

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

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## Management Summary

The powder metal (P/M) process is making inroads in automotive transmission applications due to substantially lower costs of P/M-steel components for high-volume production, as compared to wrought or forged steel parts. Although P/M gears are increasingly 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 resistance and pitting fatigue performance equivalent to current wrought steel gears.

The ausform-finishing tooling and process were 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. The 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 the comparative bending fatigue, impact and surface durability performance characteristics of ausform-finished P/F-steel gears as well as conventional wrought steel gears.

## Introduction

The 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 (Refs. 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, comparable to current automotive wrought steel gears (Refs. 3–16). The use of P/M steel gears for power transmission applications, however, is currently limited to minimally loaded components, due to surface durability performance constraints.

The 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 (Refs. 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

A 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 16 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.

P/F-steel test gears were made from pre-alloyed 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. The 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, the process sequence used for producing baseline and mate gears involved blank machining, forging, hobbing, shaving, case hardening heat treatment and shot peen-

	Test Gears	Mate Gear
No. 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	2.744-2754	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

	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

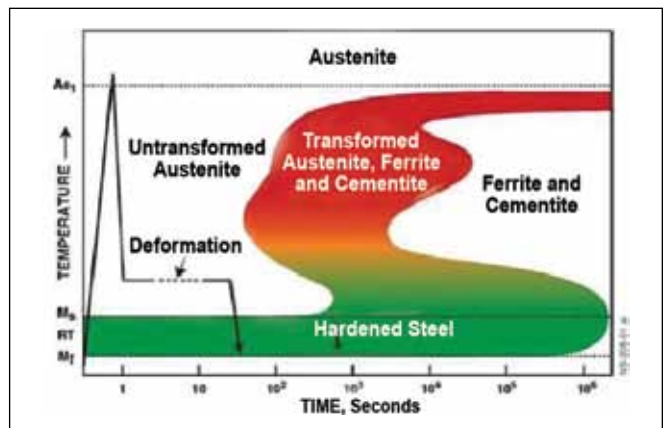


Figure 1—Ausform process schematic.

ing. The 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.

**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 MS temperature to a 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-tem-

continued

perature-transformation diagram that describes the ausforming process. Research has shown that ausformed martensite resulting from deformed austenite possesses substantially higher strength as compared to conventional martensite transformed from un-deformed austenite. An increase of up to 50% in tensile and yield strength was reported in various steels, depending on the amount of deformation induced dur-

ing ausforming (Refs. 21–25). A more than 600% increase in rolling contact fatigue of ausformed, cylindrical M50 steel specimens was demonstrated, with the degree of  $B_{10}$  fatigue life improvement increasing with the amount of deformation (Ref. 26). Bamberger reported a nine-fold increase in the  $B_{10}$  life of ausformed M50 steel bearings over conventionally heat treated bearings (Ref. 27).

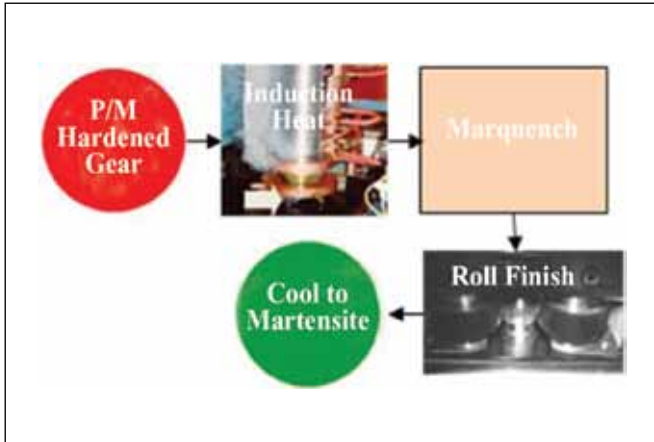


Figure 2—Ausforming process steps.

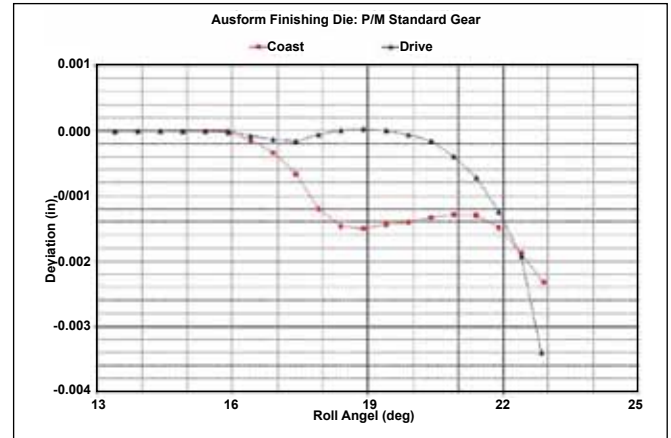


Figure 3—Ausform finishing: rolling die tooth profiles.

