

US Army TARDEC Project

**High Strength P/M Gears for Vehicle Transmissions
Phase I**

Phase I Final Report

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High Strength P/M Gears for Vehicle Transmissions

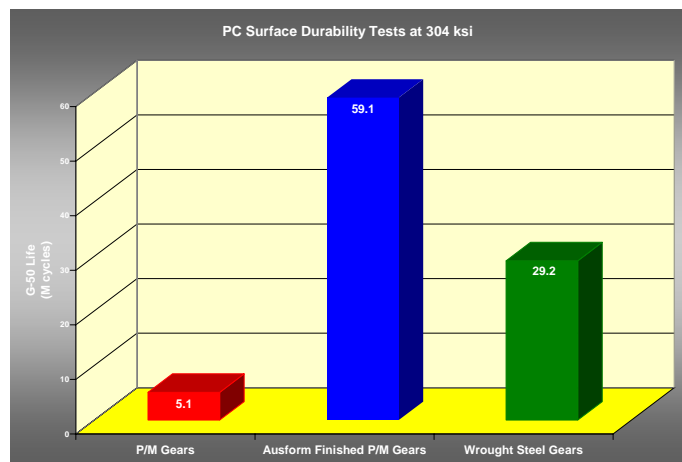
Executive Summary

Program Overview

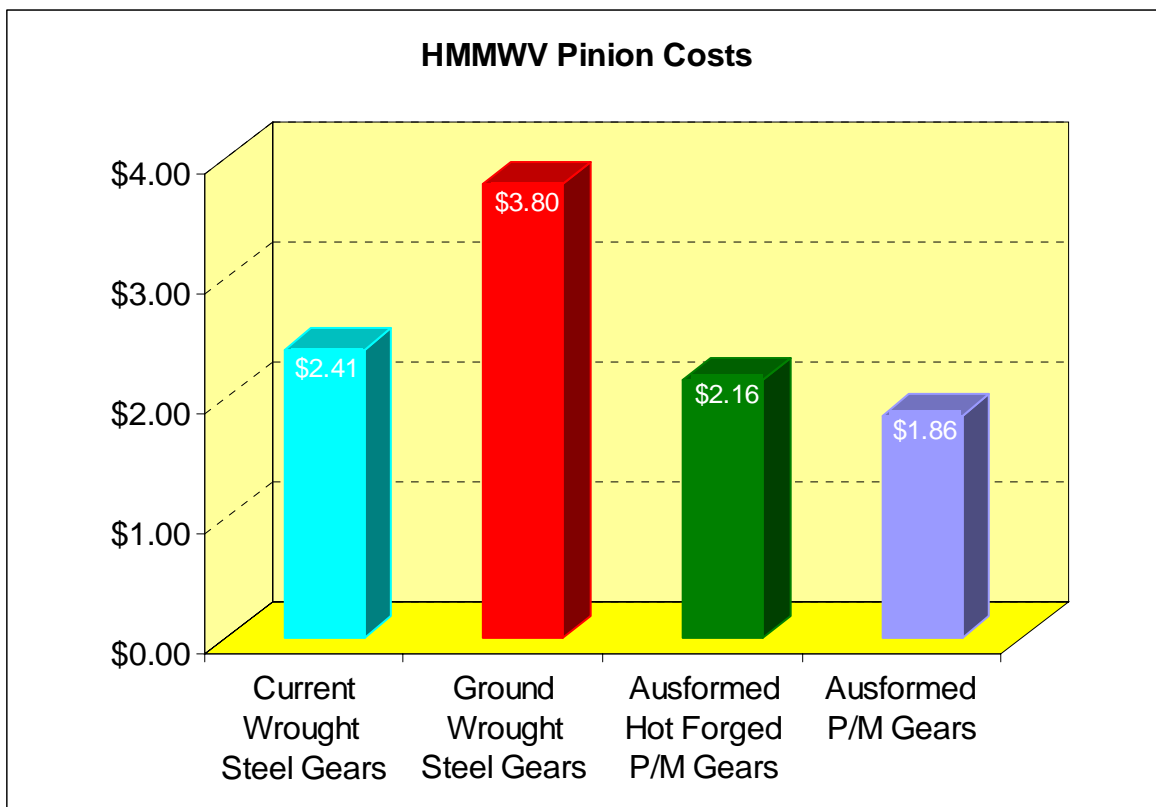
Phase I of US Army / TARDEC sponsored project entitled *High Strength P/M Gears for Vehicle Transmissions* has been successfully completed at ARL Penn State. The primary objective of the project was to develop high strength P/M steel gears with bending strength and surface durability performance equivalent to current wrought steel gears, and to demonstrate potential for significant cost savings. The project technical approach was to apply ausform gear finishing to P/M steel gears in order to increase the bending strength, and more importantly the surface durability of P/M gears, thereby making ausform finished P/M gears the preferred components for US Army / DoD ground vehicle transmissions. In the just completed Phase I of the project, ausform processing technology was developed and applied to hot forged P/M gears produced by Keystone Powdered Metal Company, selected as the prime industrial partner for the program. Performance of ausform finished P/M forged steel gears was demonstrated to be comparable to or better than wrought steel gears in comparative bending fatigue, surface durability and gear tooth impact tests. Cost of producing high strength P/M steel gears produced by processing techniques developed in this program is about 43% lower than for wrought steel gears of equivalent quality.

Major Project Accomplishments

- Ausform finishing technology was developed for hot forged P/M standard test rig gears, and processing specifications were established for two P/M steel formulations namely P/M forged 4620 carburized/hardened steel and P/M forged 4680 steel. Process specification included the design and prior processing methodology for preausform hot forged P/M gears, as well as tooling and process needed to ausform finish P/M gears to specified accuracy and metallurgical characteristics.
- G-50 pitting fatigue life of ausform finished P/M 4620 C/H steel hot forged and ausform finished (P/M-4620-HF-Ausf) gears was determined to be over 100% higher than wrought steel gears produced by current conventional processing techniques.
- Bending fatigue strength of ausform finished P/M-4620-HF-Ausf gears was demonstrated to be comparable to wrought steel gears produced by current conventional processing techniques.



- Scoring resistance of P/M-4620-HF-Ausf gears was superior to wrought steel gears produced by current conventional processing techniques. Four out of four wrought steel gears scored at oil temperature of 260-270°F, as compared to only one out of ten P/M-HF-AF gears that scored at a higher temperature of 300°F
- Tooth impact fracture energy of P/M-4620-HF-Ausf gears ranged from 40 to 52 N.m at various strain rates, as compared to 39 to 44 N.m for wrought steel gears produced by current conventional processing techniques.
- Based on detailed cost analysis, P/M-4620-HF-Ausf gears are estimated to cost about 43% lower as compared to current wrought steel gears of equivalent quality.
- P/M ausform finishing technology was also developed for HMMWV planetary helical pinion selected as the candidate focus gear for the program. Process specification included design and prior processing methodology for preausform hot forged P/M focus gears, as well as tooling and process needed to ausform finish P/M focus gears to specified accuracy and metallurgical characteristics.



High Strength P/M Gears for Vehicle Transmissions

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High Strength P/M Gears for Vehicle Transmissions

1. Introduction

Powder metal (P/M) process is making inroads in vehicle transmission applications because of substantially lower cost of P/M steel components for high volume production as compared to wrought or forged steel parts. [1, 2] P/M gears are increasingly being used in powered hand tools, gear pumps, and as accessory components in automotive transmissions. However, P/M steel gears are not used currently for power transmission applications due to performance limitations. [2] Recent advances in P/M technology and formulations have resulted in increase in bending strength of P/M steel gears to be comparable to current automotive wrought steel gears. [3-5] However, surface durability of P/M components is still inadequate in terms of pitting fatigue, scoring, and wear resistance, and therefore applications in vehicle power transmissions have been limited only to minimally loaded components. [6-16]

Ausform gear finishing process developed at ARL Penn State University has potential to substantially increase the surface durability of P/M steel gears. [17-20] In this US Army / TARDEC sponsored project, ausform finishing was evaluated as a means to achieve the goal to enhance performance of P/M steel gears to be equivalent to wrought steel gears. Ausform gear finishing involves contoured induction heating of case hardened gear teeth followed by marquenching at about 400-500°F, or above the martensite transformation start (M_s) temperature. The gear teeth in this marquenching condition are roll finished, and then cooled to transform back to martensite. Ausform gear finishing results in increased strength at the tooth surface combined with fine surface finish of 4 to 6 $\mu\text{in Ra}$, thus enabling improved surface durability performance.

US Army / TARDEC sponsored project entitled *High Strength P/M Gears for Vehicle Transmissions* was carried out at ARL Penn State to develop high strength P/M steel gears with bending strength and surface durability equivalent to current wrought steel gears, and to demonstrate potential for significant cost savings. This report describes in detail the program tasks that were performed including tooling and process development, comparative performance testing of baseline wrought steel gears and ausform finished P/M steel gears in terms of bending fatigue strength, power circulating surface durability and scoring resistance tests, and gear tooth impact tests. The report also summarizes the methodology and results of a detailed cost analysis for evaluating the potential cost reductions by using ausform finished P/M gears as compared to current wrought steel gears.

2. Objectives

The primary objective of the US Army / TARDEC sponsored project was to enhance the strength and durability of P/M steel gears to be equivalent to current wrought steel gears, thus making P/M gears the preferred components for vehicle transmissions. Tooling and processing techniques were developed to produce ausform finished P/M hot forged steel gears, and strength and durability of high strength P/M vehicle gears were demonstrated to be equivalent to current wrought steel gears. Additionally, a detailed processing time and cost model was developed, and

significant cost advantage of high strength P/M steel gears over wrought steel gears was demonstrated.

