

# HIGH PERFORMANCE APPLICATIONS OF CHROMIUM STEELS SINTERED AT CONVENTIONAL TEMPERATURES

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## **ABSTRACT**

To meet the rigorous demands of automotive gearing, sprocket and other power transmission applications, double-press / double-sinter (DP/DS) techniques are often used to achieve the desired level of static and fatigue performance. Ancorsteel 4300, a new Cr-bearing material, has shown improved strength levels compared to traditional P/M steels. By employing such an alloy, core property requirements can be met at densities around 7.0 g/cm<sup>3</sup>. Replacing the pre-sinter and secondary press operations with selective densification, which will ensure sufficient contact fatigue resistance, can provide an economic benefit. The current work demonstrates the viability of processing a sprocket for a power transmission application with this high performance alloy system sintered at 1120 °C (2050 °F) in a production furnace. Subsequent selective densification and surface carburization provides a wear resistant and durable case layer. The results are compared with those achieved using FLN2-4405 processed through the traditional route of DP/DS, heat-treat.

## **INTRODUCTION**

In order to meet the high static and fatigue resistance that is required for automotive gearing applications, parts producers have often employed double-press / double-sinter (DP/DS) techniques to achieve densities of 7.4 g/cm<sup>3</sup> or more. A more economic solution, however, would be to single-press / single-sinter (SP/SS) to a lower core density, and selectively densify the areas of critical importance. Indeed it has been shown that rolling contact fatigue properties of P/M materials can mimic those of wrought steels when near full density is achieved at the surface [1].

The strengths of typical P/M materials at densities around 7.0 g/cm<sup>3</sup> have limited the use of processing components by SP/SS and selective densification techniques. A new commercially available chromium steel, Ancorsteel<sup>®</sup> 4300, was specifically engineered to simulate wrought steel compositions and achieve high performance levels at sintering temperatures as low as 1120 °C (2050 °F). This binder-treated system has a nominal composition of 1.0 Cr, 1.0 Ni, 0.8 Mo, and 0.6 wt.% Si, and can provide sintered oxygen contents below 500 ppm [2]. It realizes a synergistic effect of both chromium and silicon in one

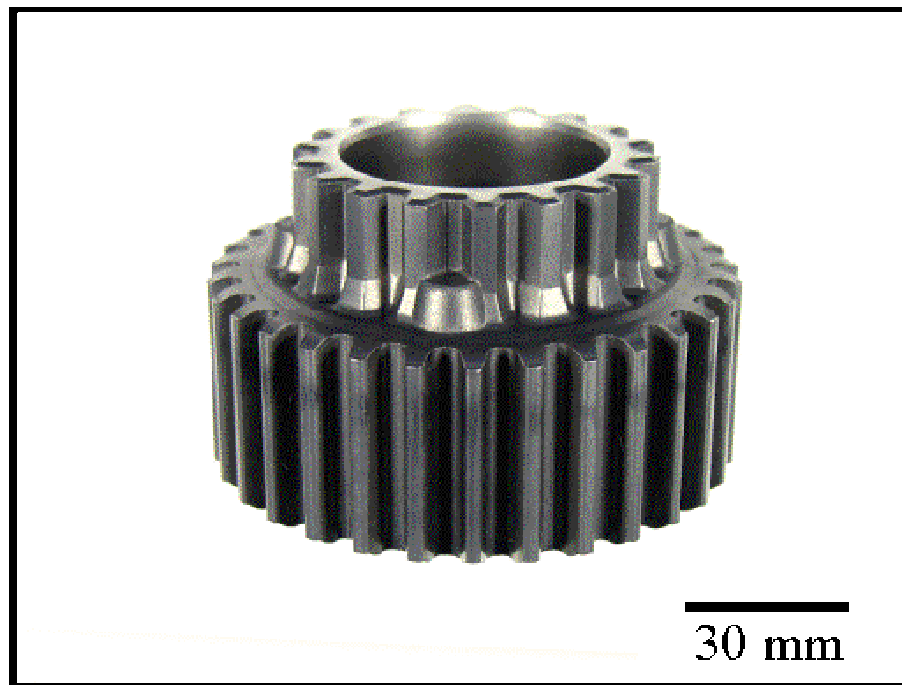
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<sup>®</sup>Ancorsteel is a registered trademark of Hoeganaes Corporation.

alloy system while minimizing the oxygen-related issues that are often associated with these two elements. Yield strengths that are 40 and 60% greater than hybrid alloy FLN4-4405 and diffusion alloyed FD-0405, respectively, could enable applications that were previously unattainable with traditional P/M materials [3].