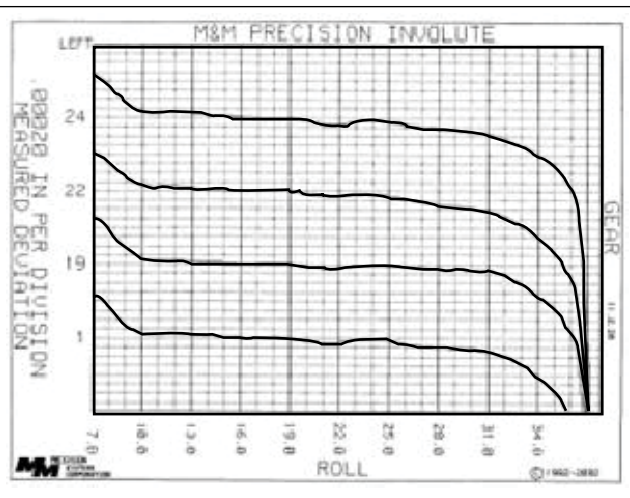
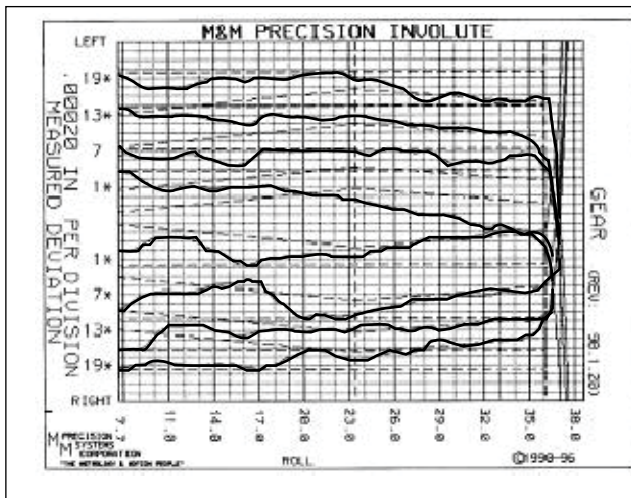


Figure 4—P/F gear tooth profile charts: pre-ausform (left) and ausform-finished (right).

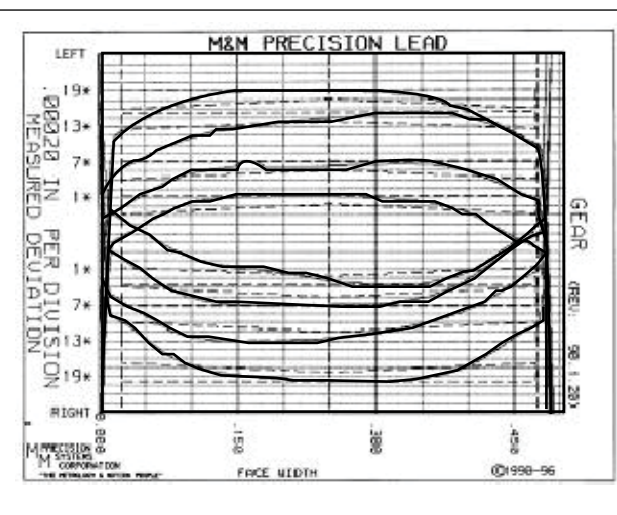
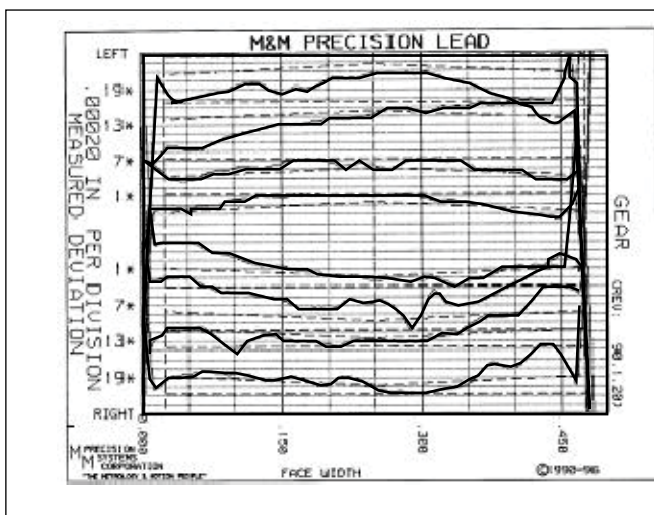


Figure 5—P/F gear lead charts: pre-ausform (left) and ausform-finished (right).

Penn State's technique applies ausforming to localized surface layers of contacting machine elements, such as gears (Refs. 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 austenization, marquenching, roll finishing and then cooling to martensite. Ausform finishing of spur and helical gears results in a very fine surface finish of 4 to 8  $\mu\text{m}$  Ra in both the radial and tangential tooth profile directions. Furthermore, fully optimized ausforming tooling and process have been demonstrated to result in a 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.

**Ausform finishing of P/F steel gears.** A 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 the 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 pre-

**continued**

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

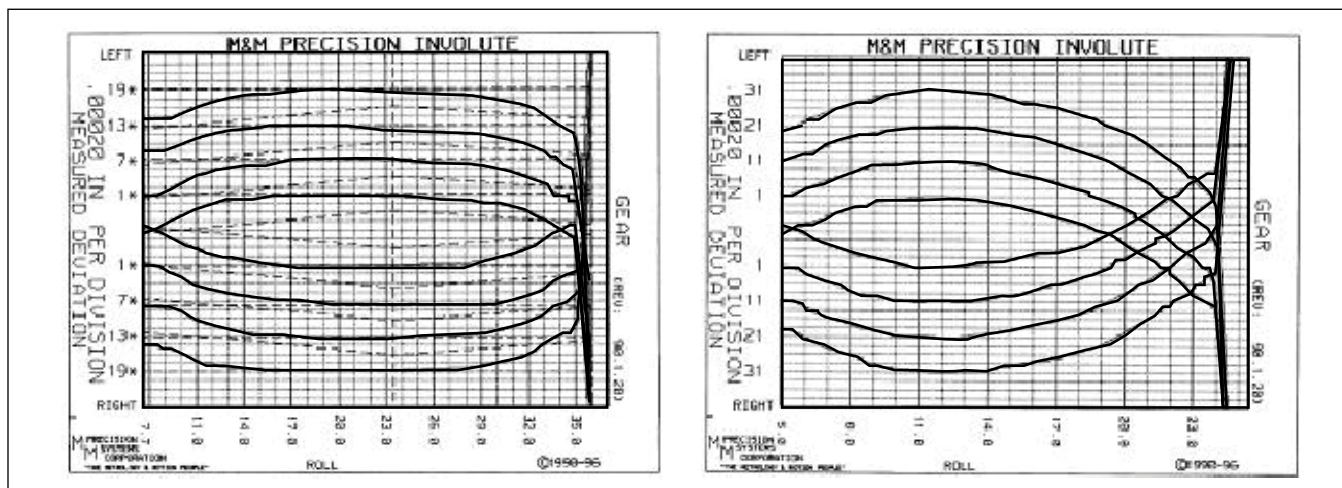


Figure 6—Profile charts: baseline gear (left) and mate gear (right).