3. Program Technical Team

ARL Penn State teamed with Keystone Powdered Metal Company of St. Mary's, Pennsylvania, to develop P/M processing technology capable of producing high strength P/M gears for vehicle applications with bending strength and surface durability equivalent to wrought steel gears. The technical approach selected was to utilize Keystone's patented hot forging technique for producing nearly full density P/M steel gears, and to apply Penn State's patented ausform gear finishing process to the hot forged and case hardened P/M gears in order to achieve the high surface strength, dimensional accuracy and fine surface finish. It was anticipated that application of ausform finishing to hot forged P/M steel gears would result in enhanced surface durability performance, and in concert with demonstrated bending strength of Keystone's hot forged P/M gears, the program objectives were achievable. Keystone was contracted to develop the tooling and processing capability to produce preausform P/M standard gears, to develop the tooling required for ausform finishing of P/M standard gears, and to produce preausform focus pinions.

An additional goal of the project was to demonstrate the high strength P/M gear processing technology in an industrial environment, and on a candidate focus gear that was currently used in vehicle transmissions and produced in large quantities. The planetary helical pinion from HMMWV transfer case produced by New Process Gear Company (NPG), a division of Magna International, was selected in this the program as the candidate focus gear for demonstration of the high strength P/M steel gear technology. A teaming arrangement with NPG was established for utilizing the focus gear design for the program and for OEM evaluation of P/M focus gears resulting after successful completion of the program. NPG's contribution to the development program included providing the focus gear design and processing details, and producing baseline and mate gears (see Figures 1 and 2, respectively) required for surface durability performance testing tasks described later in the report.

Both Keystone and NPG also provided detailed manufacturing process information that was required to develop the process cycle time and cost models.

4. Candidate Test Gears

In a prior program sponsored by the Center for Powder Metal Technology (CPMT) that was completed by ARL Penn State in 2002, gear tooth bending strength and surface durability of sixteen different P/M steel formulations and/or processing techniques (including Keystone's hot forging technique) were evaluated using Gear Research Institute's P/M Standard gear design (24 teeth, 8 DP, 20° pressure angle, 0.5" face width spur gear, shown in Figure 1). For the current development program, the same P/M standard gear design was selected as the candidate test gear for the task of tooling and process development as well as to demonstrate the enhanced strength and performance of high strength P/M steel gears. Utilizing the P/M standard gear design for these tasks resulted in significant program cost savings as some of the existing tooling at Keystone, as well as test capability previously established at ARL Penn State, could be

utilized. Furthermore, using P/M standard gear facilitated direct comparison of test data generated in the current program with the published CPMT test results.

In addition, the planetary helical pinion from HMMWV transfer case produced by NPG was selected as the candidate focus gear for the program. The focus gear (shown in Figure 3) is a 19 teeth, 16 TDP, 17.5° normal pressure angle, 1.4" face width, 19° right helical angle helical pinion with a straight bore of 0.713".

5. Phase I Program Tasks

Phase I program tasks are outlined as follows, and are described in various sections of this report.

Task 1: Develop Tooling and Process to Produce Preausform P/M Standard Gears

- Design and develop molds and hot forging dies to produce preausform P/M standard gears
- Establish process and produce preausform P/M 4620 carburized/hardened standard test gears
- Establish process and produce preausform P/M 4680 quench/tempered standard gears

Task 2: Develop Tooling and Process for Ausform Finishing of P/M Standard Gears

- Design and develop ausform finishing tooling for P/M standard gears including induction coils, roll finishing dies, work holding chucks, and other automation hardware
- Optimize ausform finishing process, and demonstrate metallurgical characteristics and dimensional accuracy of P/M 4620 carburized/hardened standard gears
- Optimize ausform finishing process, and demonstrate metallurgical characteristics and dimensional accuracy of P/M 4680 quenched/tempered standard gears
- Produce ausform finished P/M standard gears for performance evaluation

Task 3: Establish Performance Testing Capability

- Develop test plan for comparative performance evaluation
- Design and develop baseline wrought steel gears and mate gears for comparative performance evaluations
- Modify and assemble power circulating surface durability test equipment
- Modify and assemble test equipment for single tooth bending fatigue strength evaluation
- Design and develop test equipment for impact strength evaluation

Task 4: Conduct Comparative Gear Performance Testing

- Evaluate comparative tooth bending strength of ausform finished P/M standard gears and baseline wrought steel gears
- Evaluate comparative rotating surface durability (pitting and wear resistance) of ausform finished P/M standard gears and baseline wrought steel gears

- Evaluate comparative scoring resistance of ausform finished P/M standard gears and baseline wrought steel gears
 - Evaluate comparative tooth impact strength of ausform finished P/M standard gears and baseline wrought steel gears
- Task 6: Select “Focus” Gear for OEM Evaluation of Metallurgical and Dimensional Quality*
- Design and develop molds and hot forging dies to produce preausform P/M focus helical gears
 - Establish process and produce preausform P/M 4620 carburized/hardened focus helical gears
- Task 7: Develop Tooling and Process to Produce Preausform P/M Focus Helical Gears*
- Design and develop molds and hot forging dies to produce preausform P/M focus helical gears
 - Establish process and produce preausform P/M 4620 carburized/hardened focus helical gears
 - Establish process and produce preausform P/M 4680 quench/tempered focus helical gear
- Task 8: Develop Tooling and Process for Ausform Finishing of P/M Focus Helical Gears*
- Design and develop ausform finishing tooling for P/M focus helical gears including induction coils, roll finishing dies, work holding chucks, and other automation hardware
 - Optimize ausform finishing process, and demonstrate metallurgical characteristics and dimensional accuracy of P/M 4620 carburized/hardened focus helical gears
 - Optimize ausform finishing process, and demonstrate metallurgical characteristics and dimensional accuracy of P/M 4680 quenched/tempered focus helical gears
- Task 9: Produce Ausform Finished P/M Focus Helical Gears for OEM Evaluation*
- Task 10: Perform Cost/Benefit Analysis*
- Develop methodology for comparing processing time and cost of producing ausform finished P/M focus helical gears and baseline wrought steel gears
 - Establish comparative processing time and costs for baseline and ausform finished P/M focus helical gears
- Task 11: Develop Concepts for Prototype Production Ausform Gear Finishing Machine*

6. Process Description

6.1. Current Processing of Vehicle Gears

NPG utilizes wrought AISI-4023 low alloy carbon steel for producing HMMWV transfer case planetary helical pinions. Composition of AISI-4023 steel is shown in Table 1. NPG procures forged cylindrical blanks from several qualified vendors, and the forged blanks are then subjected to hobbing, shaving, heat treatment, shot peening, final machining and other related

operations. The entire processing sequence used by NPG to produce the planetary pinions is shown in Figure 4.

6.2 *Current Capability of P/M Steel Gear Technology*

Conventional P/M processes to produce steel gears involve pressing and sintering followed by case hardening heat treatment and related operations. However, such a processing sequence produces P/M steel components with final density of only about 7.0 gm/cc, as compared to near fully dense steel density of 7.8 gm/cc.[2] Conventional pressed and sintered P/M parts therefore possess large amount of porosity and hence inadequate mechanical properties as compared to wrought steel components. Recent advances in P/M processing have been focused to improve the finished component density in order to achieve improved mechanical properties. Examples of recent advances in P/M steel gear processing include double pressing and sintering, elevated temperature pressing and sintering, surface densification by rolling, and hot forging. Each of these P/M processing advances results in various degrees of porosity reduction and density improvements, with associated proportional increase in P/M component performance and costs. [4-16]

Prior research at ARL Penn State has demonstrated that although each of the above advanced P/M processing techniques enhances the mechanical properties to some degree, hot forging of P/M steel parts has the maximum potential to increase the bending strength of P/M gears. Furthermore, prior research at ARL Penn State has also demonstrated that in spite of enhanced mechanical strength achieved by the above advanced P/M processing techniques, surface durability of the P/M parts in terms of pitting, scoring and wear resistance is still inadequate for vehicle power transmission applications as compared to current wrought steel parts.

6.3 *Proposed Technical Approach*

The technical approach selected to achieve the program objectives was to utilize Keystone's patented hot forging technique for producing nearly full density P/M steel gears, and to apply Penn State's patented ausform gear finishing process to the hot forged and case hardened P/M gears in order to achieve the high surface strength, dimensional accuracy and fine surface finish. It was anticipated that utilizing P/M hot forging process will impart high bending strength to P/M steel vehicle gears. In order to then increase the surface durability performance in terms of pitting, scoring and wear resistance, the proposed approach was to ausform finish the surface layers of hot forged P/M steel gears, thus imparting fine surface finish and accuracy to gear tooth surfaces. Such an integration of P/M hot forging technology with ausform gear tooth finishing capability was expected to result in a combination of surface and subsurface characteristics that would in turn enhance strength and surface durability performance equivalent to current wrought steel gears. The P/M hot forging and ausform gear finishing processes are briefly described in the following sections.

6.3.1 Hot Forging of P/M Gears

Keystone's patented P/M hot forging process involves heating of pressed and sintered P/M steel gears to temperatures over 2000°F in an induction heating furnace, and then hot forging the gear blank to near full density of 7.8 gm/cc. The hot forging dies are designed to induce substantial axial reduction of the pressed and sintered P/M component combined with some radial expansion into the hot forging die cavity. The forged gear is then air cooled, followed by normalizing to produce a homogenous microstructure that is amenable to subsequent machining, case hardening and ausform gear finishing operations. Keystone's hot forging equipment has capability of in-line induction heating and forging of gears at high production speeds of several gears per minute, depending on gear size, and is equipped with automatic part loading, transfer and unloading hardware.

6.3.2 Ausform Finishing of Gears

Ausforming, a thermal-mechanical manufacturing process, is a modification to conventional heat treatment process applicable to medium to high alloyed carbon steels, and is capable of producing very high strength steels. [21] In conventional hardening heat treatment, a steel component is first heated to above the A_1 temperature to the austenitic phase, and then quenched to below the martensite start (M_s) temperature to produce martensite. In contrast, for ausforming a steel component, the quenching operation is interrupted at above the M_s temperature, and the part is plastically deformed in the metastable austenitic condition. The deformed austenite is then cooled to martensite. Figure 5 shows a schematic time-temperature-transformation diagram that describes the ausforming process. Requirements for any steel to be ausformable are presence of carbon about 0.3% or higher by weight, and presence of carbide forming elements such chromium, molybdenum, niobium and titanium.