A sprocket for an automotive power train application (Figure 1) is currently processed with a hybrid alloy FLN2-4405 (0.2 wt.% graphite), DP/DS to  $7.4 \text{ g/cm}^3$ , sintered at  $1120 \text{ }^\circ\text{C}$  ( $2050 \text{ }^\circ\text{F}$ ) and gas carburized for surface durability. The high performance capabilities of the new chromium steel at a density of  $7.0 \text{ g/cm}^3$  make it potentially applicable to this component via two alternative processing routes. A graphite addition of 0.3 wt.% to 4300 provides an apparent hardness of approximately 90 HRB after sintering at  $1120 \text{ }^\circ\text{C}$  ( $2050 \text{ }^\circ\text{F}$ ) with a conventional cooling rate [3]. This hardness level would allow for selective densification by rolling, while the reduced carbon level would be advantageous for vacuum carburization, two steps that would improve the wear resistance and durability of the surface. Alternatively, a higher graphite addition (0.6 wt.%) to Ancorsteel 4300 (without selective densification) would provide excellent hardenability, and result in high strength, high hardness, and a predominantly martensitic microstructure. Table I shows a comparison of the current processing route and the two proposed processing routes.

This manuscript investigates the viability of processing the sprocket with Ancorsteel 4300 at  $1120 \text{ }^\circ\text{C}$  ( $2050 \text{ }^\circ\text{F}$ ). Mechanical properties were developed to compare the expected core performance using current processing and the two proposed processing routes. Prototype components were then produced using 4300 + 0.3 wt.% graphite. After sintering in a production furnace, these samples were selectively densified in the active profile area of the flange sprocket. Metallography of the densified teeth of the sprocket is examined in this paper, and implications regarding the effect of a selectively densified and carburized surface on contact fatigue performance are discussed. Dynamometer results are also presented comparing the chromium steel to the current material FLN2-4405.



**Figure 1.** The component of interest in this study, used in a power transmission application.

**Table I.** Comparison of the current processing route and the proposed processing route.

**Current Process**

1. Ancorsteel 85HP + 2%Ni + 0.2% graphite (FLN2-4405)
2. Press component to 7.0 g/cm<sup>3</sup>
3. Pre-sinter
4. Repress to 7.4 g/cm<sup>3</sup>
5. Sinter at 1120 °C (2050 °F), conventional cooling
6. Surface carburization / heat-treat
7. Temper at 175 °C (350 °F)

**Proposed Process #1**

1. Ancorsteel 4300 + 0.3% graphite (4300+0.3gr)
2. Press component to 7.0 g/cm<sup>3</sup>
3. Sinter at 1120 °C (2050 °F)
4. Selective densification
5. Surface carburization / heat-treat
6. Temper at 175 °C (350 °F)

**Proposed Process #2**

1. Ancorsteel 4300 + 0.6% graphite (4300+0.6gr)
2. Press component to 7.0 g/cm<sup>3</sup>
3. Sinter-harden at 1120 °C (2050 °F)
4. Temper at 175 °C (350 °F)

**EXPERIMENTAL PROCEDURE**

Pilot scale mixes of FLN2-4405, Ancorsteel 4300 + 0.3 wt.% graphite (4300+0.3gr), and Ancorsteel 4300 + 0.6 wt.% graphite (4300+0.6gr) were prepared for evaluation with 0.75 wt.% ethylene bisstearamide (EBS) in each mix. The alloy compositions are summarized in Table II. Tensile and impact specimens were compacted to green densities of 7.0 and 7.2 g/cm<sup>3</sup> for all materials. Samples of FLN2-4405 were also pressed to a density of 7.4 g/cm<sup>3</sup> to demonstrate the performance levels that are obtained under the current DP/DS processing route. All samples were sintered at 1120 °C (2050 °F) for 35 minutes at temperature in an atmosphere of 90N<sub>2</sub>-10H<sub>2</sub> (vol.%). The 4300+0.6gr samples were subjected to accelerated cooling. After sintering, the FLN2-4405 and 4300+0.3gr samples were heat-treated to mimic the core microstructure that would be obtained from a carburizing cycle. These samples were austenitized for 30 minutes in 25N<sub>2</sub>-75H<sub>2</sub> (vol.%) at 870 °C (1600 °F), then quenched in oil that was held at 65 °C (150 °F). All samples were tempered at 175 °C (350 °F) for 1 hour.

