

Wrought steel gears and surface densified powder metallurgy gears – a comparison

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Abstract

Near net shape powder metallurgy components are used in a wide range of medium to heavy duty applications in automotive engines and transmissions due to their cost effectiveness as well as weight and energy savings. Powder metallurgy, nevertheless, is yet to penetrate the market for gears in automotive powertrains, despite past successes in other automotive applications. At first sight it may seem that traditional machining of transmission gears is a complex and expensive process. However, the reality today is that the design and manufacturing of gears is still an OEM core competence and the PM industry has been unable to convince automotive OEMs that it can produce parts that match the performance and dimensional accuracy of machined gears.

This paper compares powder metallurgy gears manufactured using surface densification technology with gears machined from wrought steel blanks. A detailed comparison of fatigue properties and dimensional precision capabilities between the two types of gears is presented.

The potential to manufacture transmission gears with superior fatigue performance and dimensional accuracy using powder metallurgy to meet the exacting needs of the automotive industry is discussed.

Key Words

Powder metallurgy, surface densification, DensiForm[®], transmission, gears.

Introduction

Automotive transmission gears are responsible for transmitting torque from the engine to the wheels. In the process of transferring torque, gear teeth are subjected to cyclic loading. The cyclic loading in turn translates into cyclic tooth bending stresses along the root fillet and cyclic contact stresses on the active tooth surfaces.

Historically, high quality wrought steel alloys have been the only materials used in the high volume manufacturing of torque transmitting components such as transmission gears. Although powder metallurgy technology offers lower cost components, limitations in static and fatigue properties of sintered materials preclude the utilization of conventional powder metallurgy for these applications.

The quest for high strength PM components capable of replacing traditional steel in high torque carrying applications is an eternal challenge for powder metallurgy. Different approaches based on alloying and selective densification have been tried in the past and significant improvements in fatigue performance of powder metallurgy parts have been reported [1, 2, 3, 4, 5]. In particular cases, it has been reported that surface densified powder metallurgy gears can achieve both dimensional precision and durability of hobbled and shaved wrought steel gears [6,7,8].

Since many transmission gears have a helical tooth form with a helix angle above 30 degrees, it is a challenge for the PM industry to manufacture these components in a cost competitive manner when compared with the current hobbing of wrought steel blanks. Typically, the high helix angle poses a challenge for compaction because the geometry results in loads atypical of conventional compaction, thus limiting the achievable pressures for high core densities and increasing the risk of premature tool breakage. Nevertheless, a combined effort between PM parts producers, tooling and press manufacturers has enabled significant progress in helical compaction. This technology, although expensive in nature and limited to few companies, is available for the powder metallurgy industry. Today, it is possible to compact a helical gear with a 33° helix angle at a maximum density close to 7.2 g/cm³ using conventional low alloy steel powders.

In addition to complexity in compaction and the difficulties to achieve high core density, PM gear blanks require deep surface densification to maximize strength along the root fillet and on the active tooth surfaces. As stated above, surface densification has shown dramatic improvements in properties of PM parts in general and it has opened new possibilities for PM industry. The powder metallurgy industry has developed various methods for local densification of critical surfaces on parts. All known densification methods have in common the plastic deformation of a part with excess material presented to the forming tools in the areas that require densification.

In this paper, DensiForm[®], a proprietary densification method developed by PMG Corporation is used for manufacturing the studied gears. This surface densification method is performed in a conventional powder metallurgy press with the added benefit of substantially increasing the core density while performing sizing and surface densification [9, 10]. Simulation of the densification process is used to predict with a high level of precision the amount of densification and the uniformity of the densified layer. The important benefit of simulation is the design of densification tools and of the blank geometry to achieve the level of densification needed. Furthermore, simulation of the

densification process also allows for accurate predictions of final part geometry and dimensions.

For this study, gears produced by surface densification are characterized for dimensional accuracy and compared with solid steel gears manufactured by conventional broaching. In addition to dimensional capability comparison, rolling contact fatigue tests are conducted on wrought steel (AISI 8620) pinions and on surface densified pinions using a back-to-back gear testing rig. As shown in previous publications [1, 2], surface densification raises the bending fatigue strength of sintered gears to the level of wrought steel gears. For application in a transmission gear box, gears must resist pitting over the life of a vehicle in order to prevent loss of performance and noise associated with damage to the gear teeth. Therefore, powder metallurgy gears must match the contact fatigue strength of the wrought steel in a similar operating environment. In a gear meshing condition at high torque, normal surface contact stresses can be very high; it is however, the deviatoric (shear) stress under the surface, typically at a depth of 0.1 – 0.3 mm that initiates the pitting failure. Powder metallurgy gears are therefore required to achieve full density under the surface at greater depths in order to increase life at the contact stresses seen in modern automotive transmissions.