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, as seen in Figure 6. [22-25] Over 600% increase in rolling contact fatigue of ausformed cylindrical M50 steel specimens was demonstrated as seen in Figure 7, and degree of B_{10} fatigue life improvement increasing with the amount of deformation, as shown in Figure 8. [26] Bamberger reported nine-fold increase in B_{10} life of ausformed M50 steel bearings over conventionally heat-treated bearings, as shown in Figure 9. [27]

ARL Penn State's efforts have been directed towards ausforming limited to localized surface layers of contacting machine elements such as gears. [28-36] Figure 10 shows a schematic description of the ausforming process as a gear tooth finishing operation for a typical carburized and hardened low alloy steel gear. The first step in the ausform gear finishing operation as indicated by line a-b in Figure 5 is the austenitization of the case hardened surface layers of the gear teeth by high powered dual frequency contour induction heating. The component is then rapidly quenched (line b-c) into a hot martempering oil maintained at a temperature at least 50-150°C (90-270°F) over the local M_s temperature. The outer surface layers of the gear teeth now comprise of metastable austenite, and the third step of ausform finishing

(line c-d) involves plastically deforming the outer surface layers of the gear teeth in the metastable austenitic condition using precision roll finishing tooling. The final step of the ausforming process (line d-e) is cooling to transform the deformed metastable austenite to martensite. A prototype double die ausform gear finishing developed at ARL Penn State is shown in Figure 11. Remaining post-processing operations after ausform finishing are tempering, and cryogenic treatment if necessary to control the retained austenite content.

Ausform finishing of spur and helical gears results in very fine surface finish of 4-6 μin Ra in both the radial and tangential tooth profile directions. Furthermore, finished gear tooth accuracy of less than 0.0002" in both the profile and lead inspections has been demonstrated. Fine surface finish and gear teeth accuracy have been shown to contribute significantly to improved surface fatigue performance. Finally 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 ideally suited for in line large production applications such as vehicle planetary gear manufacture.

6.3.3 Candidate P/M Steel Compositions & Processing Sequences

Table 1 shows the composition of 4620 steel, a carburizing grade formulation that is typically used commercially to manufacture P/M gears. This alloy was selected as the primary candidate P/M steel to evaluate hot forged, carburized/hardened and ausform finished gears for vehicle application. Figure 12 describes the manufacturing process sequence that was used to produce high strength P/M 4620 steel hot forged, carburized/hardened and ausform finished (P/M-4620-HF-Ausf) gears.

In addition, a high carbon 4680 alloy steel composition was also selected for the program. The high carbon P/M steel composition has the advantage that it eliminates the need for carburizing and related batch operations. Due to high carbon content, the steel is induction hardenable and is ideally suited for in line hot forging and ausform finishing. Although use of this alloy eliminates the need for carburizing, it does require additional operations such as quenching and tempering after hot forging to produce a homogenous microstructure that is amenable to machining as well as induction heating and ausform finishing. It also requires an additional induction hardening operation if the bore needs to be hardened. However, it was decided to evaluate the performance of 4680 steel composition as well, and Figure 13 shows the manufacturing process sequence used to produce high strength P/M 4680 steel hot forged, quench/tempered, and ausform finished (P/M-4680-HF-Ausf) gears.

7. Test Gear Manufacture

7.1 Preausform Hot Forged P/M Standard Gears

Figure 14 shows the design of the preausform P/M-4620-HF test gears, and the associated heat treat specifications are shown in Figure 15. Preausform P/M-4620-HF test gear design is identical to the baseline wrought steel gear design shown in Figure 1, except for two features. First, it incorporates a straight bore, used for accurate locating and holding of the gear during the subsequent ausform gear finishing operation, as compared to the splined bore featured for the

baseline gears required for the subsequent surface durability testing. Second, the tooth thickness of preausform gears are larger by about 0.003-0.004" which provides the rolling stock during the finishing operation by ausforming. Keystone produced the preausform P/M-4620-HF test gears using the processing steps shown in Figure 12 up to the 'Ausform Gear Teeth' operation. Keystone's processing of preausform P/M-4620-HF gears included pressing, sintering, hot forging, tumble cleaning, machining of end faces, outer diameter and the bore, carburizing and hardening, washing, tempering, and honing of bore. Ausform finishing and subsequent operations were carried out ARL Penn State as described in later sections.

Additionally, Keystone produced preausform P/M-4680-HF test gears, of the same geometric design as shown in Figure 14, in which the initial powder composition consisted of higher carbon content of about 0.8% by weight as shown in Table 1. Heat treat specifications associated with P/M-4680-HF-Ausf gears are shown in Figure 16. Keystone produced the preausform P/M-4680-HF test gears using the processing steps shown in Figure 13 up to the 'Ausform Gear Teeth' operation. Keystone's processing of preausform P/M-4680-HF gears included pressing, sintering, hot forging, tumble cleaning, re-austenitizing, quenching, washing and tempering to 34-36 HRC, and then machining of end faces, outer diameter and the bore, induction hardening of bore, degreasing and washing, and honing of bore. Ausform finishing and subsequent operations were carried out ARL Penn State as described in later sections. Quenching and tempering of P/M-4680-HF-Ausf gears after the hot forging operation was required to ensure a fine tempered martensitic structure that facilitated good machinability and more importantly, a homogenous microstructure that was amenable to efficient induction austenitization during the ausforming cycle.

Quality of preausform P/M-4620-HF gears and P/M-4680-HF-Ausf gears was evaluated in terms of metallurgical characteristics and geometric accuracy for conformance with the preausform gear specifications, and preausform test gears were determined to meet all metallurgical specifications.

Gear inspection was carried out on representative parts to document the tooth profile, lead and spacing accuracy of preausform test gears produced by Keystone. Figures 17 through 19 compare these tooth accuracy characteristics for preausform P/M-4620-HF and P/M-4680-HF test gears, and show that the preausform test gears meet the profile, lead and tooth spacing specifications. However, due to different material properties and therefore associated shrinkage and distortion aspects for the two materials, the hot forged and heat treated gear tooth size is significantly different for the two lots of gears in terms of outer diameter, tooth thickness and root diameters, as shown in Figure 20. These differences had a significant impact on the program in that the optimal roll finishing die geometry required for P/M-4680-HF-Ausf gears was substantially different as compared to P/M-4620-HF-Ausf gears, as described in later sections. Table 2 summarizes the difference in gear tooth dimensions of P/M-4620-HF-Ausf and P/M-4680-HF-Ausf gears, with nearly 0.010" variation in root diameters and tooth thickness measurements over pins of diameter 0.216".

7.2 *Preausform Hot Forged P/M Focus Gears*

Figure 3 shows the design of P/M focus gears required for the program to demonstrate the viability of high strength P/M steel gear manufacturing technology in a high volume production environment on a commercially produced gear. Keystone produced preausform P/M-4620-HF focus helical gears as well as preausform P/M-4680-HF focus helical gears, per above design and per associated heat treat specifications similar to as shown in Figures 15 and 16 respectively for P/M standard gears. Processing sequences used by Keystone for producing the P/M focus gears were also identical to as described in Figures 12 and 13 for P/M standard gears.

Quality of preausform P/M steel focus gears was evaluated in terms of metallurgical characteristics and geometric accuracy for conformance with the preausform gear specifications, and were determined to meet the specifications. Gear inspection was carried out on representative parts to document the tooth profile, lead and spacing accuracy of preausform focus gears produced by Keystone. Figures 21 through 23 compare these tooth accuracy characteristics for preausform P/M-4620-HF and P/M-4680-HF focus helical gears, and show that the preausform focus gears meet the profile, lead and tooth spacing specifications. Figure 24 shows the shape of preausform focus gear teeth determined by Zeiss CMM inspection. As indicated for P/M standard test gears, the final tooth size and shape of P/M-4620-HF-Ausf and P/M-4680-HF-Ausf focus helical gears was substantially different due to material response to prior processing.

7.3 *Baseline Wrought Steel Gears*

The primary objective of the program was to demonstrate bending fatigue strength and surface durability of P/M gears to be equivalent to baseline wrought steel gears. In order to meet this objective, baseline gears were produced for comparative performance evaluation using AISI-4023 steel which is the steel currently used by NPG to manufacture the HMMWV planetary helical Pinions (focus gears in this program). Furthermore, baseline wrought steel gears were produced using the manufacturing process sequence identical to that currently used by NPG, as shown in Figure 4. Finally, the baseline wrought steel gears were produced by NPG in their prototype gear shop in Syracuse, NY, thus ensuring valid comparison with current wrought steel processing procedures and equipment.

Quality of baseline wrought steel gears was evaluated in terms of metallurgical characteristics and geometric accuracy for conformance with the baseline gear specifications, and these were determined to meet all specifications. Gear inspection was carried out on representative parts to document the tooth profile, lead and spacing accuracy of preausform focus gears produced by Keystone. Figures 25 through 27 show these tooth accuracy characteristics for baseline test gears, and show that the baseline wrought steel test gears meet the profile, lead and tooth spacing specifications.

7.4 *Mate Gears for Surface Durability Testing*

Mate gears (40 teeth, 8 DP, 18.65° pressure angle, 1” face width spur gears) were required for power circulating surface durability and scoring resistance tests described in later sections. Mate gears, design shown in Figure 28, were made of wrought AISI-8620 steel using a

manufacturing process similar to that used for producing baseline gears, and as shown in Figure 29. 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. Mate gears were produced by NPG in their prototype gear shop in Syracuse, NY, thus ensuring valid comparison with current wrought steel processing procedures and equipment.

Quality of mate gears was evaluated in terms of metallurgical characteristics and geometric accuracy for conformance with specifications, and these were determined to meet all specifications. Gear inspection was carried out on representative parts to document the tooth profile, lead and spacing accuracy of preausform focus gears produced by Keystone. Figures 30 through 32 show these tooth accuracy characteristics for baseline test gears, and show that the mate gears meet the profile, lead and tooth spacing specifications.