Tensile testing was performed with standard dog-bone specimens using a crosshead speed of 0.065 cm/min (0.025 in/min). The machine is equipped with a 25 mm (1 in) extensometer, which was left on until failure. Impact testing was conducted at room temperature on unnotched Charpy samples.

Prototype components for the automotive sprocket were compacted to a 7.0 g/cm<sup>3</sup> density with 4300+0.3gr. After sintering under the conditions described above, components were subjected to selective densification in the active profile area of the flange sprocket and heat-treated. These components were also tempered at 175 °C (350 °F) for 1 hour. Surface carbon was measured to be 0.80 wt.%.

**Table II.** Comparison of the three alloy compositions evaluated in this study.

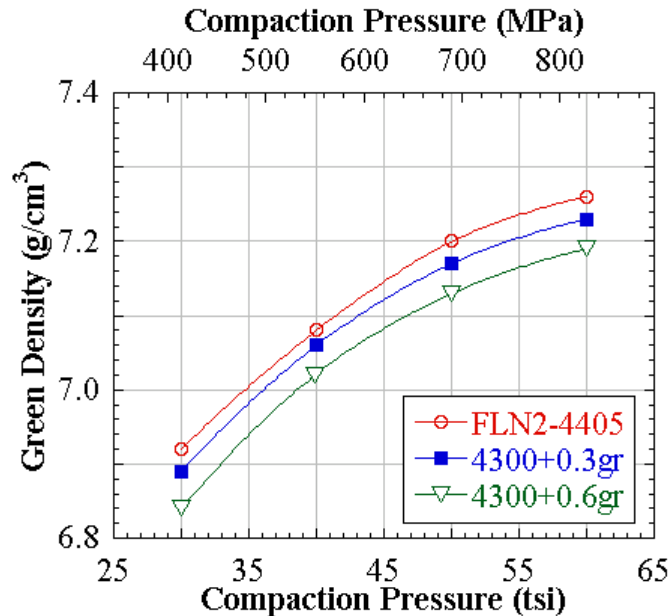
ID	Mo (wt.%)	Cr (wt.%)	Si (wt.%)	Ni (wt.%)	Gr (wt.%)	Processing Method
FLN2-4405	0.8	-	-	2.0	0.2	Oil quench
4300+0.3gr	0.8	1.0	0.6	1.0	0.3	Oil quench
4300+0.6gr	0.8	1.0	0.6	1.0	0.6	Sinter-harden

## RESULTS AND DISCUSSION

### **Core Property Development**

A compressibility plot of the three materials studied is shown in Figure 1. As would be expected, reducing the graphite content from 0.6 to 0.3 wt.% increases the green density of the chromium steel by about  $0.03 \text{ g/cm}^3$ . Interesting to note is that 4300, despite having a higher alloy content, has similar compressibility compared to FLN2-4405. To achieve the  $7.4 \text{ g/cm}^3$  target density for the FLN2-4405 component, it is clear that DP/DS steps are required. The  $7.0 \text{ g/cm}^3$  density targeted for both the 4300+0.3gr and 4300+0.6gr compositions requires a modest compaction pressure of 550 MPa (40 tsi).

In order to compare the three alloys for core performance, static properties were generated at various densities. These properties are summarized in Table III. Because of the presence of more nickel in the FLN2-4405, this alloy had more dimensional shrinkage during sintering than the other two alloys. As a result, the sintered densities increased up to  $0.05 \text{ g/cm}^3$  from the green densities, while the two 4300 compositions had green and sintered densities that were the same.



**Figure 2.** Compressibility plot of the three materials studied, all with 0.75 wt.% ethylene bisstearamide. The yield strength and tensile strength levels at  $7.0 \text{ g/cm}^3$  for both the 4300+0.3gr and 4300+06.gr compositions under their respective processing conditions matched up well with the reference

composition at 7.4 g/cm<sup>3</sup>. The ability to achieve similar static properties without the need for the DP/DS steps could provide a significant economic advantage, both in piece price and tooling cost.

