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Bending Fatigue, Impact and Pitting Resistance of Ausform Finished P/M Gears

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[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

Powder metal (P/M) process is making inroads in automotive transmission applications because of substantially lower cost of P/M steel components for high volume production as compared to wrought or forged steel parts. Although P/M gears are increasingly being used in powered hand tools, gear pumps, and as accessory components in automotive transmissions, P/M steel gears are currently in limited use in vehicle transmission applications. The primary objective of this project was to develop high strength P/M steel gears with bending fatigue, impact, and pitting fatigue performance equivalent to current wrought steel gears. Ausform finishing tooling and process was developed and applied to powder forged (P/F) steel gears in order to enhance the strength and durability characteristics of P/M gears, while maintaining the substantive cost advantage for vehicle transmission applications.

Bending fatigue and impact strength of ausform finished P/F steel gears were demonstrated to be comparable to conventional wrought steel gears. Pitting fatigue life of ausform finished P/F gears was about 85% higher than wrought steel gears produced by current conventional processing techniques. Scoring and wear resistance of ausform finished P/F steel gears were also shown to be substantially superior to conventional wrought steel gears. This paper presents the processing techniques used to produce ausform finished P/F steel gears, and comparative bending fatigue, impact and surface durability performance characteristics of ausform finished P/F steel gears as well as conventional wrought steel gears.

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Introduction

Powder metal (P/M) process has the potential for substantial cost advantage for high volume vehicle transmission applications as compared to current wrought or forged steel parts. [1, 2] Recent advances in P/M technology such as double pressing/sintering, high temperature sintering, surface densification and powder forging have substantially enhanced the tooth bending fatigue and rolling contact fatigue performance of P/M steel gears to be comparable to current automotive wrought steel gears. [3–16] Use of P/M steel gears for power transmission applications, however, is currently limited to minimally loaded components due to surface durability performance constraints. Ausform gear finishing process developed at Penn State University has the potential to induce improved accuracy and surface finish in a cost effective manner and thereby enhance the performance characteristics of P/M steel gears to be equivalent to current wrought or forged steel gears. [17–20] Powder forged (P/F) and case hardened P/M steel gears were ausform finished in order to achieve bending fatigue strength, impact resistance and surface durability performance at least equivalent to current wrought steel gears. Test results from a comparative performance testing program are presented comparing ausform finished P/F steel gears, and baseline wrought steel gears.

Materials and processing details

P/M standard gear design (24 teeth, 8 diametral pitch, 0.5" face width), which had been previously used in a CPMT sponsored Gear Research Institute program to compare sixteen different P/M formulations and/or processing techniques, was selected as the candidate test gear, with some alterations. Table 1 summarizes the test gear geometry details for baseline wrought steel gears and ausform finished P/F steel gears. Table 1 also describes the mate gears used for surface durability

testing including pitting fatigue, scoring and wear resistance tests.

Table 1. Gear dimensions

	Test gears	Mate gear
# of teeth	24	40
Diametral pitch	8	8
Pressure angle	18.65°	18.65°
Tooth thickness	0.235–0.237	0.146–0.148
Base diameter	2.842469	4.737449
Root diameter	2.744–2.754	4.543–4.555
SAP diameter	2.8944	4.77
Pitch diameter	3	5
EAP diameter	3.357	5.147
Outside diameter	3.36	5.152
Fillet radius	0.0536	0.0507

P/F steel test gears were made from prealloyed P/M 4620 steel composition, a carburizing grade P/M formulation that is typically used to produce automotive P/M parts. Baseline gears were produced from wrought 4023 steel, and mate gears (40 teeth, 8 diametral pitch, 1.0" face width) used for power circulating (PC) surface durability tests were produced from wrought 8620 steel. Table 2 shows the chemical composition of the respective steels. Case hardening specifications for all test and mate gears required a surface hardness of 58–63 HRC, effective case depth to 50 HRC of 0.030 – 0.040" at mid tooth height and 0.15" minimum at root fillet, and core hardness of 28–34 HRC. Process sequence used for producing P/F steel test gears involved pressing, sintering, powder forging, case hardening heat treatment, followed by ausform finishing. In comparison, process sequence used for producing baseline and mate gears involved blank machining, forging, hobbing, shaving, case hardening heat treatment, and shot peening. Tooth profile design of mate gears incorporated a pronounced tip and root relief in order to accommodate tooth bending effects in the test gear teeth during surface durability testing. Table 3 compares the

processing steps used for the manufacture of ausform finished P/F steel test gears and wrought steel baseline and mate gears.