8. Ausform Finishing of P/M Steel Gears

Ausform finishing of P/M gears involves several operations namely MF and RF induction heating to austenitize the case region, marquenching to metastable austenite, roll finishing to final dimensions, and final cooling for transformation back to martensite. The four ausform processing steps were carried out in an integrated prototype double die ausform gear finishing machine shown in Figure 11 capable of processing gears at a rate of about 2 gears per minute. After ausform finishing, post processing operations included tempering to reduce the brittleness and enhance the toughness of martensite, followed by deburring and machining of bore and end faces. Tooling required for ausform gear finishing includes MF and RF induction heating coils, roll finishing dies, work holding tooling for the induction heating station and the roll finishing station, and other automation related hardware specific to each gear. Following sections describe tooling and process development tasks carried out for optimal ausform finishing of P/M steel standard and focus gears.

8.1 Induction Heating Process Optimization for P/M Standard Gears

Of the four processing steps involved in ausform gear finishing, the most critical is induction heating operation carried out on previously case hardened preausform gears. Dual frequency MF and RF induction heating is used for contoured induction austenitization of gear teeth. The medium frequency MF induction heating preferentially heats the dedendum and root/fillet regions of gear teeth due to the characteristic eddy currents produced in that region of the gear. On the other hand, high radio frequency RF induction heating favors the outer tip regions of the gear teeth. An optimal combination of MF and RF heating is needed to achieve a contoured heating pattern, and the degree of specific MF and RF heating used depends primarily on the gear tooth sizes or diametral pitch of the gear.

MF and RF induction coils were developed for the P/M standard gear. Process optimization involved judicious selection of following settings:

- MF heating: Frequency, power, MF heating cycle time, rotational speed
- Transfer time From MF coil to RF coil
- RF heating Frequency, power, RF heating cycle time, rotational speed
- Transfer time From RF coil to ausform processing oil for marquenching

Iterative induction heating experiments were carried out on preausform P/M standard test gears and metallographic examination was used to verify desired final metallurgical characteristics such as surface and core hardness, hardness gradient and residual stress depth profile. Figures 33 and 34 show the microhardness profiles measured at mid-tooth and mid fillet, respectively, for P/M-4620-HF-Ausf and P/M-4680-HF-Ausf standard test gears that were induction heated to verify the metallurgical features and quality. As seen in Figures 33 and 34, the hardness specifications described earlier for the finished standard gears (Figure 15) were achieved for both P/M steel alloys.

A similar approach was used to optimize the induction heating process for P/M focus gears and Figure 35 and 36 show the mid tooth and fillet hardness profiles achieved in focus gears. Table 3 summarizes the induction heating process used to achieve the above results. For P/M focus gears, two optional induction heating processes were developed as shown in Table 3, first for dual frequency MF and RF induction heating, and the second for single frequency MF induction heating.

8.2 *Marquenching Process Development*

Marquenching process parameter to be selected is the ausform processing oil temperature, which is typically about 100 to 150°F above the M_s temperature of the candidate gear steel. Based on the alloying content of P/M 4620 C/H and 4680 steels used for the manufacture of the P/M standard and focus gears, M_s temperature for the candidate steel was determined to be about 300°F, and therefore a marquenching temperature of 425-430°F was used for the program.

8.3 *Die Tooth Profile Development for P/M Standard Gears*

Ausform gear finishing process utilizes gear roll finishing operation to finish the induction heated and marquenching gear teeth. Gear roll finishing is widely used as an alternative to gear shaving for prefinishing of automotive gears. Nachi Machining technology (previously known as National Broach and Machine Company), Macomb, MI, developed the rolling dies for the P/M standard and focus gears. In order to achieve the desired finished gear tooth accuracy, the required rolling die teeth profiles are typically modified from nominally involute tooth shape, and therefore must be optimized for any given test gear. Die tooth profile development involves grinding of die teeth to an initial estimation, usually a best guess based on past experience. For the current program to ausform finish P/M steel gears, the initial die tooth geometry was estimated based on process modeling as well as prior results from similarly sized test gears. Die tooth optimization involves implementing the estimated tooth profile geometry on the rolling by tooth grinding operation, followed by experimental iterative approach by rolling finishing a few test gears, measuring the errors on the drive and coast sides of the roll finished gear, and regrinding the rolling dies by compensating for the error on the corresponding rolling die teeth.

Die tooth profile development required two iterations of die regrinding to achieve the desired finished gear tooth accuracy for P/M-4620-HF-Ausf standard gears. Figures 37 and 38 show the developed die tooth profiles on the drive and coast sides of the rolling dies required for

ausform gear finishing of P/M standard gears. As seen in the Figures 37 and 38, the deviations from involute in the die profiles are in the range of $+0.001$ to -0.002 ", and also consist of varying curvatures in various regions of die teeth. Furthermore, the tip regions of the rolling die teeth required a radius of about 0.030 - 0.035 ", and the tip radii were implemented in a secondary grinding operation.

Figure 39 shows ausform finished gear tooth profiles on the drive side of P/M-4620-HF-Ausf gears, and show the profile accuracy of about ± 0.0002 " achieved across the contact region of the teeth. Furthermore, ausform finished tooth profiles in figure 39 also show the desired tip relief of about 0.001 " implemented by the rolling dies. The finished profile accuracy shown in figure 39 for the drive side meets specifications, and die optimization tasks will be continued in Phase II of the program to achieve the desired accuracy on the coast side as well. Based on the successful drive side accuracy results for ausform finished P/M-4620-HF-Ausf gears, several test gears were processed for subsequent performance testing tasks as described in later sections.

It is critical to meet accuracy specifications for test gears that are to be subjected to power circulating surface durability testing, described in later sections. However, for static tooth bending fatigue tests, similar level of tooth accuracy is not required. Therefore, although the die shape described in Figures 37 and 38 was not optimal for P/M-4680-HF-Ausf gears due to substantially different profile shape and gear tooth dimensions (as described in Table 2), a few P/M-4680-HF-Ausf gears were processed for subsequent tooth bending fatigue tests. Further die development effort for P/M steel gears however was abandoned due to time and funding constraints.

Figures 40 and 41 compare the lead and tooth spacing accuracy of ausform finished P/M-4620-HF-Ausf and P/M-4680-HF-Ausf gears, and show that the lead and tooth spacing accuracy specifications were achieved. Lead profiles in Figure 40 for ausform finished P/M steel gears also show a prominent lead crown that is inherently produced as a result of the induction heating and roll finishing operational characteristics. As a result, the effective contact width of the test gears is reduced, and the power circulating test conditions were adjusted as described later to achieve equivalent contact stresses for high strength P/M steel gears and baseline wrought steel gears.

Zeiss CMM inspection was carried for a representative ausform finished P/M-4620-HF-Ausf gear to evaluate the effectiveness of root roll finishing implemented by the tips of the rolling dies. Figure 42 show root fillet geometry of a representative ausform finished P/M-4620-HF-Ausf gear and shows successful root rolling implemented by the tips of the rolling dies profiles shown in figure 37 and 38.

The die development task for P/M focus gears could not be completed due to time and funding constraints. Because of the size of the focus gear and the ausform finishing machine constraints, the required diameter of the rolling dies was larger than previously estimated, and therefore required a new set of dies to be developed. The larger focus gear dies will be procured and developed during the second phase of the program as part of the process optimization tasks.

8.4 Metallurgical Features of Ausform Finished P/M Gears

Metallurgical quality of ausform finished P/M-4620-HF-Ausf steel and P/M-4680-HF-Ausf gears was verified in terms of surface, case and core hardness, and structures. Residual stresses were measured using x-ray diffraction technique, and figure 43 compares the measured compressive residual stress of about 30 ksi in test gears.

9. Performance Testing

An important objective of the project was to evaluate the fatigue performance of high strength P/M steel gears as compared to baseline wrought steel gears. The primary modes of gear failure are tooth fracture due to bending fatigue, surface distress due to subsurface shear induced pitting fatigue, surface 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. Gear performance testing therefore included tooth bending fatigue (STF) testing, power circulating rotating surface fatigue (RSF) testing for pitting and wear resistance evaluation, scoring resistance (SR) testing, and impact testing, of both high strength P/M steel gears and baseline wrought steel gears. [37] Testing details and results are described in the following sections for each of these tests.

9.1 STF Testing

STF test is used to generate a statistically significant quantity of gear bending fatigue data. Gear teeth are tested individually with test loads applied at a fixed radial location, in order to achieve only bending fatigue failure in the critical root/fillet region of gear teeth and to prevent failure via other mechanisms such as scoring, pitting, wear, etc. STF testing therefore allows generation of accelerated bending fatigue data at comparatively high cycles without risk of losing tests to other modes of failure. A gear is placed in a fixture such that load is applied at a defined location on one tooth while a different tooth nearby is used as a reaction tooth, thus facilitating a non-rotating test arrangement. Such a non-rotating test arrangement ensures minimal migration of load and reaction locations. Positive contact between the loading anvil and the test gear tooth is maintained throughout the test by selecting an R-value (ratio of minimum to maximum fatigue load) of 0.1. A test frequency of up to 50 Hz is selected depending on the test loads, tooth compliance and test machine constraints. The test is continued until tooth fracture occurs or until a run-out condition is reached, run-out defined for this test program as seven million cycles without a test tooth failure.

9.1.1 STF Test Machine and Fixture

STF testing was carried out on a servo-hydraulic 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 testing machine provides the platform for the STF test fixture that is mounted on the bottom platen of the fatigue testing machine, and the servo-hydraulic actuator mounted on the top platen applies the cyclic fatigue loading. The 5 kip fatigue testing machine shown in Figure 44 is instrumented with a load cell to monitor and control the cyclic loads, as well as with an extensometer to monitor the actuator traverse, and therefore tooth deflections. The fatigue

testing machine instrumentation is calibrated periodically to ensure accuracy of measurements. Test data collected include the maximum and minimum loads, the maximum and minimum actuator positions (or tooth deflections), and cycles to tooth failure by fracture in the critical section of tooth. Programmed operation of the fatigue testing machine ensures automatic shut down of the test upon overload or over-traverse conditions, or if the run-out condition is reached.