Apparent hardness values for actual heat-treated sprockets for the three alloy compositions are shown in Table IV. These values were not recorded in the areas that were selectively densified, and thus are representative of the nominal part densities listed on the left-hand side of the table. Because apparent hardness is so dependent on density, a difference is to be expected between FLN2-4405 at 7.4 g/cm<sup>3</sup> and the 4300 compositions at 7.0 g/cm<sup>3</sup>. However, micro-hardness values for the two compositions would likely be similar because of the similarity in microstructure.

As expected, metallographic analysis revealed the presence of fully martensitic microstructures in oil quenched FLN2-4405 and 4300+0.3gr (Figure 3). The sinter-hardened 4300+0.6gr composition also showed a predominantly martensitic microstructure, though there was some divorced pearlite and bainite present. Increasing the graphite content to either 0.7 or 0.8 wt.% would likely increase the hardenability enough that a fully martensitic microstructure would be formed under the accelerated furnace cooling rate. The increased martensite would improve both the yield strength and apparent hardness.

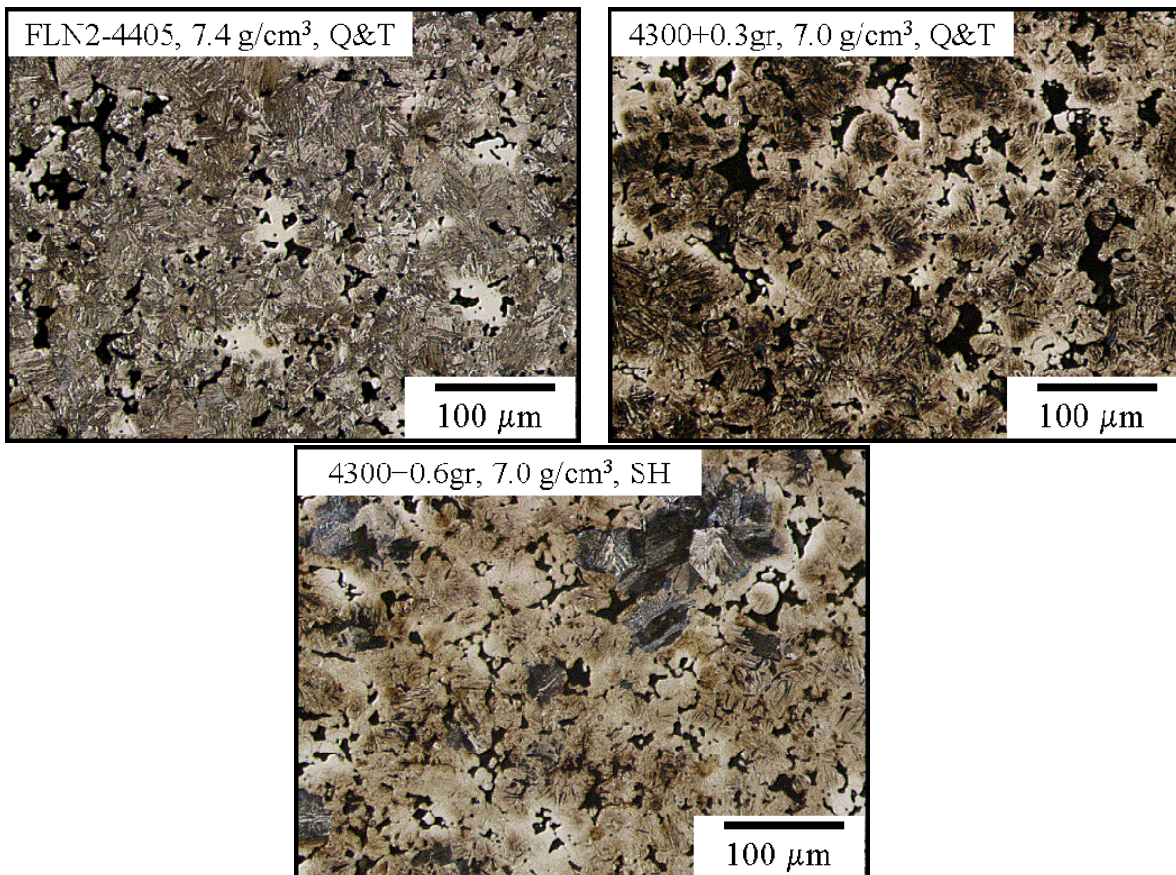
The use of the component in an automotive sprocket application necessitates high contact fatigue resistance. It is widely known that fatigue is a surface driven phenomena, and particularly dependent on the finish and amount of porosity that exists at the surface [4]. With such a high demand on surface performance, the heat-treated 4300+0.3gr or sinter-hardened 4300+0.6gr might not provide sufficient contact fatigue resistance at 7.0 g/cm<sup>3</sup>. To ensure that the desired fatigue performance level is achieved, a selective densification technique could be employed with 4300+0.3gr. While this would add cost to the part, net cost of the component would be less because of elimination of the DP/DS steps.