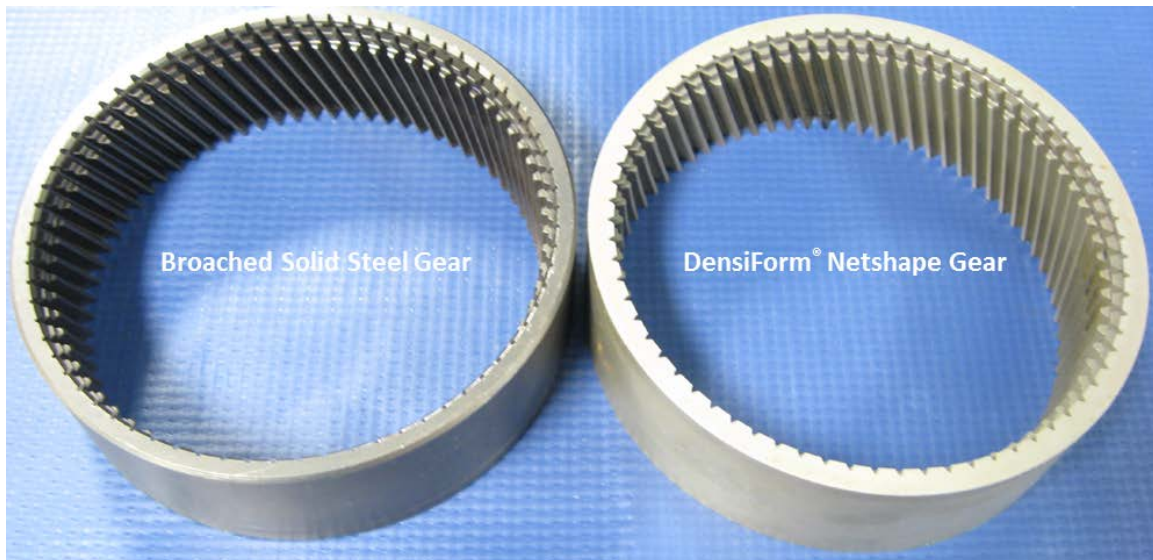


Figure 1: Broached Steel Gear and Surface Densified Powder Metallurgy Helical gear

Experimental Procedure

Automatic transmission ring gears (Figure 1) with the gear data given in Table 1 were used in this study for process dimensional capability. The powder metallurgy gear was compacted using Mo prealloyed steel powder (0.85 wt% Mo) mixed with 0.3 wt% graphite and lubricant. Parts were compacted at 7.2 g/cm³, sintered at conventional temperature (1120 °C) on a belt furnace and surface densified at a minimum core density of 7.30 g/cm³. The core density increase was obtained by sizing right after densification in the same press stroke. This is a significant difference from existing densification processes which take place in different equipment than traditional powder

metallurgy presses. It is important to emphasize here the importance of achieving a high core density to improve fatigue life for high torque applications.

The solid steel gears were purchased after broaching. The manufacturing process of a solid steel gear consists of broaching a precision machined blank. The large majority of ring gear blanks are produced either by forging or by tubing and cutting. The as forged blank or the blank cut from a steel tube undergoes significant machining to produce the correct internal diameter sizes and tolerances before broaching the teeth. In the case of ring gears with external teeth or splines, a separate broaching or hobbing is performed.