STF testing of P/M standard gears and baseline wrought steel gears was carried out by cyclic loading of a test tooth near the tooth tip via a load anvil, with the reaction support on a corresponding reaction tooth typically near the root fillet region. Figure 45 shows the test gear tooth geometry details for the P/M hot forged standard gear, showing the location of the test load at 1.668" radius (35.2° roll angle), as well as the width and height for the of the critical section in the root fillet region determined by the Lewis parabola.

As mentioned above, typical location of the reaction contact is in the root/fillet region of the gear teeth. However, for the current STF test program to evaluate high strength P/M standard gears, an alternate test design was used wherein the reaction tooth is also loaded at the same radial location as the test tooth, as shown in Figure 46. In such a test procedure, two test teeth were simultaneously tested until one of the teeth failed – called 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, when 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 the test teeth were loaded in a similar manner, a test that ran out counted as two data points. Similarly, failure of either upper or lower test tooth counted as a valid data point. In contrast, if the reaction tooth - that is not a fully loaded tooth - fails, then the entire test is invalid and wasted.

The location of the loading point was chosen close to the tooth tip while ensuring that the estimated contact region under estimated maximum test load does not extend beyond the gear tooth tip. The basic test dimensions and conditions are listed in Table 4. Test load contact location data was used to design the test fixture to ensure that the loading anvils precisely contact the test and reaction gear teeth and to firmly hold the gear and for the load and reaction inserts to contact at specified locations. The test and reaction teeth, as well as location of the loading points from the gear center are shown in Figure 46, and the STF test fixture is shown in Figure 47.

9.1.2 STF Test Procedure

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. The modified staircase sequence is a term used to describe the structured load selection procedure for fatigue testing. The first test is conducted at a load high enough to ensure failure (selection based on experience or preliminary set up tests). Subsequent test loads are then selected based upon the outcome of the previous test. If the test fails, the next test is conducted at a lower load. If the test runs out, the next test is conducted at a higher load. Load levels and number of tests were selected to achieve several failures at the highest loads, several

run-outs at the lowest loads, and a combination of failures and run-outs at the intermediate loads. Test loads and cycles to failure are recorded for the STF tests and Weibul analysis used to analyze the fatigue failures.

9.1.3 STF Test Results

9.1.3.1 Baseline Wrought Steel Gears

A total of 16 STF tests were carried out on baseline 4023 C/H wrought steel gears at test loads ranging from 3200 lbs to 4000 lbs, resulting in maximum tooth bending stress of about 152 to 190 ksi. The 16 STF tests resulted in the generation of 24 bending fatigue test data points due to each run out counting as two data points. Table 5 summarizes STF test results for the baseline gears.

Figure 48 shows a typical tested tooth of baseline wrought steel gear showing the crack progressed to about mid way of the tooth thickness. After crack initiation and during steady state crack growth, tooth deflection increases steadily due to changing tooth compliance with increasing crack length. STF test machine was programmed to automatically shut off after a preselected increase in tooth deflection of 0.005" to ensure consistent end the test for valid comparison between various test gear lots.

9.1.3.2 P/M-4620-HF-Ausf Gears

A total of 18 STF tests each were conducted for P/M-4620-HF-Ausf gears at test loads ranging from 2800 to 3600 lbs, resulting in maximum tooth bending stress of about 133 to 171 ksi. The 18 STF tests resulted in the generation of 26 bending fatigue test data points due to each run out counting as two data points. Tables 6 summarize the STF test results for P/M-4620-HF-Ausf gears.

Figure 49 shows a typical tested tooth of P/M-4620-HF-Ausf gear showing the tested tooth broken off from the body of the gear. STF test machine was programmed similar to as described for baseline gears to automatically shut off after a preselected increase in tooth deflection of 0.005" to ensure consistent end the test for valid comparison between various test gear lots. However, such a setting still resulted in a separated tooth after crack initiation.

9.1.3.3 Preausform P/M-4620-HF Gears

A total of 20 STF tests each were conducted for preausform P/M-4620-HF gears that had been hot forged but not ausform finished gears, at test loads ranging from 2000 to 4500 lbs, resulting in maximum tooth bending stress of about 95 to 214 ksi. The above 18 STF tests 20 resulted in the generation of 28 bending fatigue test data points due to each run out counting as two data points. Tables 7 summarize the STF test results for preausform P/M-4620-HF gears. Shape of fractured test teeth was similar to P/M 4620 C/H steel gears as seen in figure 49.

9.1.3.4 P/M-4680-HF-Ausf Gears

A total of 18 STF tests each were conducted for P/M-4680-HF-Ausf gears that had been hot forged and ausform finished gears at test loads ranging from 2400 to 3200 lbs, resulting in maximum tooth bending stress of about 114 to 152 ksi. The 18 STF tests resulted in the generation of 26 bending fatigue test data points due to each run out counting as two data points. Tables 8 summarize the STF test results for P/M-4680-HF-Ausf gears. Shape of fractured test teeth was similar to P/M-4620-HF-Ausf gears as seen in Figure 49.

9.1.4 Statistical Analysis of STF Test Results

Above STF test results for the four lots of test gears are shown in Figure 50, plotted as maximum bending stress as a function of cycles to failures. As seen in Figure 50, wrought steel gears performed the best showing the maximum bending fatigue strength, with P/M-4620-HF-Ausf gears showing performance close to wrought steel gears. P/M-4680-HF-Ausf gears as well as the preausform P/M-4620-HF showed the lowest bending strength.

For statistical analysis, the STF test data is shown sorted by the test load in Tables 9 through 12 for the baseline wrought steel gears, P/M-4620-HF-Ausf gears, preausform P/M-4620-HF gears, and P/M-4680-HF-Ausf gears, respectively. Failure rates shown in Tables 9-12 were used to determine the load corresponding to 50% failure at 7 million cycles for the four lots of gears. Figure 51 shows a plot of the test loads vs. normal probability variate for baseline wrought steel gears, and similar plots for the three P/M gear lots are shown in Figures 52 through 54, respectively. The mean failure point represents the average result of tests conducted at loads that resulted in a mixture of failures and run-outs. The heavy vertical lines with the heavy horizontal ends at various test loads for each set of gears shown in Figures 51-54 represent approximate confidence bands for failure rates at these loads, and are based on what the failure rates would have been had one more test been conducted at each of these loads, and had resulted in either failure (higher limit) or run out (lower limit). The STF tests were conducted at an R ratio of 0.1 or with test loads varying from 10% to 100% of maximum test load. All Normal Probability calculations are based on 50% confidence values.

Test load for 50% failures at 7 million cycles for baseline wrought steel gears was determined to be about 3780 lbs, that for P/M-4620-HF-Ausf gears was about 3250 lbs, that of preausform P/M-4620-HF gears was about 2850 lbs, and that of P/M-4680-HF-Ausf gears was about 2810 lbs. Figure 55 summarizes the test loads for 50% failures at 7 million cycles for the three lots of gears. Baseline wrought steel gears therefore demonstrated about 14% higher load for 50% failure at 7 million cycles as compared to the P/M-4620-HF-Ausf gears, and about 26% higher as compared to P/M-4620-HF-Ausf gears. Also, the ausform finished P/M-4620-HF-Ausf gears demonstrated an increase of about 15% in load for 50% failure at 7 million cycles as compared to the preausform P/M-4620-HF gears.

It is to be noted that baseline wrought steel gears had been shot peened after heat treatment, and therefore demonstrate higher bending fatigue performance. P/M-4620-HF-Ausf as well as P/M-4680-HF-Ausf gears were not subjected to shot peening, and it is anticipated that bending fatigue strength of P/M steel gears would have improved substantially if subjected to shot

peening. As such, the bending fatigue strength of P/M-4620-HF-Ausf gears was comparable to the wrought steel gears. As P/M-4680-HF-Ausf gears demonstrated substantially lower tooth bending strength as compared to both baseline wrought steel gears and the P/M-4620-HF-Ausf gears, further development and evaluation of P/M-4680-HF-Ausf gears was abandoned.

9.2 Surface Durability RSF Testing

Pitting is a fatigue failure phenomenon primarily due to cyclic shear in the subsurface regions of gear teeth. Maximum shear stress under tooth contact in gear mesh occurs a few thousands of an inch below the surface, and the depth of maximum shear stress is brought closer to the tooth surface due to traction forces. Gear teeth in mesh are subjected to both rolling and sliding and therefore subsurface origins of pitting fatigue cracks are a dominant failure mode. Presence of fine intermetallic inclusions in gear steels can also act as initiation sites for pitting failure. In addition, pitting initiated in surface origins may be caused due to surface asperities in mating gear teeth sliding against each other when the elastohydrodynamic lubricant film thickness is insufficient to prevent asperity contact. Finally, pitting failure origins may sometimes be found well below the tooth surface closer to the case/core interface of case-hardened gear teeth, and can be traced to improper processing history. Pitting fatigue cracks initiate at 45° a few thousands of an inch below the surface, and under cyclic shear, cracks propagate and link up to separate a chunk of surface material forming a pit a few thousandths deep. Microstructure examination often reveals a pattern of microcracks that resemble wings and hence are called a butterfly pattern.

Power circulating (PC) gear tests are used to conduct accelerated gear surface durability tests to evaluate pitting and wear resistance, wherein a locked-in torque is recirculating between a test and torque-reversing gear set. Figure 56 shows the PC surface durability testing machine used and the test torque loop. The test machine consists of a test gear box and a slave reversing gear box. The two gear boxes are located over 36" apart using long slender shafts to reduce the torsion stiffness of the system, and splash lubrication was used for the RSF tests. The torque is induced by mechanical means using flanged plates, and locked in by twisting one of the gear shaft with respect to the other. The locked in torque may be introduced by mechanical or hydraulic means, and the entire arrangement is driven by an electric motor, the motor supplying only the lost torque of about 5-10%. The test gear meshes with a 40 teeth mate gear, and due to the rolling/sliding conditions as well as the larger number of teeth, pitting occurs preferentially on the test gears. Such PC testing machines therefore facilitate testing at substantially higher input torque than the supplied drive torque. Furthermore, as the surface durability data is generated between mating gears and under controlled lubrication and operating conditions, the test data can be used for design purposes. The machine is equipped with accelerometers, thermocouples, and a chip detector for monitoring various test conditions and for automatic shut down of the machine upon detection of surface pitting. Test machine instrumentation is calibrated periodically to ensure valid test results.