**Table III.** Static properties for three compositions sintered at 1120 °C (2050 °F). Tempered at 175 °C (350 °F) for 1 hour.

<b>ID</b>	<b>Processing</b>	<b>SD g/cm<sup>3</sup></b>	<b>YS MPa (10<sup>3</sup> psi)</b>	<b>UTS MPa (10<sup>3</sup> psi)</b>	<b>Elong %</b>	<b>Impact J (ft.lbf)</b>
FLN2-4405	Oil quench	7.05	695 (101)	840 (122)	1.5	14 (10)
		7.22	760 (110)	925 (134)	1.7	19 (14)
		7.42	795 (115)	985 (143)	2.1	28 (21)
4300+0.3gr	Oil quench	7.01	810 (117)	925 (134)	1.1	14 (10)
		7.22	965 (140)	1085 (157)	1.2	19 (14)
4300+0.6gr	Sinter harden	6.99	841 (122)	1069 (155)	1.5	14 (10)
		7.18	931 (135)	1103 (160)	1.5	20 (15)

**Table IV.** Apparent hardness of actual components for three compositions sintered at 1120 °C (2050 °F). Tempered at 175 °C (350 °F) for 1 hour.

ID	Processing	Part Density g/cm <sup>3</sup>	App. Hardness HRC
FLN2-4405	Carburize / heat-treat	7.05	38
		7.22	45
		7.42	50
4300+0.3gr	Carburize / heat-treat	7.01	39
		7.22	49
4300+0.6gr	Sinter harden	6.99	36
		7.18	41