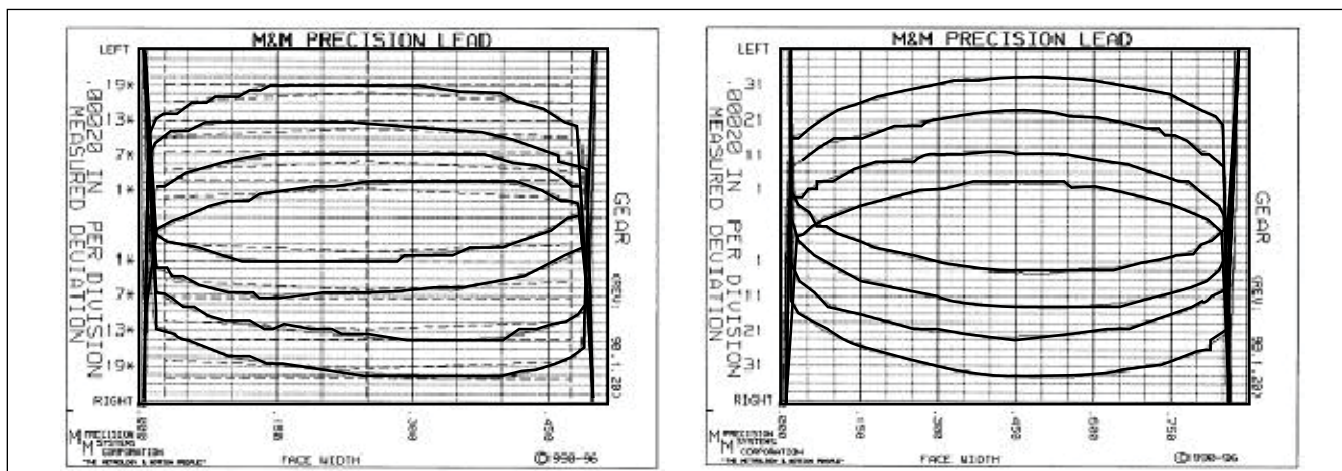


Figure 7—Lead charts: baseline gear (left) and mate gear (right).

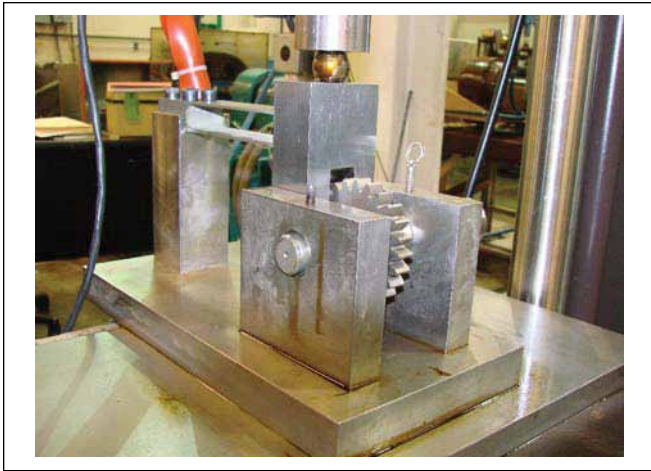


Figure 8—STF test fixture.

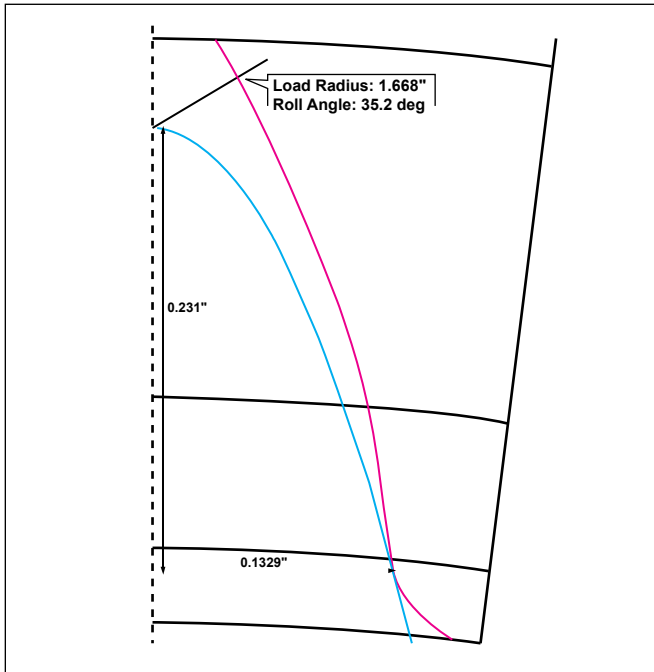


Figure 9—STF test loading details.