Figure 57 shows the testing conditions used for the PC surface durability tests. In addition to evaluating pitting resistance, PC surface durability is also used to evaluate wear resistance of running gears under high contact stress conditions. The failure criteria for the PC surface durability tests was therefore either pitting of up to 5% tooth surface area, or wear of

tooth surface defined as loss of profile by over 0.001". For each RSF test, a standard break-in procedure was used by testing for 30 minutes at 50% load and lubricant at 80°F. Failure was determined by automatic shut down due to vibration sensors and/or by visual examination. RSF testing were performed at 1800 rpm, and run out was initially set at 30 million cycles or about 278 hours after break-in. However, based on preliminary results for baseline wrought steel gears and superior performance of P/M-4620-HF-Ausf gears, run out condition was increased to 60 millions cycles or about 556 hours to ensure a clear separation between the two groups of test gears.

9.2.1 RSF Testing of Baseline Wrought Steel Gears

Table 13 summarizes preliminary RSF test results for baseline wrought steel test gears, and also lists the test conditions used for RSF testing of baseline wrought steel gears such as test torque, effective contact width and the induced contact stress on the gear tooth surface, and also shows baseline gear RSF test results. The preliminary RSF test results are also shown in Figure 58 as a plot of cycles to failure vs. contact stress.

A total of nine RSF tests have been conducted on baseline wrought steel gears, of which seven RSF tests were at 304 ksi contact stress, and one each at 320 ksi and 335 ksi. The seven tests at 304 ksi all resulted in pitting failures, with life to failure ranging from about 192 to 364 hours or 20.3 to 39.2 million cycles. A typical pitted baseline gear tooth surface is shown in Figure 59.

RSF test at a higher contact stress of 335 ksi was attempted to induce a pitting failure with reduced life. However, the 335 ksi test resulted in a scoring failure at/near the tip region of all teeth on the wrought steel test gear after only 4.6 hours or less than half a million cycles. Testing at the high 335 ksi contact stress was therefore abandoned. A test at an intermediate contact stress of 320 ksi was then attempted to induce pitting failure with reduced life. The test resulted in a failure at about 269 hours or about 29 million cycles. Due to the spread in test results for the baseline gears, all further tests were then run at 304 ksi, as it would be difficult to separate the test results at stress levels of 304 and 320 ksi. None of the nine RSF tests conducted on baseline wrought steel gear resulted in a run out defined as 30 million cycles of testing without pitting or wear.

9.2.2 RSF Testing of P/M-4620-HF-Ausf Gears

Table 14 summarizes preliminary RSF test results for P/M-4620-HF-Ausf gears, and also lists the test conditions including test load and resulting torque, effective contact width and induced contact stress on the gear tooth surface. The induced contact stress on tooth surfaces during RSF test is determined by the applied torque, material properties such as the elastic modulus and Poisson's ratio, and also by contact conditions such as the effective contact width, and tooth curvatures in the two principal planes. As seen in Figure 40, ausform finishing of P/M-4620-HF-Ausf gears resulted in a pronounced lead crown and the effective face width of contact at the applied torque was measured to be about 0.37", or about 80% as compared to the effective face width of wrought steel gears. Furthermore, the elastic modulus for fully dense hot forged P/M steel gears was estimated to be about 29.5E6 psi, slightly lower than 30E6 psi for wrought

steel gears. The applied torque was therefore adjusted to result in contact stress for P/M-4620-HF-Ausf gears to be equivalent to that used to test wrought baseline steel gears.

Preliminary test results for P/M-4620-HF-Ausf gears are shown in Figure 58 as a plot of cycles to failure as a function of contact stress. A total of 10 RSF tests have been completed for P/M-4620-HF-Ausf gears and two tests are currently in progress. Two tests were conducted at the highest contact stress of 335 ksi, with one test resulting in the mate gear failing by pitting after about 15.6 hours of testing or 1.7 million cycles (see Figure 60 showing the pitted tooth surface of the mate gear), and the other test resulting in scoring on three teeth of the P/M steel test gear after about 4.2 hours of testing, or at less than half a million cycles. Further RSF testing of P/M-4620-HF-Ausf gears at 335 ksi contact stress was abandoned, as failure by surface distress such as pitting could not be ensured at this stress level. RSF test at an intermediate contact stress of 320 ksi was then attempted, and resulted in pitting failure of the P/M-4620-HF-Ausf gear after about 304 hours of testing or about 33 million cycles. Figure 61 shows the pitted gear tooth surface.

Of the seven tests conducted at 304 ksi, four tests were stopped after 30 million cycles of testing and listed as run out tests, as run out was initially defined in the test plan. Similarly two RSF tests conducted at 294 ksi contact stress on P/M-4620-HF-Ausf gear also resulted in run out at 30 million cycles. In order to generate pitting failures in P/M 4620 C/H steel gears at the equivalent contact stress of 304 ksi, the run out condition was therefore doubled to 60 million cycles (over 23 days of 24/7 testing). The sixth test at 304 ksi ran out with no pitting or wear failure after 60 million cycles. The seventh test at 304 ksi resulted in a pitting failure after about 59 million cycles. Two more RSF tests are currently in progress at the same stress level. Profile inspections were carried out on all tested P/M-4620-HF-Ausf gears to measure profile loss during RSF tests due to wear, if any, and no wear failures were found in any of the RSF tested P/M-4620-HF-Ausf gears to date.

To date, only two RSF tests on P/M-4620-HF-Ausf gears resulted in pitting failure. The pitting failure at contact stress of 320 ksi performed for about 13% longer than the baseline wrought steel gear tested at similar contact conditions. The other pitting failure was at the contact stress of 304 ksi and failed after 59 million cycles..

9.2.3 Analysis of RSF Test Results

Based on tests completed to date, a Weibul analysis of the test data was carried out for the baseline wrought steel gears and the P/M-4620-HF-Ausf gears, and figure 62 shows the Weibul chart for the two groups of gears with 5% and 95% confidence bands, as well a summary of G-10, G-50 and G-90 life estimates for baseline and P/M-4620-HF-Ausf. Superior performance of P/M-4620-HF-Ausf gears was statistically significant as compared to the baseline wrought steel gears, with over 100% increase in fatigue lives. Figure 63 shows the estimated G-50 life of about 29.2 million cycles for baseline wrought steel gears as compared to about 59.0 million cycles for high strength P/M-4620-HF-Ausf gears produced by processing techniques developed in this program, or over 100% increase in estimated G-50 life. Also shown in Figure 63 is the estimated G-50 life of about 5 million cycles for P/M steel parts that are produced by conventional P/M processing techniques and not ausform finished. Ausform

finished P/M gears demonstrated a ten fold increase in RSF life as compared P/M parts that are not ausform finished, and also nearly double RSF life as compared to current baseline wrought steel gears.

9.3 Scoring Resistance Tests

The program test plan required comparative scoring resistance testing of baseline wrought steel gears and ausform finished P/M steel gears. Scoring occurs due to breakdown of lubrication film that protects the two mating surfaces of meshing gears, and depends on test load and rotational speed, tooth geometry details of the mating gears, surface finish characteristics, lubricant properties and operating temperature. At some combination of adverse conditions, breakdown of lubrication film results in mating surfaces coming in to nascent metal to metal contact, and the surface asperities form localized solid phase bonds or micro-welds. As the gear teeth come in and out of mesh, these micro-welds form and are sheared off repeatedly, and result in rapid deterioration of surface finish and therefore generation of increased frictional heat. Onset of scoring of tooth surfaces results in rapid increase in localized temperature and vibration.

In this program, a PC surface durability testing machine of the type shown in Figure 56, and operating at 2600 rpm, and with capability of oil jet lubrication was used for scoring resistance test. Test conditions used for scoring resistance tests are shown in Figure 64. After initial breaking procedure similar to as described in Figure 57 for surface durability RSF tests, scoring tests were initiated at a locked in torque of 2000 lb-in and at a rotational speed of 2600 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 in steps of 10°F, and the test run for ten minutes. If no scoring was detected as monitored by oil outlet temperature and / or vibration sensors, then 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 without onset of scoring was used as a measure of scoring resistance of the test gear. If no scoring resulted at up to 300°F, then the torque was increased to 2200 lb-in, and the scoring test repeated as described above. If no scoring occurred even at 2200 lb-in torque, then the test was repeated at a torque of 2400 lb-in, the highest torque allowed without fear of causing other modes of failure.

A total of four baseline wrought steel gears were subjected to scoring resistance tests as described above. Table 15 summarizes scoring test results for baseline gears, and shows that all four gears scored at the applied torque of 2000 lb.in and at oil temperature in the range of 260-270°F, the scoring temperature being a measure of scoring resistance of the gears – higher scoring temperature is better performance. Figure 65 shows the tooth surface of a typical baseline test gear after scoring has occurred, and shows severe damage on the tooth due to breakdown of the lubrication film and the ensuing repeated welding and tearing up of asperities.

A total of ten scoring tests were conducted on four P/M-4620-HF-Ausf gears. As described above, the first test on a test gear was conducted at the lowest applied torque of lb.in, and the oil temperature progressively increased to precipitate scoring. If no scoring occurred even at oil inlet temperature of 300°F, then the test was declared to be complete with no scoring. The system was allowed to cool down to ambient, and the test was repeated at the next higher

torque of 2200 lb.in, and so on. Table 16 summarizes the scoring resistance test results for P/M-4620-HF-Ausf gears, and shows that of the ten scoring tests conducted, only one test resulted in scoring failure, at a torque of 2000 lb.in and oil temperature of 300°F. Figure 66 shows scored tooth surface of the only P/M-4620-HF-Ausf gear that failed in scoring tests.

Two scoring tests were conducted on preausform P/M-4620-HF gears to evaluate the specific influence of ausform finishing. However, due to the surface condition and gear quality of preausform P/M-4620-HF gears, scoring tests were conducted at a lower torque of 1800 lb.in. Both tests resulted in scoring failures of preausform P/M-4620-HF gears at 220°F and 300°F respectively, at the lower torque of 1800 lb.in. Table 17 summarizes the scoring resistance test results for preausform P/M-4620-HF gears.