Table 1: Ring Gear Data

Number of Teeth	z	72
Normal Module (mm)	m_n	1.35
Normal Pressure Angle (deg)	α_n	21.5
Helix Angle (deg)	β	20.5
Face Width at Tooth Root (mm)	b	23.250
Measurement under Balls, Max, Min (mm)	M_{dk}	100.544 100.791
Tip Diameter (mm)	d_a	108.450
Reference (Pitch) Diameter (mm)	d	103.772
Base Diameter (mm)	d_b	95.657

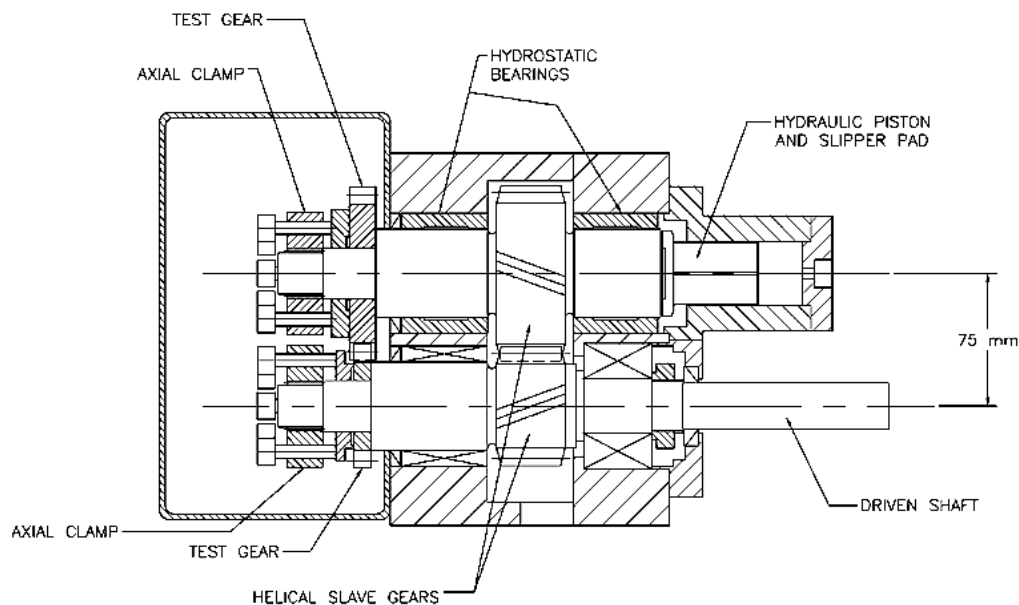


Figure 2: Layout of the 75 mm center distance back to back gear testing rig

For contact fatigue failure study, a 75 mm center distance back-to-back test rig was used (Figure 2). The back-to-back rig consists of two parallel shafts, one fixed axially and the other free to float axially. Mounted on each shaft is a helical slave gear and a spur test gear. The gears on each shaft mesh with each other. The gears are loaded by applying an axial force to the floating shaft. This force is reacted to by the floating helical gear meshing with the axially fixed helical gear. The spur gears prevent the two shafts from rotating independently. The applied force equals the axial force on the helical gears and

this generates a torque on the spur gears proportional to the force. The axial force is applied by a hydraulic piston loading a slipper pad which reacts against the end of the floating shaft. The hydraulic pressure is regulated accurately by a proportional solenoid valve. The torque is proportional to the applied pressure which is measured by a precision sensor.



Contact Fatigue Gear Data		
Center Distance; mm		75
Number of teeth	pinion	14
	gear	21
Module; mm		4.2
Pressure angle; °		20
Helix angle; °		0
Face width; mm	pinion	7.5
	gear	15
Pitch Diameter; mm	pinion	58.8
	gear	88.2
Base Circle Diameter; mm	pinion	55.25
	gear	82.88
Tip Diameter; mm	pinion	70.56
	gear	95.59

Figure 3: Contact fatigue test gear and pinion with their respective gear data

The test samples are the gear and the pinion pair as shown in Figure 3.

The main goal of this study was to characterize the pitting resistance of surface densified powder metallurgy gears and compare their performance with broached solid steel gears. Since the pinion has 14 teeth as opposed to 21 teeth for the gear, the gear will see only 67% of the total pinion loading cycles and consequently should not fail first during the test. For that reason, all the testing gears were hobbled from precision machined blanks using AISI 8620 steel.

Test pinions were manufactured from a solid steel hobbing process and from powder metallurgy process. Solid steel pinions were hobbled from precision machined blanks using AISI 8620 steel. Powder metallurgy pinions were manufactured using Mo prealloyed steel powder (0.85 wt% Mo) mixed with 0.3 wt% graphite and lubricant. Pinions were compacted at 7.2 g/cm³, sintered at conventional temperature (1120 °C) on a belt furnace and subjected to surface densification to achieve a fully dense layer up to 0.5 mm on tooth flanks and tooth root and a minimum core density of 7.30 g/cm³.