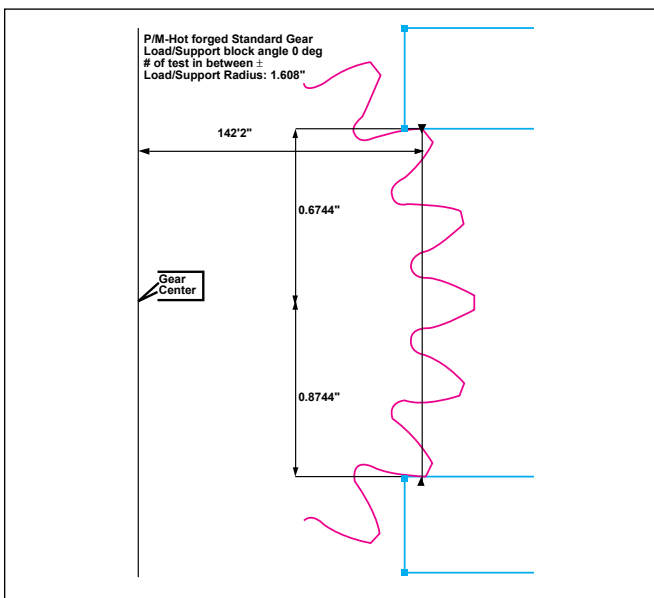


Figure 10—STF test layout.

ausformed P/M-steel gears.

The next step to ausform finish P/F-steel gears was to establish a 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 the 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. Figures 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 the right flank of gear teeth to be less than  $\pm 0.0001$ " 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. The die tooth profile requires further development to optimize the profile accuracy on the left flanks, which show a localized hollow of 0.0003".

Lead charts shown in Figure 5 also demonstrate the ability of the ausforming process to produce uniform tooth surfaces with very fine surface finish. Ausform-finished P/F-steel gears show a characteristic lead crown—a straight region in the middle with edges rounding that falls off by over 0.001"—that is inherently produced as a result of the induction heating and roll finishing process characteristics. As a result, the effective contact of test gears was reduced to an effective face width of about 0.37", requiring the power circulating test conditions to be adjusted as described later to achieve equivalent contact stresses for ausform-finished P/F-steel gears, as compared to the baseline wrought steel gears.

Ausform finishing of P/F-steel gears resulted in additional densification in surface layers.

The densification effect due to ausforming of P/F-steel gears was determined by weight measurements in air and water of sections cut from pre-ausform and ausform P/F test gears. Pre-ausform P/F gears, which were already nearly fully dense, were measured to have an average density of 7.81 g/cc, and subsequent ausform finishing of P/F-steel gears resulted in an average density (of a sector of gear) of 7.83 g/cc. The densification due to ausform finishing is localized in the surface layers of the P/F-steel gear teeth.

After ausform finishing, post processing operations included final tempering operation, deburring and machining of bore and end faces to facilitate surface durability testing.

**Baseline and mate gears.** Mate wrought steel gears required for power circulating surface durability tests, as

well as baseline wrought steel test gears required for comparative performance evaluation, were produced by New Process Gear, Syracuse NY, using a process sequence as described in Table 3 and to heat treatment specifications as described above. Figures 6 and 7 show profile and lead charts for baseline and mate gears.

### Gear Performance Testing

Gears can fail due to bending fatigue, surface distress due to subsurface shear-induced pitting fatigue, wear, surface and/or subsurface pitting fatigue due to and initiating at intermetallic inclusions, scoring of tooth surfaces due to breakdown of lubrication film and fracture due to impact loading conditions (Ref. 37). Test results to establish the comparative performance of ausform-finished P/F-steel gears are presented in the following sections.

**Tooth bending fatigue testing.** Single-tooth fatigue (STF) testing of individual gear teeth has been used widely to generate accelerated bending fatigue data at comparatively high cycles without risk of losing tests to other modes of failure. STF testing of ausform-finished P/F-steel gears and baseline wrought steel gears was carried out on a 5 kip servohydraulic universal fatigue testing machine utilizing a specially designed test fixture to hold the test gear and to facilitate fatigue loading via a flexure arm. The STF test fixture is shown in Figure 8.

Figure 9 shows the loading geometry for the test gears, showing the location of cyclic test load at 1.668" radius (35.2° roll angle), as well as the width and height of the critical section in the root fillet region determined by the Lewis parabola. Two teeth were tested simultaneously by applying cyclic load at the above radius (Fig. 10) until runout (defined as no failure after seven million cycles) or when one of the teeth failed—known in statistical analysis as a “sudden death test.” Sudden death fatigue tests are widely used in the bearing industry wherein several bearings are tested simultaneously until one bearing fails, then all bearings are replaced. Statistical analysis of sudden death fatigue tests takes advantage of improved statistical confidence due to the other parts not having failed yet. In this case of one of two teeth failing, ranking theory determined that the lowest value, in a set of two, clustered about a median location of  $B_{29,29}$  point of the population. Also, as both test teeth were loaded in a similar manner, a test that ran out counted as two data points. The STF test machine was programmed to automatically shut down after a preselected increase in tooth deflection of 0.005" to ensure a consistent end of the test for valid comparison between various test gear lots.

STF tests are conducted at 3–4 load levels determined based on preliminary set-up tests. Several tests are conducted at each load level for replication and to establish the endurance limit. A modified staircase sequence technique was used to determine the fatigue endurance limit at seven million cycles. Load levels and number of tests were selected to achieve several failures at the highest loads, several runouts at the lowest loads and a combination of failures and runouts

at the intermediate loads. STF test results for the three lots of test gears are shown in Figure 11, plotted as maximum bending stress as a function of cycles-to-failures. Numbers on the right side indicate data points of tests that ran out after seven million cycles. As seen in Figure 11, wrought steel gears performed the best showing in maximum bending fatigue strength, with ausform-finished P/F-steel gears showing performance close to wrought steel gears.