Figure 67 graphically shows the above scoring resistance test results conducted on the baseline wrought steel gears, P/M-4620-HF-Ausf gears and preausform P/M-4620-HF gears. As seen in figure 66, scoring resistance of P/M-4620-HF-Ausf gears was significantly superior as compared to wrought steel gears as well as preausform P/M-4620-HF gears.

9.4 *Gear Tooth Impact Tests*

Although vehicle gears are typically not subjected to impact loading during service, off-road vehicles are subjected to substantial impact loads due to uneven and rough terrains, and characterization of gear tooth impact test performance is necessary to evaluate the performance of P/M steel gears, due to the inherent presence of porosity. Therefore, gear tooth impact testing was prescribed as the fourth gear performance test in the test plan. Gear tooth impact testing was carried out using the drop weight gear tooth impact testing machine shown in Figure 68, wherein a target weight block is dropped from a preset height on to a particular gear tooth being tested. The machine is instrumented with a load cell to record the instantaneous load generated during the impact fracture of the tooth as a function of time.

The fixture designed to hold the test gears during impact test is shown in Figure 69, and is similar to the STF test fixture shown in Figure 47, except that the in-line reaction support contacts the support tooth close to the root fillet region, thus causing only the test tooth on top to fail during the impact test. Figure 70 shows the test layout used for tooth impact testing of P/M standard 4620 C/H steel gears as well as the baseline wrought steel gears, and shows the location of the test tooth with impact block on top and the reaction support tooth at the bottom. As seen in Figure 70, tooth adjacent to the reaction support tooth must be removed by EDM or similar process to facilitate mounting of the gear on to the impact test fixture.

Gear tooth impact test procedure involves dropping the 62.8 kg mass on to the test tooth from various drop heights representing varying strain rates. The load cell output of reaction load generated as a function of time is recorded during each tooth impact test. The recorded data is analyzed at very fine resolution in steps of one microsecond, and the traverse of the mass calculated based on initial velocity at impact, and deceleration due to the tooth impact calculated from the measured instantaneous load. A plot of load vs. traverse is thus generated based on the measured data, and a representative chart for a 10” drop height is shown in figure 71 for several

tooth impact tests. The area under the force-traverse curve represents the energy absorbed during a specific gear tooth impact test.

A total of nine gear tooth impact tests were conducted for wrought steel test gear teeth, with three tests each carried out with drop heights of 5", 10" and 20" respectively to evaluate effects at three strain rates. Table 18 summarizes the tooth impact test data for baseline wrought steel gears, and shows the peak load measured as well as absorbed energy for each test. Figure 72 shows a typical impact tooth fracture surface of a wrought steel gear, and indicates a brittle fractured surface.

For the P/M-4620-HF-Ausf gears, a total of seven tooth impact tests were conducted, three tests with a drop height of 5" and two each with drop heights of 10" and 20" respectively. Figure 73 shows a typical tooth impact fracture surface of a P/M-4620-HF-Ausf gear, and shows substantially more ductility in the fractured surface indicated by the shear ridges as well as bending and tear of the tooth shape. Table 19 summarizes the tooth impact test results for the P/M-4620-HF-Ausf test gear teeth.

For the preausform P/M-4620-HF gears, a total of four tooth impact tests were conducted, two tests with a drop height of 5" and two with drop heights of 10". Tooth impact fracture surface of a preausform P/M-4620-HF gear was similar to that of baseline wrought steel gears as shown in figure 72 indicating a brittle fractured surface. Table 20 summarizes the tooth impact test results for the P/M-4620-HF-Ausf test gear teeth.

Figure 74 shows a plot of mean energy absorbed during the impact fracture of baseline wrought steel gears, P/M-4620-HF-Ausf gears and preausform P/M-4620-HF gears. As seen in figure 74, impact resistance of P/M-4620-HF-Ausf gears as well as preausform P/M-4620-HF gears as measured by mean impact energy absorbed are equal to or slightly better than wrought steel gears. Furthermore, characteristic difference in the fractured tooth surface as seen in figures 72 and 73 indicate potentially superior performance of P/M-4620-HF-Ausf gears as compared to the wrought steel gears or preausform P/M-4620-HF gears.

10. Analysis of Process Cycle Time & Costs

One of the objectives of the program was to estimate the cost of producing high strength P/M steel helical focus pinions produced using the advanced P/M processing and ausforming finishing technology developed in this program, as compared to current manufacturing process used by NPG to produce wrought steel helical focus pinions. Several manufacturing process sequences were evaluated using the analysis methodology described below to 1) estimate current NPG wrought steel gear manufacturing cycle time/cost, 2) estimate manufacturing process time/cost to produce wrought steel gears of accuracy equivalent to ausform finished gears 3) estimate the most cost effective P/M gear manufacturing process sequences, and 4) determine the cost-benefit of implementing ausform finishing compared to conventional process methods for the planet pinion.

10.1 Manufacturing Processes Analyzed

Processing time/costs analysis were carried out for both P/M steel gear lots investigated in this program, namely P/M-4620-HF-Ausf and P/M-4620-HF-Ausf with associated processing sequences as shown in Figures 12 and 13 respectively. Furthermore, high strength P/M steel gears produced by process sequences shown in Figures 12 and 13 were expected to result in substantially superior surface finish in P/M steel gears due to ausform finishing operation than was possible with hobbing and shaving process as used by NPG for wrought steel helical focus pinions shown in Figure 4. In order to compare process sequences that result in equivalent gear quality, a variation of NPG process was also analyzed wherein additional gear tooth grinding and related operations were added that would result in comparable gear quality and surface finish. The modified NPG process is shown in Figure 75. The following manufacturing process sequences were analyzed to estimate the total processing time and manufacturing costs:

- a. NPG's current process (Figure 4) to produce wrought steel helical focus pinions;
- b. Modified NPG process (Figure 75) to produce wrought steel helical focus pinions with improved gear accuracy and surface finish;
- c. P/M-4620-HF-Ausf gear manufacturing process (Figure 12) involving pressing, sintering, hot forging, carburizing/hardening, and ausform finishing;
- d. P/M-4680-HF-Ausf gear manufacturing process (Figure 13) involving pressing, sintering, hot forging, and ausform finishing;
- e. Same as 'c' except with no hot forging and related operations (Figure 76);
- f. Same as 'd' except with no hot forging and related operations (Figure 77).

10.2 Activity Based Cost Methodology

The manufacturing costs were calculated utilizing an Activity Based Cost (ABC) methodology approach. Manufacturing costs include the fixed and variable costs associated with each process operation. Operation fixed costs were sub-divided into two categories, *factory fixed* comprised of overhead/utilities/indirect labor/ profit and *equipment fixed* including capital equipment purchases and financing costs. Equipment data sources included Keystone, NPG, Almco Inc., G Montgomery, C & B Machinery Co., Gleason, Reishauer Corporation, and Eldec Induction. Equipment fixed costs were calculated based on an annual build schedule of 40,000 units / day rather than maximum equipment capacity. Capital equipment assumed a 5 yr property MACR depreciation rate, with purchasing costs amortized over a three year period @ 6.5% including a 5% purchasing fee. Variable costs included raw materials, required tooling, direct labor, operating consumables, maintenance, and scrap. Raw materials, required tooling, and direct operating labor data were provided by Keystone Powdered Metal, New Process Gear, and industry suppliers. Industry data sources included Nachi Machining Tech Co., Teledyne Landis Machine, Pillar Induction Company, McMaster-Carr Supply Company, and J&L Industrial Supply. Due to the proprietary nature of the data, detailed process cost information cannot be detailed in the report. For this analysis, the operating consumables were assumed equivalent to 10% of the raw material costs, and preventative/corrective maintenance, spare parts, and related direct labor costs were equivalent to 5% of the equipment purchase cost. In addition, an industry standard scrap rate of 5% was applied, or 95% product yield assumed for each manufacturing process sequence.

10.3 Manufacturing Cost Analysis Results

The six manufacturing process sequences listed in section 10.1 above were evaluated to identify the manufacturing costs associated with conventional and ausform finishing manufacturing as well as respective modified processes. The manufacturing cost estimates for each process described above are shown in Table 21. Table 21 presents the cost per unit as well as annual costs for the various process sequences analyzed based on a daily production requirement of 40,000 units. The cost avoidance for each of the high strength P/M steel gear process sequences is compared to the both the current NPG process for wrought steel gears and the 'modified' NPG process for wrought steel finish ground gears.

As shown in Table 21, the cost to manufacture the helical focus pinion using the current NPG wrought steel process was estimated to be about \$2.41 per piece resulting in an annual cost of \$23.1 M. Similarly, the 'Modified' NPG wrought steel ground gear process to produce the form, dimensional accuracy, and surface finish equivalent to ausform finished gears was about \$3.80 per piece, resulting in an annual cost of \$36.5 M. The cost for improved quality, compared to the current NPG manufacturing process, was \$13.4 M or equivalent to a 37% increase in cost.

In comparison, the average cost to produce P/M-4620-HF-Ausf gears or P/M-4680-HF-Ausf gears including the hot forging operation as well as ausform finishing was estimated to be approximately \$2.15 per piece resulting in an annual cost of \$20.6 M. This amounts to a 10.8% reduction in the cost of P/M-4620-HF-Ausf gears as compared to current NPG wrought steel gear manufacturing process, and over 43.4% reduction as compared to the 'Modified' NPG wrought steel gear manufacturing process – a more realistic and valid comparison for equivalent quality.

Eliminating the hot forging operation from the high strength P/M steel gear manufacturing process resulted in the most significant cost avoidance compared to current NPG wrought steel gear manufacturing process. The average cost of ausform finished P/M steel gears but without the hot forging operation was about \$1.85 per piece, a manufacturing cost reduction of \$0.56 per piece (over 23.2% reduction) from current NPG wrought steel gear manufacturing process. Moreover, compared to the 'Modified' NPG wrought steel gear manufacturing process, eliminating the hot forging operation from the high strength P/M steel gear manufacturing process resulted in much higher operation cost savings of \$1.95 per piece, or over 50.1 % decrease in the manufacturing cost.