All the test pinions were carburized and oil quenched at the same time to achieve a minimum case depth of 0.6 to 0.8 mm.

For comparison between the two manufacturing processes, i.e. hobbing and powder metallurgy, surface finish was measured on each pinion using a Taylor Hobson – Form TalySurf Series 2 profilometer.

For this study, each test was performed at a constant gear speed of 3000 rpm which corresponds to 4500 rpm for the pinion speed. Calculated tangential velocity based on gear data for the two test parts gives 3.89 m/sec for the pinion and 5.36 m/sec for the gear. The velocity ratio of 1.377 between the 21T gear and the 14T pinion corresponds to a -37.7% sliding at the lowest point of single tooth contact for the test pinion.

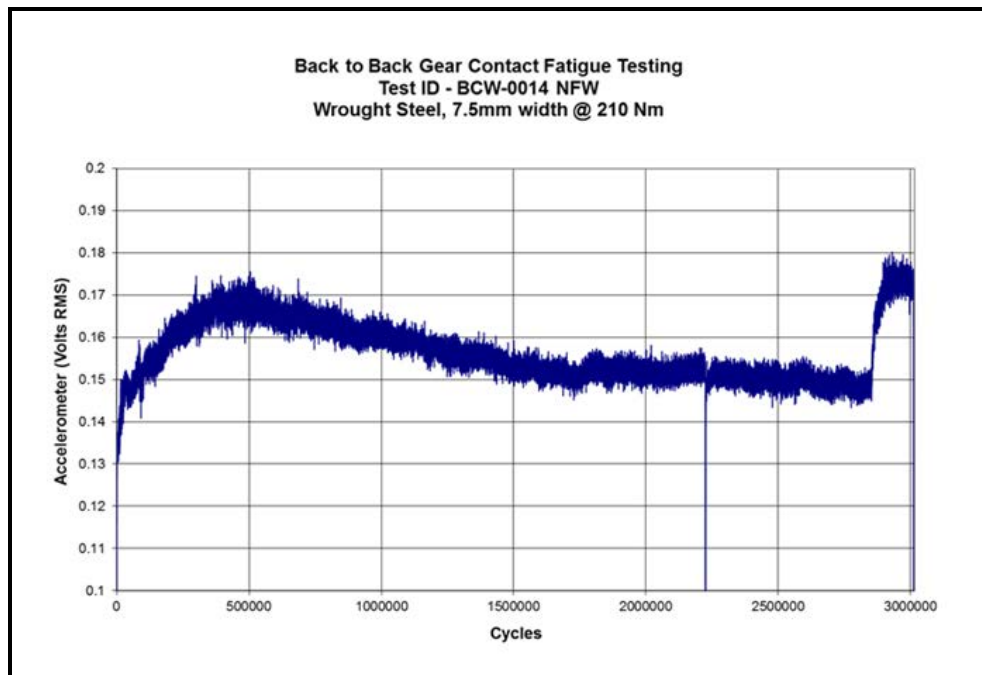


Figure 4: Example of vibration signal indicating onset of pitting during test

Several torque levels were used to assess the endurance limit for the test pinions. Tests were suspended after 10 million cycles in the absence of any failure. Pitting failure was determined by monitoring gear pair vibration using a piezoelectric accelerometer which converts the vibration into a voltage signal. The onset of pinion pitting is accompanied by an increase in system vibration, leading to an increase in the output voltage. The voltage signal is collected using a National Instruments data acquisition system. When pitting occurs, the RMS voltage increases by approximately 20% with respect to normal operating levels of vibration. Figure 4 shows an example of vibration signal increase due to pitting at 2.8 million cycles.

Results

Automatic Transmission Ring Gears

To compare dimensional precision of the as broached solid steel ring gears and the surface densified powder metallurgy ring gears, minor internal diameter roundness was measured using a coordinate measuring machine (CMM) and total profile error as well as total lead error were measured using an analytical gear inspection machine (ND430 gear checker).

Figure 5 gives a comparison of the ID roundness between the two manufacturing processes.