Statistical analysis of STF test data was carried out using normal probability techniques to determine the load corresponding to 50% failure at 7 million cycles, or mean runout load (MROL) for the three lots of gears, which represents the 50% endurance strength at the runout life of seven million cycles. Based on limited tests that were carried out, 50% was chosen for improved confidence. The MROL for baseline wrought steel gears was determined to be about 3,780 lbs., corresponding to a maximum bending stress of 179.8 ksi. Ausform-finished P/F-steel gears demonstrated an MROL of about 3,250 lbs., corresponding to a maximum bending stress of 154.6 ksi. Baseline wrought steel gears demonstrated about 14% higher MROL, as compared to ausform-finished P/F-steel gears.

It is to be noted that baseline wrought steel gears had been shot peened after heat treatment, which would explain the higher bending fatigue performance. Ausform-finished P/F gears were not subjected to shot peening, due to programmatic constraints. It is anticipated that the bending fatigue strength of ausform-finished P/F-steel gears would have improved further if subjected to shot peening after ausform finishing.

**Impact resistance testing.** Off-road vehicle gears may be subjected to substantial impact loads due to uneven and rough terrains. Characterization of gear tooth impact resistance was carried out to evaluate ausform-finished P/F-steel gears, and the effect of inherent porosity, although substantially surface-densified, as compared to baseline wrought **continued**

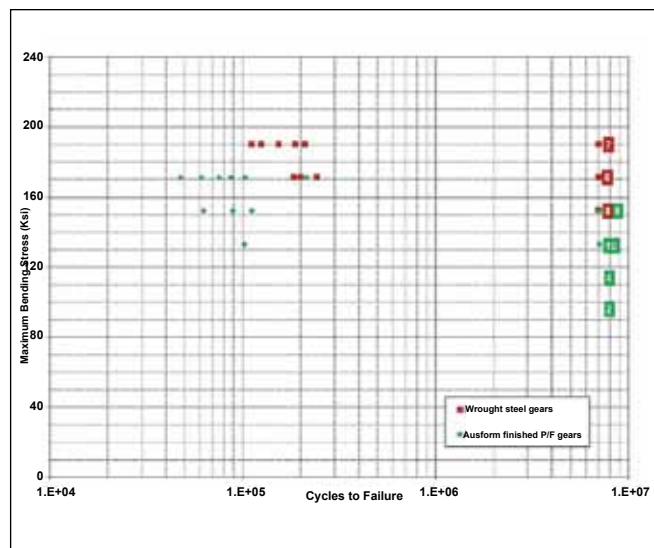


Figure 11—STF test results: maximum bending stress versus life.



Figure 12—Tooth impact test machine.

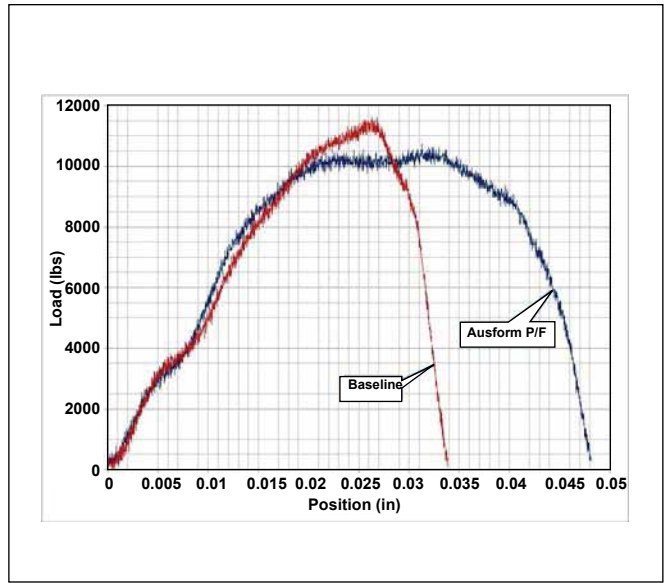


Figure 13—Impact load versus traverse (10" drop height).

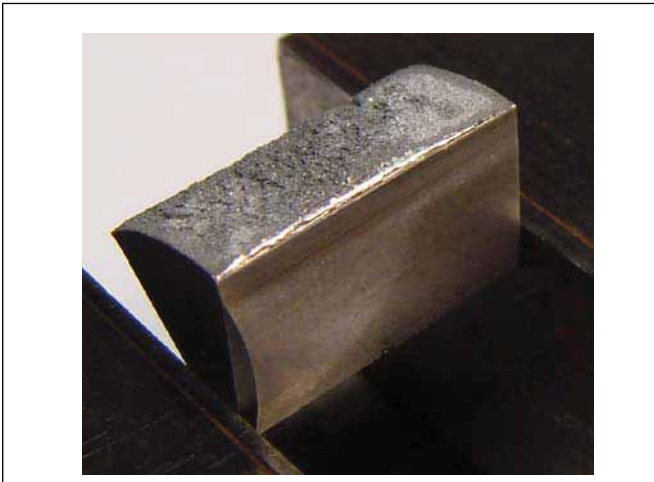


Figure 14 (a)—Wrought steel gear tooth impact fracture surface.



Figure 14 (b)—Ausform-finished P/F gear tooth impact fracture surface.