Table 2. Chemical compositions

	4620	4023	8620
C	0.17-0.22	0.2-0.25	0.18-0.23
Mn	0.45-0.65	0.7-0.9	0.7-0.9
Si	0.15-0.35	0.15-0.35	0.15-0.35
Ni	1.65-2.0		0.4-0.7
Cr			0.4-0.6
Mo	0.2-0.3	0.2-0.3	0.15-0.25
P (max)	0.035	0.035	0.035
S (max)	0.04	0.04	0.04

Table 3. Process sequence comparison

P/F test gears	Baseline/mate gears
Press	Barstock cut
Sinter	Forge
Powder forge	Normalize
Machine	Machine
Heat treat	Hob
Hone bore	Shave
Ausform finish	Heat treat
Temper	Hone bore
Deburr	Finish faces
Finish faces	Shot peen

Ausform gear finishing

Ausforming is a modified heat treatment process applicable to medium to high carbon low alloyed steels, wherein the steel is first austenitized followed by interrupted quenching to above the M_s temperature to metastable austenitic state. The part is then plastically deformed in the metastable austenitic condition and finally cooled to martensite. Figure 1 shows a schematic time-temperature-transformation diagram that describes the ausforming process. Research has shown that ausformed martensite resulting from deformed austenite possess substantially higher strength as compared to conventional martensite transformed from undeformed austenite. Up to 50% increase in

tensile and yield strength was reported in various steels depending on amount of deformation induced during ausforming. [21-25] Over 600% increase in rolling contact fatigue of ausformed cylindrical M50 steel specimens was demonstrated, and degree of B_{10} fatigue life improvement increasing with the amount of deformation. [26] Bamberger reported nine-fold increase in B_{10} life of ausformed M50 steel bearings over conventionally heat-treated bearings. [27]

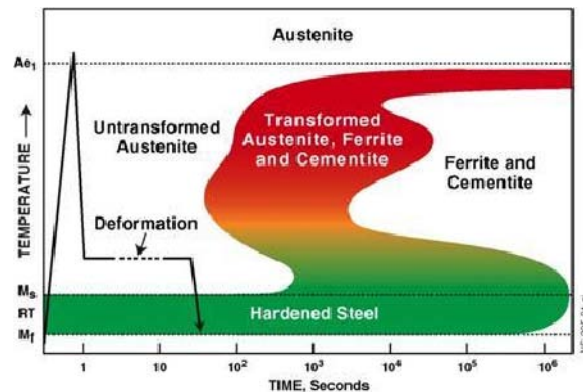


Figure 1. Ausform process schematic

Penn State's technique applies ausforming to localized surface layers of contacting machine elements such as gears. [28-36] Figure 2 shows a schematic description of the ausforming process as a gear tooth finishing operation for a typical case hardened low alloy steel gear, and involves induction austenitization, marquenching, roll finishing and then cooling to martensite. Ausform finishing of spur and helical gears results in very fine surface finish of 4 to 8 $\mu\text{in Ra}$ in both the radial and tangential tooth profile directions. Furthermore, fully optimized ausforming tooling and process have been demonstrated to result in finished gear tooth accuracy of less than 0.0002" in both the profile and lead inspections. Fine surface finish and gear teeth accuracy have been shown to contribute significantly to improved surface fatigue performance. Cycle times involved in ausform gear finishing are of the order of several seconds per gear as compared to several minutes for gear grinding, and therefore the process is capable of integration in large production applications.