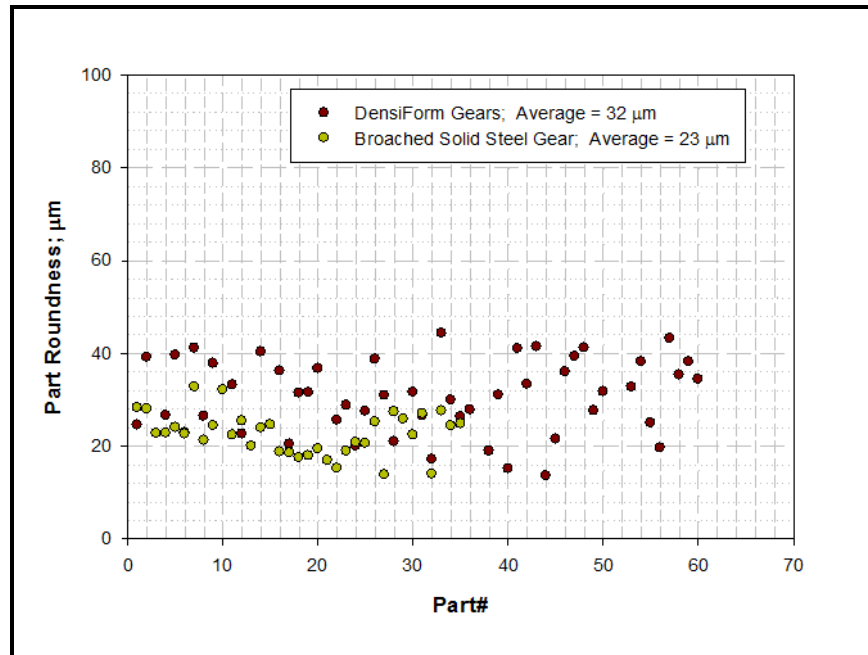


Figure 5: Minor ID roundness of broached and surface densified ring gears prior to heat treatment.

As seen in the above figure, the powder metallurgy process can produce low out of round parts which are needed to meet low radial runout (F_r) in the finished gear. As a reference, the studied gear with 72 teeth and 1.35 mm module will require a radial runout of less than 35 μm to meet AGMA 2015-1 grade A8. For reference, AGMA 2015-1 defines 10 accuracy grades numbered from A2 through A11 in order of decreasing accuracy.

Figure 6 compares the profile total error between broached ring gears and PM ring gears. Based on profile total error only, the surface densified PM gears with maximum error of 7.4 μm meet AGMA 2015-1 grade A6.

Figure 7 compares the helix total error between broached ring gears and PM ring gears. Again, based on helix total error only, the PM gears with maximum error of 12.3 μm would meet AGMA 2015-1 grade A6.

Considering the roundness measurements and the errors on profile and on lead, it is clear that the surface densification process can produce a gear with similar quality to the broached gears used in today automotive transmissions.

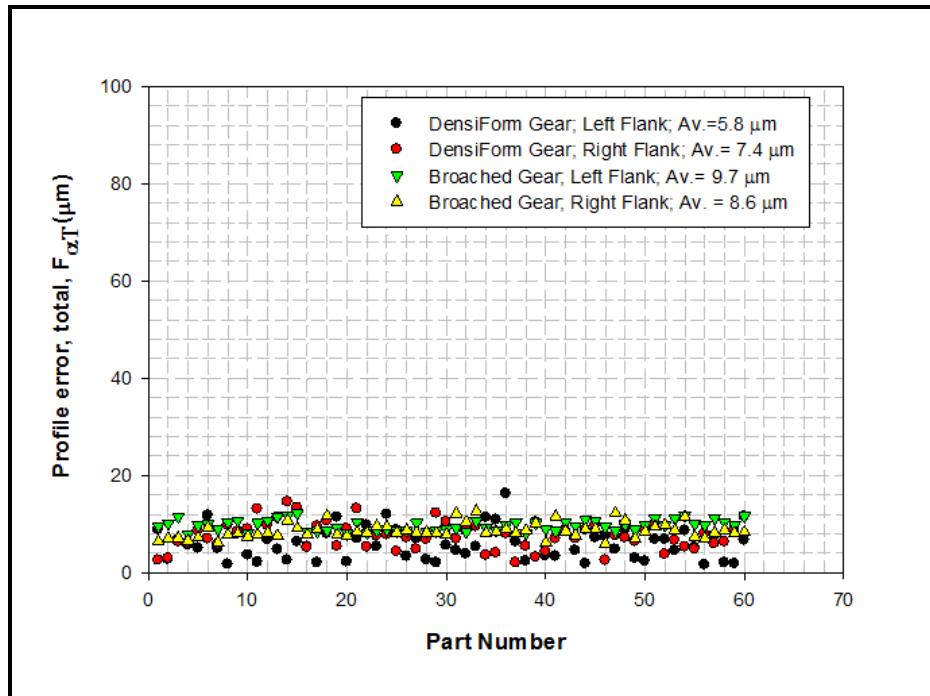


Figure 6: Profile total error of broached and surface densified PM ring gears prior to heat treatment