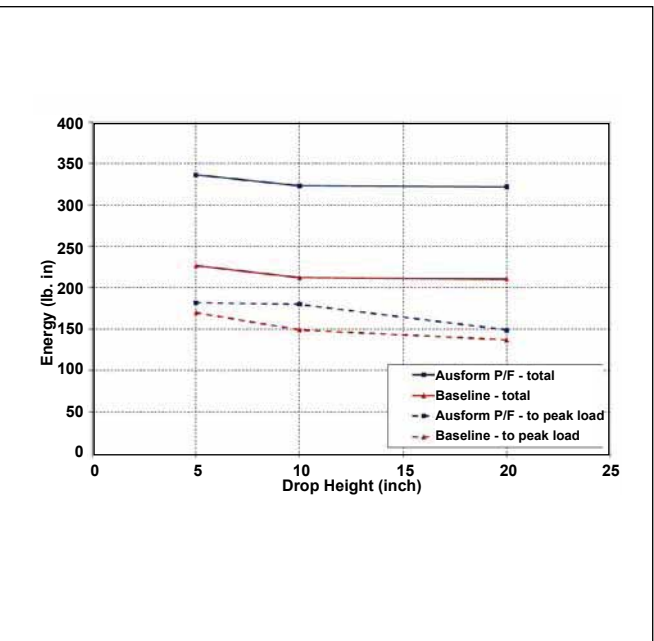


Figure 15—Impact energy versus drop height.

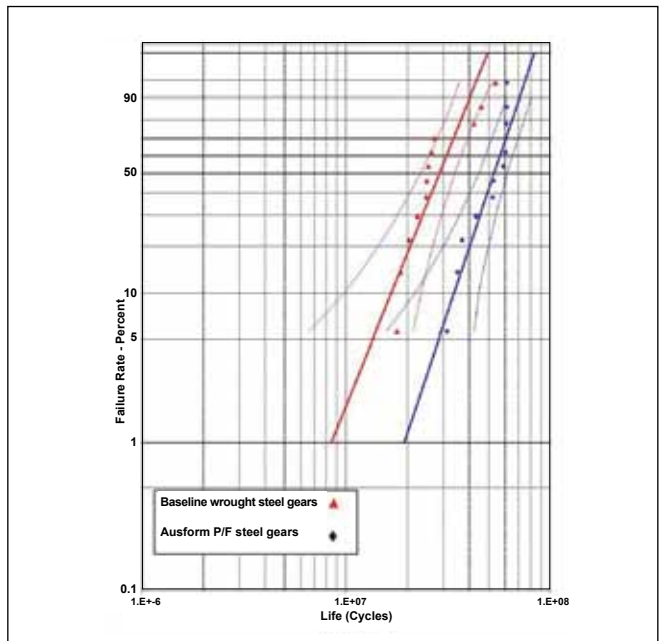


Figure 16—Pitting fatigue comparison.

steel gears. Gear tooth impact testing was carried out on a drop weight gear tooth impact testing machine (Fig. 12), wherein a target weight block is dropped from a preset height on a candidate gear tooth being tested. The machine is instrumented to record the instantaneous load generated and traverse during tooth impact fracture as a function of time.

The fixture designed to hold the test gears during impact test is similar to the STF test fixture shown in Figure 8, and impact loading of the upper tooth occurs at the same location as the STF loading shown in Figure 9. The main difference is that the in-line reaction support contacts close to the root fillet region, thus, causing only the upper test tooth to fail during the impact test. The test layout used for tooth impact testing is therefore similar to Figure 10, with the difference being that the reaction tooth is three teeth away from the upper-tested tooth. The tooth adjacent to the reaction support tooth was removed by EDM process to facilitate mounting of the gear on to the impact test fixture.

The gear tooth impact test procedure involved dropping the 138-lb. drop weight onto the test tooth from various drop heights representing increasing strain rates. The load cell output of reaction load generated as a function of time (in microseconds) was recorded during each tooth impact test. The recorded data was analyzed for each time step recorded, and the traverse of the drop weight was calculated based on initial velocity at impact and deceleration due to the tooth impact calculated from the measured instantaneous load. A plot of load versus traverse was thus generated based on the measured load data, and a representative chart for a 10" drop height is shown in Figure 13 for wrought steel gear tooth and ausform-finished P/F gear teeth. The area under the impact load versus traverse curve represents the energy absorbed during the gear tooth impact test (Ref. 38). As seen in Figure 13—although the peak impact load for the wrought steel gear tooth is slightly higher (on an average by about 5%)—the total impact energy absorbed by the ausform-finished P/F gear is substantially higher.

Figure 14 shows a typical impact fracture surface for the two types of gears tested. The wrought steel gear tooth impact fracture surface (Fig. 14a) shows a typical brittle fracture morphology, whereas the ausform-finished P/F gear tooth impact surface (Fig. 14b) indicates a combination of brittle/ductile fracture morphology that has resulted in increased impact energy absorbed.

Figure 15 summarizes the tooth impact test data for the two groups of test gears tested using drop heights of 5", 10" and 20" respectively, to evaluate effects at three strain rates. At least three tests were conducted at each drop height, and Figure 15 shows the average absorbed impact energy for respective groups of test gear teeth at various drop heights. As seen in Figure 15, the impact resistance of ausform-finished P/F-steel gears is substantially higher than baseline wrought steel gears.

*Pitting fatigue testing.* In a recent paper, surface durability testing details and comparative performance results were

presented for baseline wrought steel gears and ausform-finished P/F-steel gears (Ref. 39). A brief summary of testing methodology and results are presented here for easy reference. Power circulating (PC) gear testing machines with a 4" center distance were used to conduct accelerated gear surface durability tests to evaluate pitting and wear resistance. A standard break-in procedure was used by testing for 30 minutes at 50% load and lubricant at 80°F, prior to applying full-load test conditions.