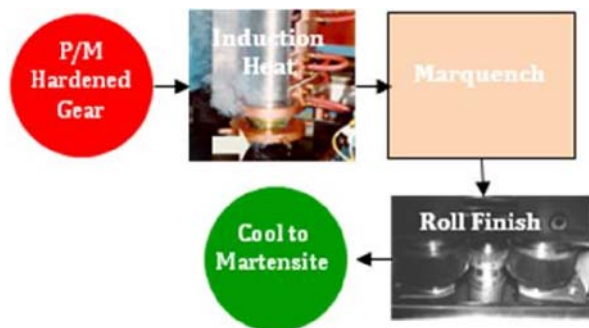


Figure 2. Ausforming process steps

Ausform finishing of P/F steel gears

Double die ausform gear finishing machine at Penn State was used to develop the tooling and process variables to process P/F steel gears. The first step was to establish the dual frequency induction heating process to be used to austenitize the case prior to roll finishing of gear teeth in metastable austenitic condition to final dimensions. The required induction heating process parameters were established for the P/F gears by experimental iterations. X-ray diffraction measurements showed a compressive residual stress at tooth surface in the root fillet region of about 31 ksi for the ausformed P/F steel gear as compared to about 22 ksi measured for preausformed P/M steel gears.

The next step to ausform finish P/F steel gear was to establish gear roll finishing tooling and process.

Ausform finishing resulted in reduction of chordal tooth thickness of about 0.003 to 0.004". Roll finishing operation of ausforming requires optimization of the rolling die tooth profile in order to achieve the desired finished gear tooth accuracy. The rolling die tooth profiles must be modified away from nominally involute tooth shape, and die tooth profile optimization typically requires several experimental iterations. For the current program to ausform finish P/F steel gears, the initial die tooth geometry was estimated based on numerical FEA based process modeling as well as prior results from similarly sized test gears. Figure 3 shows the rolling die tooth profile used on the drive and coast sides for ausform finishing of P/F steel gears. Figure 4 and 5 compare the profile and lead charts of P/F steel test gears before and after ausforming, and show the enhancements in both accuracy and surface finish of ausform finished gear teeth. Profile charts in figure 4 show the profile accuracy on right flank of gear teeth to be less than ± 0.0001 " achieved across the contact region of the teeth. Furthermore, ausform finished tooth profiles in figure 4 also show the desired tip relief of about 0.001" implemented by the rolling dies. Die tooth profile require further development to optimize the profile accuracy on the left flanks which shows a localized hollow of 0.0003".

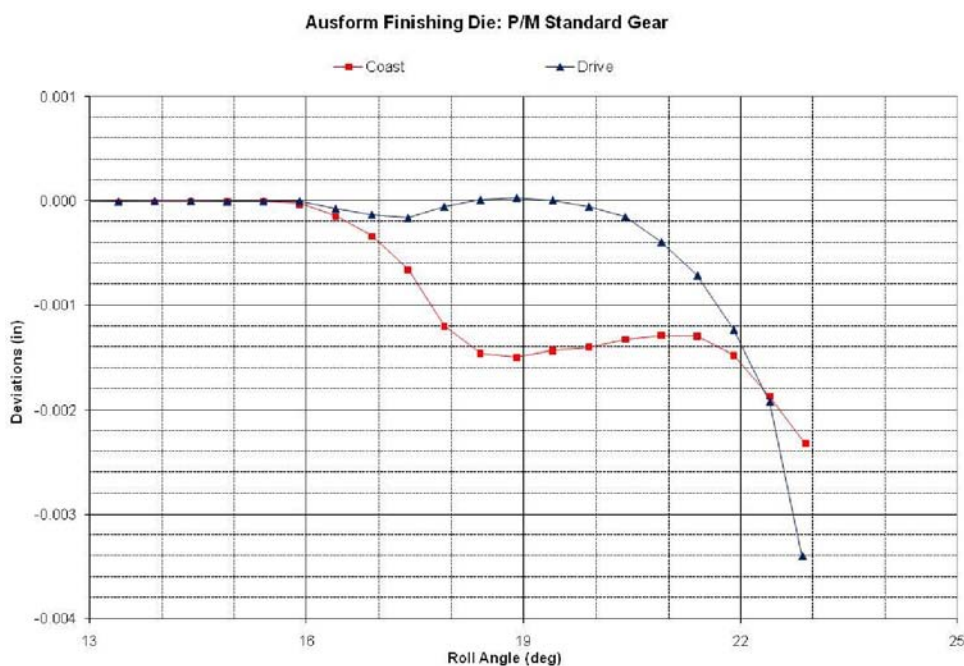


Figure 3. Ausform finishing – rolling die tooth profiles