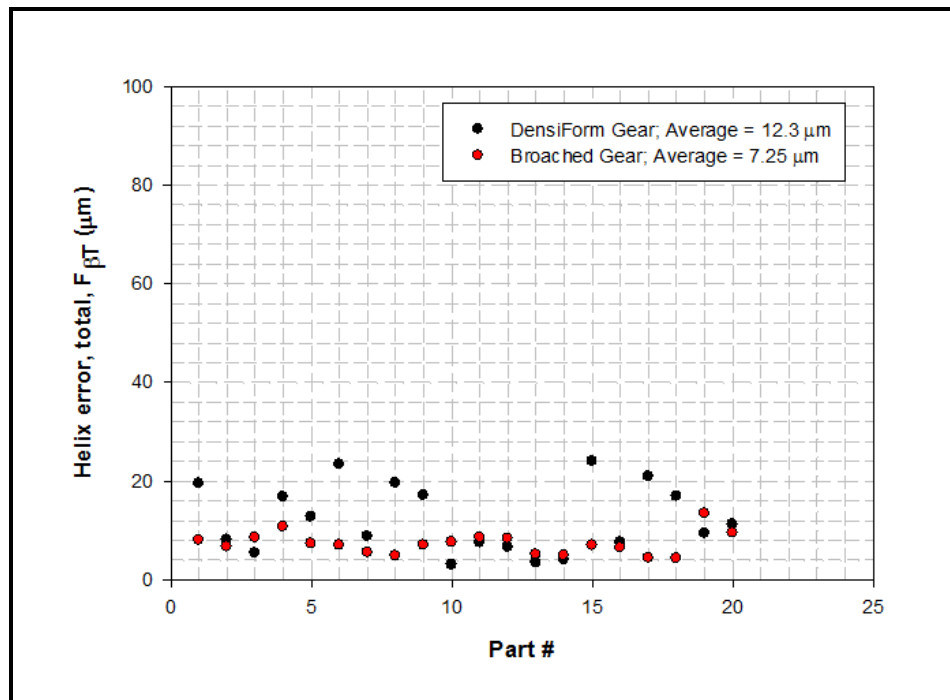


Figure 7: Helix total error of broached and surface densified PM ring gears prior to heat treatment.

Contact Fatigue Test Results

Pitting stress-life curves from contact fatigue of pinions made from hobbed wrought steel and pinions made by surface densification using a powder metallurgy manufacturing process are presented in Figure 8. As seen in this figure, surface densified PM pinions show an endurance limit around 1764 MPa compared with 1839 MPa for the hobbed pinions. The difference in fatigue life, below 5% in this case, makes the surface densified gears a viable alternative to hobbed gears with respect to performance in applications involving high contact stress.