Failure criteria used for the PC surface durability tests were either pitting of up to 5% tooth surface area on one tooth, smaller pits totaling slightly greater area, wear of tooth surface defined as loss of profile by over 0.001", progressive scoring or excessive vibration. Failure was determined by automatic shut-down due to various sensors and/or by visual examination. Runout for pitting fatigue testing was defined as 60 million cycles without failure (about 556 hours of 24/7 testing). Contact stress calculations for the pitting fatigue test program were based on the crowned gear procedure as delineated in cited Reference 37. In addition, the modulus of elasticity used for calculating the contact stress for baseline steel gears was  $30e^6$  psi and that for the P/F-steel gears was assumed to be  $29e^6$  psi.

Pitting fatigue tests were conducted to compare the pitting fatigue behavior of ausform-finished P/F-steel gears (12 tests) and baseline wrought steel gears (12 tests). Most of the tests were conducted at a maximum contact stress of 304 ksi. All tested gears were inspected for profile checks before and after testing, and in some cases, during testing. No measurable wear was observed in either the ausform-finished P/F-steel gears or the baseline wrought steel gears. Figure 16 shows the Weibull analysis plot comparing the performance of the two groups of gears, along with the respective 5% and 95% confidence bands. For the Weibull analysis, the two tests carried out at a contact stress of 320 ksi were transposed to estimated life if tested at 304 ksi using a power law relationship (power of 9.0 used for the transposition). As seen in Figure 16, the estimated G-50 life for the ausform-finished P/F-steel gears was 53.1 million cycles, as compared to 28.6 million for the baseline wrought steel gears. Ausform-finished P/F-steel gears demonstrated about an 85% increase in G-50 life compared to the baseline wrought steel gears, and they showed that ausform finishing of P/F-steel gears produced a combination of enhanced strength, gear accuracy and surface finish that resulted in pitting fatigue performance substantially superior to current wrought steel gears.

*Scoring resistance test results.* Scoring occurs due to breakdown of lubrication that protects the two mating surfaces of meshing gears and is caused by an adverse combination of test torque, rotational speed and tooth meshing characteristics with mating gears, surface finish, lubricant properties and operating temperature. A PC surface durability testing machine operating at 2,600 rpm, and with capability

**continued**



**Table 4—Scoring Test Results**

	#	Gear ID	Torque, lb in	Scored at, °F
Ausformed	1	2037	2000 2200 2400	>300 >300 >300
	2	2028	2000 2200 2400	>300 >300 >300
	3	2044	2000	300
	4	2038	2000 2200 2400	>300 >300 >300
Baseline	1	B-6	2000	260
	2	B-7	2000	260
	3	B-8	2000	270
	4	B-9	2000	270

ity of oil jet lubrication, was used for the scoring resistance test. After the initial break-in procedure similar to that described for pitting fatigue tests, scoring tests were initiated at a locked-in torque of 2,000 lb. in and at a rotational speed of 2,600 rpm. Oil inlet temperature at the beginning of the test was about 100°F.

With the torque and speed maintained at the same level, oil inlet temperature was increased progressively in steps of 10°F, with the test running for 10 minutes. If no scoring was detected during that time—as monitored by oil outlet temperature and/or vibration sensors—then the oil inlet temperature was increased to the next level. The test procedure was repeated up to oil inlet temperature of 300°F, unless scoring was detected. The highest oil inlet temperature permitted without onset of scoring was used as a measure of scoring resistance of the test gear, with a higher scoring temperature representing better performance. If no scoring resulted at up to 300°F, then the torque was increased to 2,200 lb. in, and the scoring test repeated as described above. If no scoring occurred even at 2,200 lb. in torque, then the test was repeated at a torque of 2,400 lb. in—the highest torque permissible without fear of causing other modes of failure.

Table 4 summarizes scoring resistance test results for the three groups of test gears (Ref. 39). The scoring temperature for ausform-finished P/F-steel gears was 300°F—i.e., higher than 260-270°F for baseline wrought steel gears. Scoring tests demonstrated that the scoring resistance of ausform-finished P/F-steel gears was superior to the baseline wrought steel gears.


### Summary and Conclusions

Performance of ausform-finished P/F-steel gears has been demonstrated to be comparable to or better than wrought steel gears in comparative bending fatigue and surface durability tests. In particular:

- Tooth bending fatigue strength of ausform-finished P/F-steel gears was comparable to shot peened baseline wrought steel gears.

- Impact resistance of ausform-finished P/F-steel gears was equivalent to or slightly better than baseline wrought steel gears.

- Pitting fatigue behavior of ausform-finished P/F-steel gears was substantially superior to baseline wrought steel gears produced by conventional processing techniques, with about 85% higher G-50 life at 304 ksi, as compared to wrought steel gears.

- Scoring resistance of ausform-finished P/F-steel gears was demonstrated to be superior to baseline wrought steel gears produced by current conventional processing techniques. 