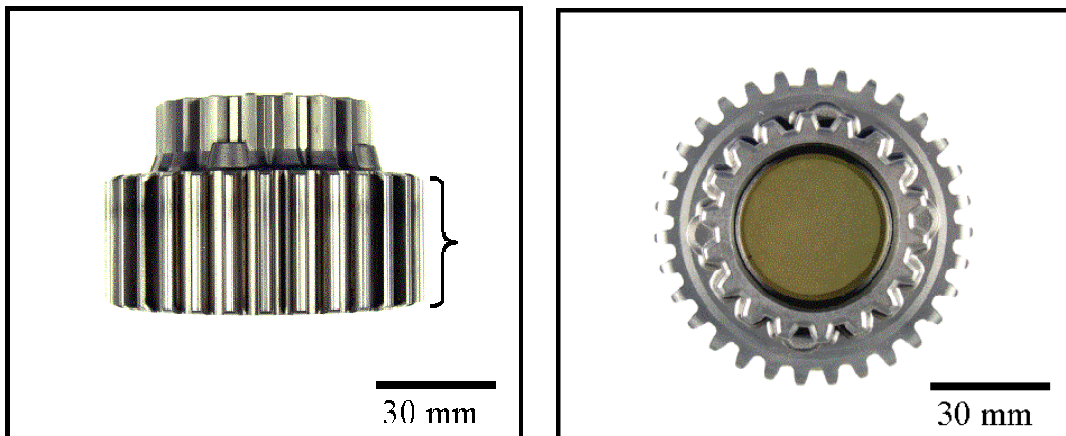


**Figure 3.** Microstructures of the three compositions under their respective processing conditions.

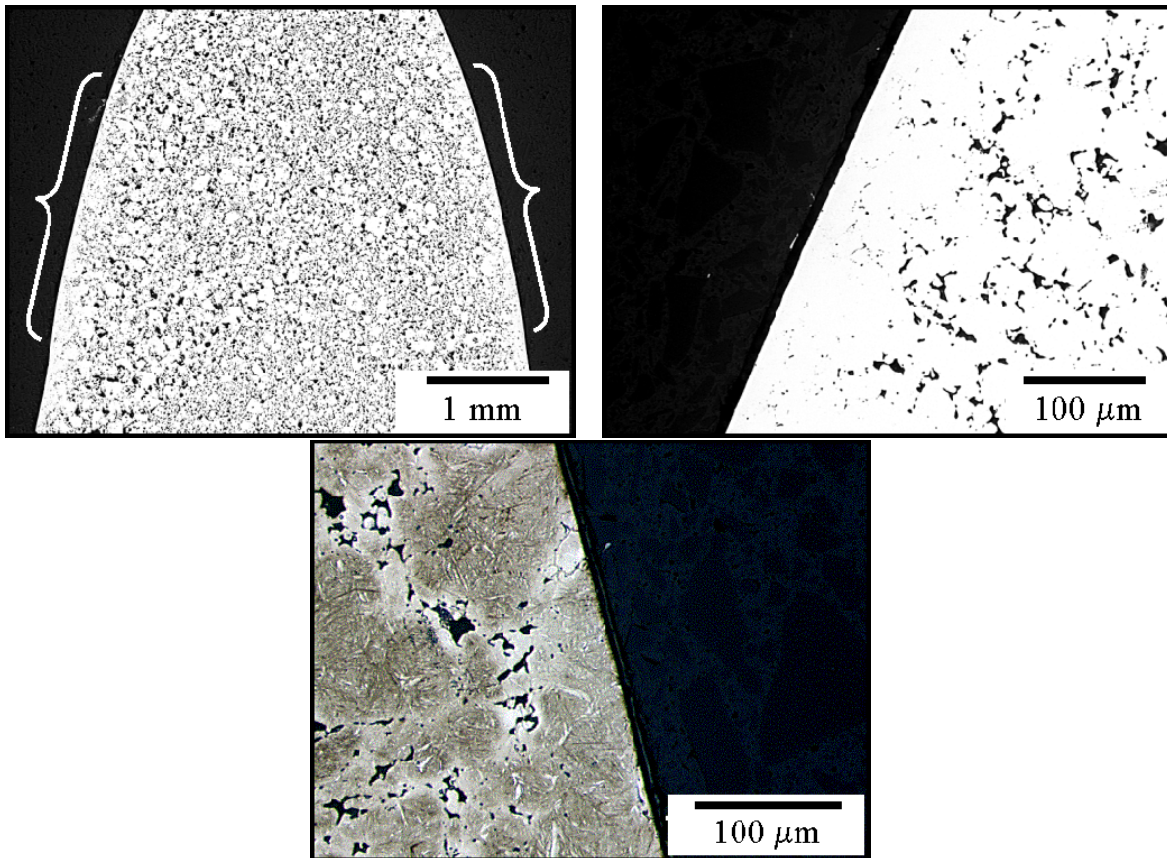
### Component Metallography

To further extend the evaluation of the chromium steel for this automotive power train application, prototype components were compacted with  $4300 \pm 0.3 \text{ gr}$  to a  $7.0 \text{ g/cm}^3$  nominal green density. After sintering at  $1120 \text{ }^\circ\text{C}$  ( $2050 \text{ }^\circ\text{F}$ ), these components were selectively densified and case carburized. Selective densification was performed on the larger sprocket, but not the pinion section, as shown in Figure 4.

Figure 5 shows photomicrographs of the selectively densified region. The lower magnification image shows the presence of surface densification primarily in the active profile region of the sprocket tooth. A higher magnification image shows the depth of densification to be nominally  $100 \text{ }\mu\text{m}$ . The case region was measured to contain approximately  $0.8 \text{ wt.}\%$  carbon after the vacuum carburizing cycle. Etched microstructures reveal a combination of plate (higher carbon martensite) and lath (lower carbon martensite) in the case, which is consistent with expectations based on this carbon level [5]. Performance of the selectively densified component is discussed in the “Dynamometer Testing” section of this manuscript.



**Figure 4.** Macroscopic photographs showing side and top views of the component. Bracket indicates the area of the component (face width of sprocket) subjected to selective densification.



**Figure 5.** Photomicrographs of 4300+0.3gr selectively densified in the area of active gear profile of the sprocket tooth. Brackets indicate areas of primary densification.