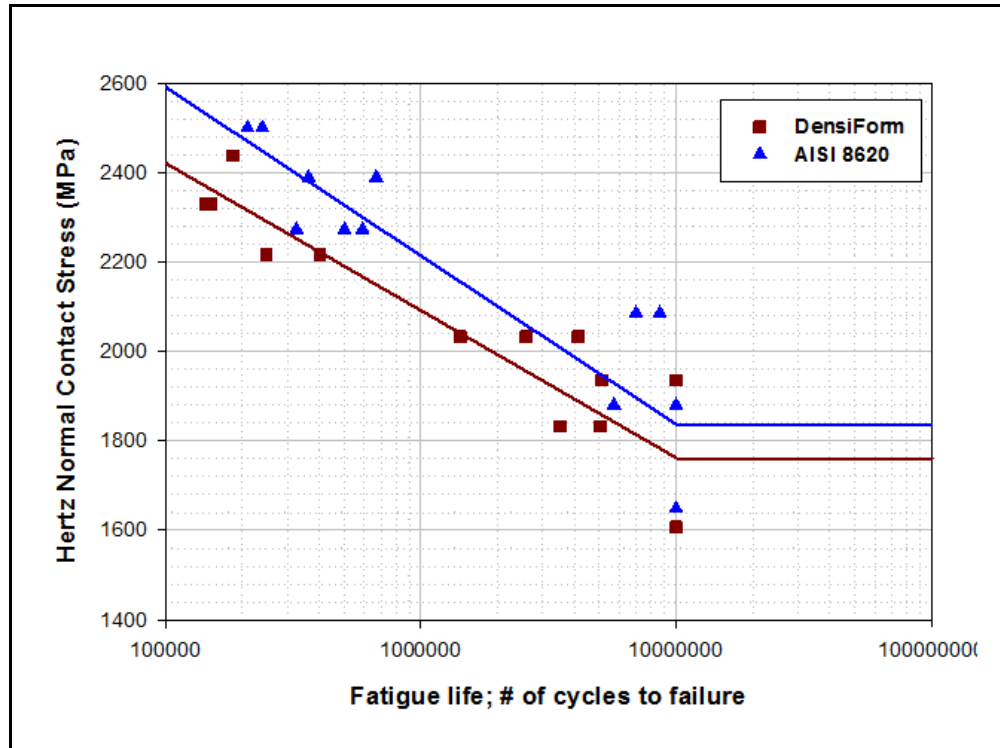


Figure 8: Contact fatigue comparing surface densified PM pinions with broached pinions

To evaluate the significance of these results, a comparison with prior results obtained from a contact fatigue study using a dual roll tester was made. Table 2 summarizes the results of a CPMT (Center for Powder Metallurgy Technology) study conducted on various materials with various manufacturing conditions [11]. As seen in this table, an endurance limit in the 1700-1900 MPa range is reported for both wrought steel and surface densified powder metallurgy components.

Material	Density g/cm ³	Contact Fatigue Stress (MPa) G50 @ 10 ⁷ cycles 50% Conf.
Fe-Mn-Mo	7.50 7.80+	1897
P/F 4628	7.85	1779
Wrought Steel 4620M	7.85+	1952
FL-4400	7.70	1807

Table 2: CPMT Dual Roll Test Results [11]

These results confirm again that regardless of the testing method or the test samples, surface densification improves significantly the contact fatigue of powder metallurgy parts and constitutes a valid alternative for manufacturing highly loaded components such as gears for automotive transmissions.

Figure 9 compares the surface finish of hobbed pinions with the surface finish of surface densified PM pinions. As seen in this figure, surface densification achieves a smooth finish with a mean roughness 3 times lower than the mean roughness of conventional gear hobbing method. Knowing that surface roughness can be a major contributor to pitting initiation in contact fatigue testing, it is possible to assume that part of the performance of the surface densified gears could be attributed to better surface finish.