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### References

1. *Powder Metallurgy Design Manual*, 2nd ed., Metal Powder Industries Federation, 1995.
2. Esper, F.J. and C. M. Sonsino. *Fatigue Design of PM Components*, European Powder Metallurgy Association, 1994.
3. Breur, D. J. “Utilization of Powder Metal and Shot Peening Residual Stresses to Maximize Cost and Performance Benefit of Highly Loaded Gearing,” *Gear Technology*, Nov/Dec 2005.
4. Lawcock, R., K. Buckley-Golder and D. Sarafinchan. “Testing of High- Endurance PM Steels for Automotive Transmission Gearing Components,” SAE Technical Paper 1999-01-0293, 1999.
5. Jones, P., K. Buckley-Golder, R. Lawcock and R. Shivanath. “Densification Strategies for High Endurance P/M Components,” *International Journal of Powder Metallurgy*, Volume 33, No. 3, 1997, pp. 37–44.
6. Lawcock, R. “Rolling Contact Fatigue of Surface Densified Gears,” *Advances in Powder Metallurgy & Particulate Materials*, 2005, Part 10, pp. 72–89.
7. Mandel, J., G. Draxler and T. Geiman. “Evaluation of Scuffing Resistance of Powder Metal Gears in the FZG Back-to-Back Test Rig,” *Advances in Powder Metallurgy & Particulate Materials*, 2005, Part 11, pp. 43–57.
8. Sonsino, C.M. and K. Lipp. “Rolling Contact Fatigue Properties of Selected PM Materials for Gear Box Applications,” SAE Technical Paper 1999-01-0333, 1999.
9. Hoffmann, G., C. Sonsino and K. Michaelis. “Rolling Contact Fatigue—Component Design and Testing for P/M Applications,” SAE Technical Paper 1999-01-0332, 1999.
10. Yoshida, A., Y. Ohue and I. Karasuno. “Comparison of Surface Durability and Dynamic Performance of Powder Metal and Steel Gears,” *Gear Technology*, September-

October, 1995, pp. 18–23.

11. Freidhoff, T. G., J.R. Spirko, M.R. Delozier and H.I. Sanderow. "Surface Fatigue of P/M Iron-Nickel Steel," *Proceedings of MPIF PM2TEC'96*, Washington D.C., 1996.

12. Cadle, T., C. Landgraf, P. Brewin and P. Nurthen. "Rolling Contact Fatigue Resistance of P/M Steels—Effects of Sintering Temperature and Material Density—1991," *Advances in Powder Metallurgy and Particulate Materials*, MPIF, 1991, pp. 175–182.

13. Prucher, T. and H. Sanderow. "Surface Fatigue of P/M Alloys," *Advances in Powder Metallurgy and Particulate Materials—1994*, Vol. 2, MPIF, 1994, pp. 99–111.

14. Mars, O., O. Jacobson, B. Axelsson, C. Kuyenstierna, F. Klocke, R. Strehl and C. Escher. "Contact Fatigue Properties of Some Low Alloyed Sintered Steels," presented at Euro PM'95, Birmingham, England, Oct., 1995.

15. Hoffmann, G. and W. Jandeska. "Effects on Rolling Contact Fatigue Performance," *Gear Technology*, Jan/Feb 2007.

16. Hoffmann, G. and W. Jandeska. "Effects on Rolling Contact Fatigue Performance –Part II," *Gear Technology*, Mar/Apr 2007.

17. Queeney, R.A., S.T. Kuplen, M.F. Amateau and N. Sonti. "Mechanical Response of Surface-Ausrolled Sintered Steel," *Advances in Powder Metallurgy—1991*, Vol. 3, pp. 159–170.

18. Kuplen, S.T., M.F. Amateau, N. Sonti and R.A. Queeney. "Ausrolling Sintered Steels for Bearing Elements," *Advances in Powder Metallurgy—1992*, Vol. 2, pp. 355–363.

19. Sonti, N., J. Puskar and R.A. Queeney. "A Case Study in Ausformed Helical Pinion Gear," *Advances in Powder Metallurgy—1996*, Vol. 4, pp. 451–461.

20. Puskar, J., G.L. Stoudt and R.A. Queeney. "Microstructure and Mechanical Response of Ausformed Steel Surfaces," *Advances in Powder Metallurgy—1996*, Vol. 4, pp. 491–500.

21. Lips, E.M.H. and H. Van Zulien. "Improved Hardening Techniques," *Metal Progress*, 10/1954.

22. Schmatz, D.J. and V.F. Zackay. "Mechanical Properties of Deformed Metastable Austenitic Ultra High Strength Steels," *Transactions ASM*, 1959.

23. Zackay, V.F., M.W. Justosson and D.J. Schmatz. "Strengthening Mechanisms in Solids," 1960.

24. Kula, E.B. and J.M. Dhoshi. "Effect of Deformation Prior to Transformation on the Mechanical Properties of 4349 Steel," *Transactions ASM*, 1960.

25. Thomas, G., D.J. Schmatz and W. Gerberich. "Structure and Strength of Some Ausformed Steels," *High-Strength Materials*, ed. V.F. Zackay, John Wiley & Sons, 1964.

26. Bamberger, E.N., "The Effect of Ausforming on the Rolling Contact Fatigue of a Typical Bearing Steel," *Transactions ASME, Journal of Lub. Tech.*, 1/1967.

27. Bamberger, E.N., "The Production, Testing and Evaluation of Ausformed Ball Bearings," U.S. Navy Contract NoW-65-0070-f, 6/1966.

28. U.S. Patent 6,779,270 dated 2004.

29. U.S. Patent 6,264,768 dated 2002.

30. U.S. Patent 6,126,892 dated 2000.

31. U.S. Patent 6,007,762 dated 1999.

32. U.S. Patent 5,799,398 dated 1997.

33. U.S. Patent 5,656,106 dated 1997.

34. U.S. Patent 5,451,275 dated 1995.

35. U.S. Patent 5,391,862 dated 1995.

36. U.S. Patent 5,221,513 dated 1993.

37. Rao, S.B. and D.R. McPherson, D.R. "Mechanical Testing of Gears," *ASM Handbook*, Vol. 8, 2000.

38. Isaacson, A., "A Strain Rate Sensitivity Investigation of Aerospace Steel Gear Teeth via Instrumented Impact Testing," M.S. Thesis, Pennsylvania State University, May 2009.

39. Sonti, N., S. Rao and G. Anderson. "Surface Durability of Ausform Finished P/M Gears," MPIF/APMI Powder Metal Conference, 2009.

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