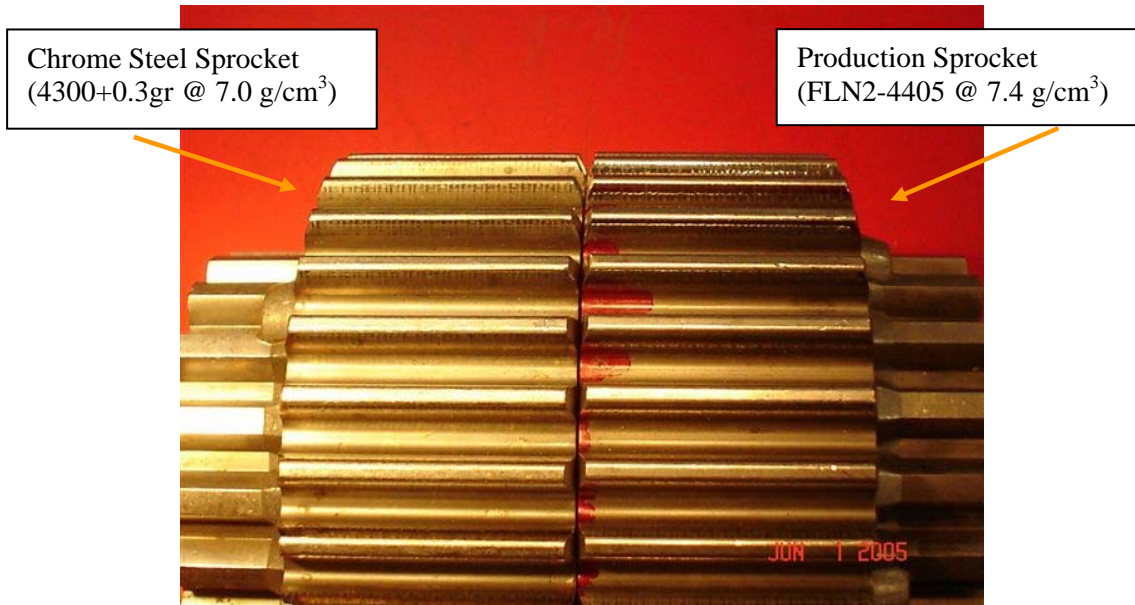
### Dynamometer Testing

Functional testing was performed on both the baseline FLN2-4405 sprocket and the single pressed, selectively densified chrome steel sprocket. The purpose of the experiment was to understand the relative durability of the two sprockets under field conditions. The assessment was intended to replicate that of a severe duty off road application. The test conducted was a twenty-two hour four-stage dynamometer test. The parts were subjected to contact stresses in excess of 276 MPa (40,000 psi) and shear stresses above 345 MPa (50,000 psi). Parts were evaluated both visually and mechanically upon test completion.

Visual examination of the parts identified consistent wear patterns on the tooth flanks, with both parts passing this aggressive dynamometer test. The tooth flank wear patterns can be observed in Figure 6.

The parts were then evaluated for surface finish on the tooth flanks using a Taylor Hobson profilometer and tooth wear using a measurement over wires (MOW) method. The results are summarized in Table V.

Both parts exhibited similar tooth finish conditions on the drive and coast flanks of the teeth. It was recognized however that the tooth thickness of the current production part was reduced significantly more than the chrome steel sprocket. Further investigation will take place to identify the specific cause of this apparent wear condition.



**Figure 6.** Wear pattern on sprocket teeth after 22-hour dynamometer test.

**Table V.** Tooth wear and finish after the 22-hour dynamometer test.

ID	Nominal Density (g/cm <sup>3</sup> )	Tooth Finish, R <sub>a</sub> (μm)	Tooth Wear – Reduction in Tooth Thickness (mm)
FLN2-4405	7.4	0.86	0.070 per flank
4300+0.3gr	7.0	0.92	0.013 per flank

## **CONCLUSIONS**

A new high performance Cr-bearing steel, Ancorsteel 4300, was evaluated in an automotive sprocket. The component is currently processed with a hybrid Ni-Mo alloy and DP/DS to a density of 7.4 g/cm<sup>3</sup>. Core property evaluation revealed that the chromium steel provided equivalent yield strength, tensile strength, and apparent hardness at a 7.0 g/cm<sup>3</sup> density versus the reference composition at 7.4 g/cm<sup>3</sup>. The components processed from the new alloy were selectively densified and vacuum carburized. Replacing the pre-sinter and secondary press operations with selective densification will ensure sufficient contact fatigue resistance and provide an economic benefit compared to the DP/DS steps that are currently used. Dynamometer results revealed that the components processed from the chromium steel matched the performance level of those of the double-pressed FLN2-4405 component.

## **ACKNOWLEDGMENTS**

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