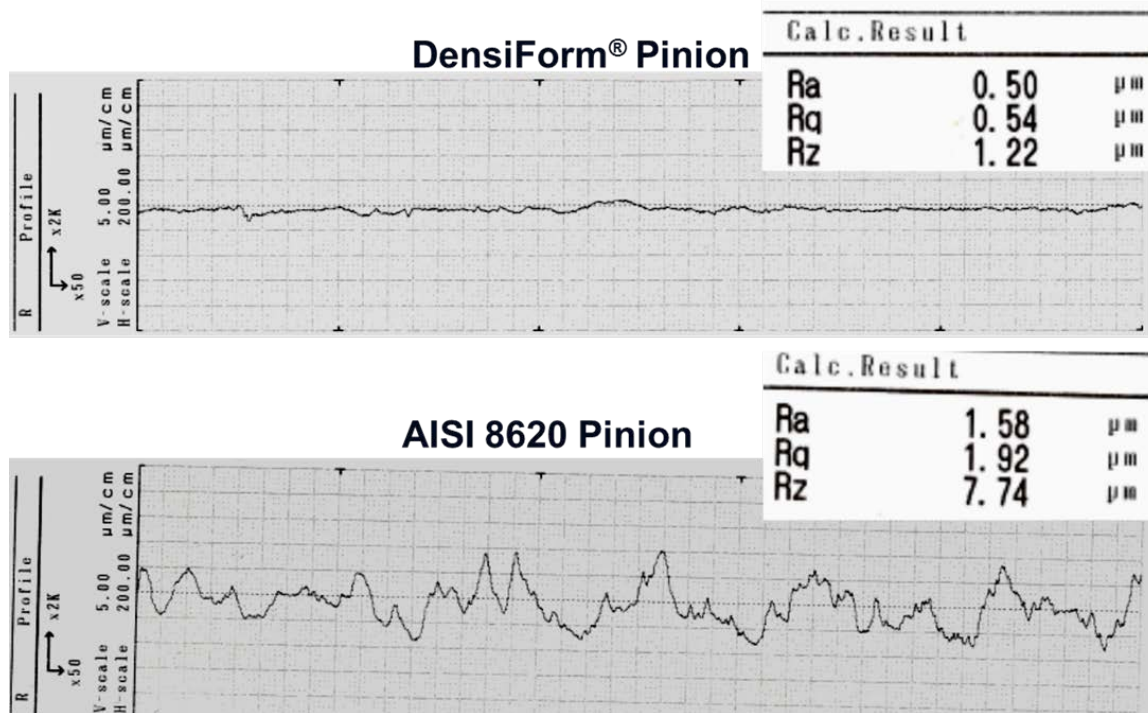


Figure 9: Typical surface roughness traces comparing broached gears with surface densified PM gears

Figure 10 presents pitting images comparing hobbed pinions with surface densified PM pinions at different torque test levels. As expected, pitting is found along the tooth dedendum at the LPSTC (Lowest Point of Single Tooth Contact) which corresponds to the worst combination of stress and sliding causing initiation and growth of fatigue pits in tested pinions.

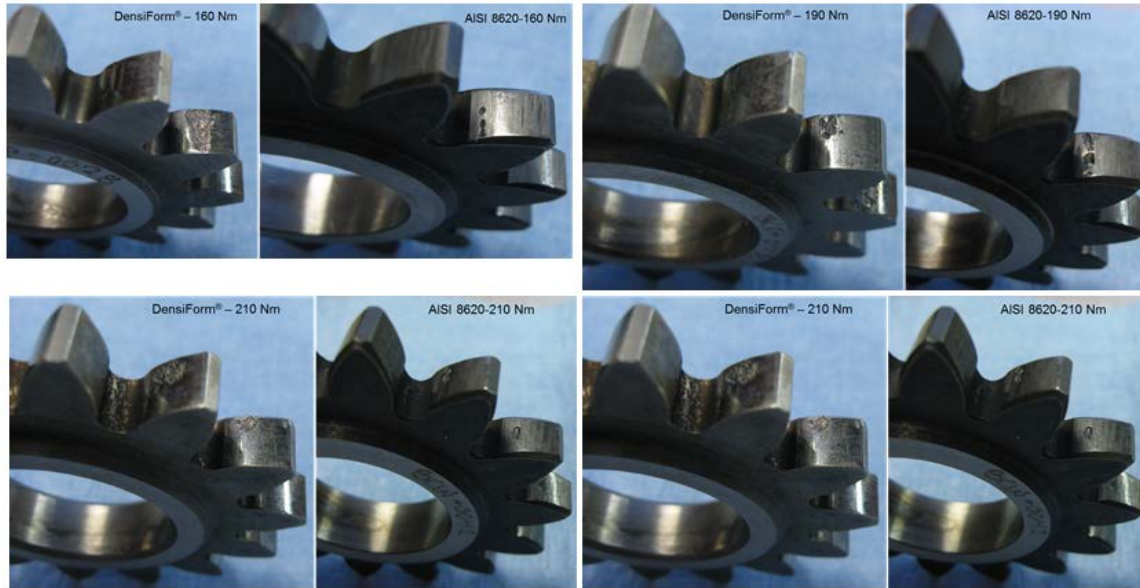


Figure 10: Typical pitting failures of broached pinions and surface densified PM pinions.

Conclusions

We have presented a comparison between transmission gears manufactured using the current broaching method of solid steel and the powder metallurgy gears manufactured using DensiForm®, a surface densification method designed to improve dimensions and performance. In this work, it was shown that surface densification is an essential step in the effort to manufacture gears with the quality and performance needed for transmission application. Powder metallurgy gears present the advantages below that are worth considering when it comes to the design of gears for automotive transmissions:

- Gears made by PM process have the inherent advantages in shape complexity and production rates over the traditional machining process. This advantage should translate into cost competitiveness for PM gears for similar applications
- Surface densified PM gears have a much better surface finish than broached or hobbed solid steel gears. The improved surface finish is a clear advantage for applications where post heat treatment grinding is not economically attractive such as ring gears for automatic gear boxes

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