosity.

Samples failed with the formation of large surface pits that result from the propagation of a network of subsurface cracks. The failure mode of samples at 2000 MPa was subsurface cracking in the region of maximum stress approximately 0.2 mm below the surface. At 2500 MPa, there appeared to be a mixture of subsurface cracks and cracks initiated at the surface. The surface cracks propagated into the steel at a characteristic 30° angle (Fig. 10). The pit depth was deeper than at 2000 MPa load and ranged from 0.31 to 0.77 mm. There appears to be a correlation in the number of cycles to failure and the depth of surface pits. Samples that failed at low number of cycles at 2500 MPa load had relatively shallow pits with subsurface cracks closer to the surface, typically inclined at an angle greater than 30° to the surface, indicating subsurface failure. The sample exhibiting the maximum number of cycles to failure at 2500 MPa had the deepest pits and surface initiated cracks inclined at 30° to the surface.

In Figure 11, the crack path does not seem to favour any specific metallurgical phases. Bulk composition was uniform throughout the core and no Ni-rich phases were detected by EDS / SEM in samples sintered at 1260 °C. This observation compares with the previous work on FLN2-4405 STD-Ni steels, which showed that Ni-rich austenitic regions persist in the microstructure after sintering at 1260 °C. Due to the low yield stress of the austenitic regions, regions of high plasticity surrounding the Ni-rich regions induced subsurface cracks. In the FLN2-4405 XF-Ni steel tested in this study, there was no evidence of Ni-rich regions and crack initiation in the microstructure. Failure of the FLN2-4405 XF-Ni steels at high contact pressure is related to the surface structure and at the time of writing this paper is thought to be the result of inadequate and / or inconsistent case depth.



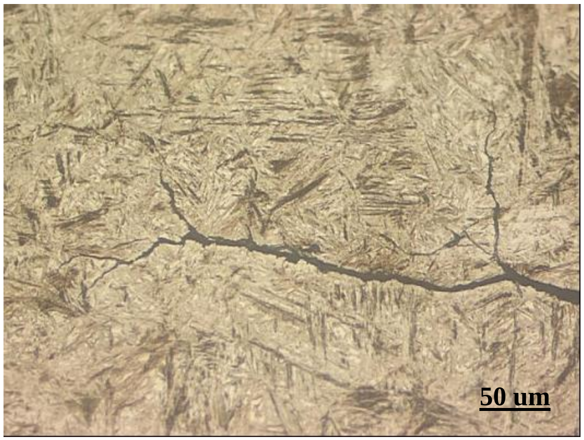


Figure 10 Crack initiation at surface of FLN2-4405 XF-Ni steel sintered at 1260 C Load = 2500 MPa; high # cycles to failure

Figure 11 Same sample as Fig. 9 showing random orientation of the crack path. No Ni-rich phases are present in the microstructure.

CONCLUSIONS

The results from this first attempt to measure RCF performance of P/M steels made with XF-Ni powder appear to be very promising. The RCF test results described by S-N curves indicate that the fatigue behaviour of FLN2-4405 steels containing admixed XF-Ni powder was significantly better than other previously tested P/M steels. The material has good potential to achieve the performance criteria required for P/M steel gears. Although at the time of writing this paper, not all of the observations in RCF behaviour of this material are understood, the following statements can be made:

1. High core densities approaching 7.5 g/cm^3 can be readily achieved with FLN2-4405 materials containing XF-Ni powder.
2. There was no evidence of Ni-rich phases in the microstructure of steels sintered at 1260 °C
3. FLN2-4405 XF-Ni sintered at 1260 °C (2300 °F) outperformed all other tested materials including the baseline wrought steel at 1900 MPa load.
4. At 2500 MPa, there was high scatter in the data, which may be related to inconsistent surface microindentation hardness.
5. The slope k of the S-N curve is improved compared to other tested P/M materials and indicates a reduced sensitivity to overloads. The slope is roughly parallel to the wrought baseline 5120 steel.
6. Failure mode was subsurface at 2000 MPa load. At 2500 MPa there was no clear mechanism as both surface initiated and subsurface cracks were found.
7. There was no clear demarcation in porosity between the surface-densified layer and the core. As a result of the higher martensite content in as-sintered microstructures of FLN2-4405 XF-Ni steels, tempering is recommended prior to roll compaction to improve the amenability of the surface to densification and prevent processing-induced subsurface cracks.

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REFERENCES

1. K. Lipp, G. Hoffmann, "Design for Rolling Contact Fatigue", *Int. J. Powder Met*., 2003 Vol. 39, No. 1, pp. 33-46
2. H. Sanderow, "Final Report, Rolling Contact Fatigue (RCF) Test Program", Prepared by the Center for Powder Metallurgy Technology (CPMT), September, 2001
3. G. Hoffmann, C. Landgraf, J. Mandel, "Effect of Pores and Porosity on Rolling Contact Fatigue of Sinter Hardened P/M Steel", *Advances in Powder Metallurgy and Particulate Materials – 2003*, Part 7, pp. 2 –299 – 7-313, Metal Powder Industries Federation, Princeton, NJ 2003
4. W. Jandeska, G. Hoffmann, R. Slattery, F. Hanejko, A. Rawling, T. Murphy, "Rolling Contact Fatigue of Surface Densified Material: Microstructural Aspects", *Advances in Powder Metallurgy and Particulate Materials – 2004,* Part 10, pp. 10-35 – 10-52, Metal Powder Industries Federation, Princeton, NJ 2004
5. R. Slattery, F. Hanejko, A. Rawlings, M. Marucci, "Powder Metallurgy of High Density Helical Gears", *Advances in Powder Metallurgy and Particulate Materials – 2003*, Vol. 9, pp. 9-56 - 9-72, Metal Powder Industries Federation, Princeton, NJ 2003
6. S. Campbell, T. Singh, T.F. Stephenson, "Improved Hardenability of P/M Steels using Extra-fine Nickel Powder", *Advances in Powder Metallurgy and Particulate Materials – 2004*, Part 7, pp. 105-115, Metal Powder Industries Federation, Princeton, NJ 2004
7. T. Singh, T.F. Stephenson, S. Campbell, "Nickel-Copper Interactions in P/M Steels", *Advances in Powder Metallurgy and Particulate Materials – 2004*, Part 7, pp. 93-104, Metal Powder Industries Federation, Princeton, NJ 2004
8. Stephenson, T.F., Singh T., Campbell, S.T., "Performance Benefits in Sintered Steels with XF-Ni powder", Proceedings of the World PM2004 Congress, Vienna, Austria, October 2004, Vol. 3 Sintered Steels, EPMA (European Powder Metallurgical Association)
9. Hoffman, Gottfried; Lipp, Klaus; Michaelis, Klaus; Sonsino, Cetin M**.**; Rice, James A., "Testing P/M materials for high loading gear applications", *Int. J. Powder Met.*, (1999), 35(6), pp. 35-44
10. J. Chen, J. Flynn, G. Semrau, "Gear Surface Durability Development to Enhance Transmission Powder Density", *Gear Technology*, July / August 2002, pp 20-25
11. L. Azzi, T. Stephenson, S. St.-Laurent, S. Pelletier, "Effect of Nickel Type of Properties of Binder-treated Mixes", *Advances in Powder Metallurgy and Particulate Materials – 2005*, Metal Powder Industries Federation, Princeton, NJ 2005, to be published