Figure 78 show the above cost comparisons for the P/M-4620-HF-Ausf gears as compared to the current NPG wrought steel gear process and the 'Modified' NPG wrought steel gear process, and demonstrate the dramatic decrease in per piece cost achievable by using high strength P/M steel gears in place of the current wrought steel gears.

10.4 Manufacturing Process Cycle Time Analysis Results

The process cycle time was also estimated for the six manufacturing processes listed in section 10.1 above including different versions for wrought steel gears and P/M-4620-HF-Ausf and P/M-4680-HF-Ausf gears. Table 22 summarizes the estimated process cycle times for the

six processes. The process cycle time was calculating assuming 85% efficiency for each manufacturing operation required to produce the planet pinion.

As seen in Table 22, NPG's manufacturing process to produce the current wrought steel gears takes approximately 14 hours to manufacture a single planet pinion. Carburizing or related heat treatment operations are batch processes that requiring several hours for each load, wherein several hundred helical focus pinions are stacked and loaded at a time in the furnace. Carburizing operation therefore contributes to the majority of cycle time for each of the six process sequences that require carburizing. In comparison, the process cycle time for P/M-4620-HF-Ausf gear process sequences that require the carburizing operation was estimated to be almost 16 hours per piece. The longer process cycle time for P/M-4620-HF-Ausf gears compared to current NPG manufacturing process for wrought steel gears is attributed to the additional tempering operation required after the ausform finishing operation.

Significant cycle time reduction resulted for P/M-4680-HF-Ausf gear manufacturing process wherein there is no carburization requirement. P/M 4680 steel with its high carbon content of about 0.8% eliminated the need for carburizing, reducing total process time to a little over 5 hours per piece, or over 64% reduction in process cycle time for each piece. Dramatically reduced process cycle time for P/M-4680-HF-Ausf gears results in several benefits such as shorter lead times, decreased inventory, reduced work in process (WIP), and lower operating expenses. In addition, improved cycle time is also likely to result in improved quality manufacturing, reduced variability, and decrease scrap quantities.

11. Summary & Conclusions

The primary objectives of the US Army / TARDEC sponsored project entitled *High Strength P/M Gears for Vehicle Transmissions* project were to develop high strength P/M steel gears with bending strength and surface durability equivalent to current wrought steel gears, and to demonstrate potential for significant cost savings. In the just completed Phase I of the project, processing technology was developed to apply ausform gear finishing to hot forged P/M steel gears in order to achieve the combination of bending strength and surface durability characteristics of P/M gears that would result in performance equivalent to current wrought steel gears. Performance of ausform finished P/M forged steel gears has been demonstrated to be comparable to or better than wrought steel gears in comparative bending fatigue and surface durability tests. Following summarizes the goals achieved in the program:

- Ausform finishing technology was developed for P/M standard test rig gears, and processing specifications were established for two P/M steel formulations namely P/M forged 4620 C/H steel, and P/M forged 4680 steel. Process specification included design and prior processing techniques for preausform P/M hot forged gears, as well as tooling and process needed to ausform finish P/M gears to specified accuracy and metallurgical characteristics. Ausform finishing technology was also developed for producing HMMWV planetary helical pinion made from P/M steels.
- Surface durability performance of P/M-4620-HF-Ausf gears was demonstrated to be superior to wrought steel gears produced by current conventional processing techniques.

- Bending fatigue strength of P/M-4620-HF-Ausf gears was demonstrated to be comparable to wrought steel gears produced by current conventional processing techniques.
- Scoring resistance of P/M-4620-HF-Ausf gears was demonstrated to be superior to wrought steel gears produced by current conventional processing techniques.
- Impact resistance of P/M-4620-HF-Ausf gears was demonstrated to be equivalent to wrought steel gears produced by current conventional processing techniques.
- Based on detailed processing cost analysis, P/M-4620-HF-Ausf gears were estimated to cost about 43% lower as compared to current wrought steel gears of equivalent quality.

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Tables

Table 1 Composition of P/M and wrought steels investigated

Steel	C	Mn	Si	Ni	Cr	Mo	P (max)	S (max)
4620	0.17 - 0.22	0.45 – 0.65	0.15 – 0.35	1.65 – 2.0		0.2 – 0.3	0.035	0.040
4680	0.8 -0.9	0.45 – 0.65	0.15 – 0.35	1.65 – 2.0		0.2 – 0.3	0.035	0.040
4023	0.2 - 0.25	0.7 – 0.9	0.15 – 0.35			0.2 – 0.3	0.035	0.040
8620	0.18 - 0.23	0.7 – 0.9	0.15 – 0.35	0.4 – 0.7	0.4 – 0.6	0.15 – 0.25	0.035	0.040

Table 2 Tooth size comparison of preausform P/M-4620-HF gears and preausform P/M-4680-HF gears

	4620 C/H	4680
Outer diameter	3.382	3.376
MoP (0.216")	3.3988	3.3905
Root diameter	2.776	2.766

Table 3 Induction heating process details used for ausforming of P/M-4620-HF-Ausf gears and P/M-4680-HF-Ausf gears

Induction Setting	P/M Standard Gear	Helical Focus Pinion Option A	Helical Focus Pinion Option B
MF Frequency	7 khz	9.6 khz	9.6 khz
MF Power	70 kw	70 kw	30 kw
MF time	2.5 sec	2.5 sec	2.5 sec
Gear rotation during MF heat	700 rpm	700 rpm	700 rpm
Dwell between MF and RF	0.25 sec		0.25 sec
RF Frequency	250 khz		250 khz
RF Power	110 kw		65 kw
RF Time	0.5 sec		0.5 sec
Gear rotation during RF heat	700 rpm		700 rpm
Transfer to quench oil	0.3 sec	0.3 sec	0.3 sec

Table 4 STF test particulars

Item	Description
Specimen gear	P/M hot forged standard gear 24 teeth, 8 DP, 18.65° pressure angle, 0.5" face width spur gear
Tooth loading	Two teeth loaded similarly as shown in Figure 46, separated by 4 teeth Load point diameter: 3.336" Load point roll angle: 35.2°
Load block tilt	0.0°
Tooth removal	None required
Load factor	One pound load results in 47.56 psi maximum bending stress
R factor	0.1 Load cycled from maximum load to 10% of maximum load
Test frequency	40 Hz
Run out limit	Tests suspended after seven million cycles without failure
Lubricant	MOBIL 600W Super Cylinder at load points and other locations subject to friction
Temperature	Ambient

Table 5 STF test results for baseline wrought steel gears

Test #	Gear #	Tooth # Upper/Lower	Frequency hz	Load (lbs)	Stress (Std) (ksi)	Cycles to failure	Points	Cum
1	3	1 and 1	40	3,200	152.2	7,000,000	2	2
2	5	1 and 1	40	3,600	171.2	242,464	1	3
3	2	1 and 1	40	3,200	152.2	7,000,000	2	5
4	3	2 and 2	40	3,600	171.2	7,000,000	2	7
5	5	2 and 2	40	4,000	190.2	210,451	1	8
6	2	2 and 2	40	3,600	171.2	184,108	1	9
7	3	3 and 3	40	3,200	152.2	7,000,000	2	11
8	5	3 and 3	40	3,600	171.2	7,000,000	2	13
9	2	3 and 3	40	4,000	190.2	111,000	1	14
10	3	4 and 4	40	3,600	171.2	200,101	1	15
11	5	4 and 4	40	3,200	152.2	7,000,000	2	17
12	2	4 and 4	40	4,000	190.2	7,000,000	2	19
13	3	5 and 5	40	4,000	190.2	187,052	1	20
14	5	5 and 5	40	4,000	190.2	152,823	1	21
15	2	5 and 5	40	4,000	190.2	124,235	1	22
16	3	6 and 6	40	3,600	171.2	7,000,000	2	24

Table 6 STF test results for P/M-4620-HF-Ausf gears

Test #	Gear #	Tooth # Upper/Lower	Frequency hz	Load (lbs)	Stress (Std) (ksi)	Cycles	Points	Cum
1	2029	1 and 1	40	3,200	152.2	7,000,000	2	2
2	2029	2 and 2	40	3,600	171.2	214,436	1	3
3	2029	3 and 3	40	3,200	152.2	63,055	1	4
4	2029	4 and 4	40	2,800	133.2	7,000,000	2	6
5	2029	5 and 5	40	3,200	152.2	7,000,000	2	8
6	2029	6 and 6	40	3,600	171.2	87,471	1	9
7	2048	1 and 1	40	3,200	152.2	89,418	1	10
8	2048	2 and 2	40	2,800	133.2	7,000,000	2	12
9	2048	3 and 3	40	3,200	152.2	111,905	1	13
10	2048	4 and 4	40	2,800	133.2	7,000,000	2	15
11	2048	5 and 5	40	3,600	171.2	103,169	1	16
12	2048	6 and 6	40	3,600	171.2	75,861	1	17
13	2053	1 and 1	40	3,600	171.2	47,970	1	18
14	2053	2 and 2	40	3,600	171.2	61,233	1	19
15	2053	3 and 3	40	3,200	152.2	7,000,000	2	21
16	2053	4 and 4	40	2,800	133.2	7,000,000	2	23
17	2053	5 and 5	40	2,800	133.2	102,349	1	24
18	2053	6 and 6	40	2,800	133.2	7,000,000	2	26

Table 7 STF results of high strength preausform P/M-4620-HF gears

Test #	Gear #	Tooth # Upper/Lower	Hzs	Load (lbs)	Stress (Std) (ksi)	Cycles to failure	Failed	Data Points	Cum Points
1	2007	1 and 1	30	4,500	214.0	45,994	Upper	1	1
2	2007	2 and 2	30	4,300	204.5	63,421	Lower	1	2
3	2007	3 and 3	30	4,000	190.2	76,740	Upper	1	3
4	2007	4 and 4	30	3,600	171.2	162,947	Upper	1	4
5	2007	5 and 5	30	3,200	152.2	121,553	Lower	1	5
6	2007	6 and 6	30	2,800	133.2	318,774	Lower	1	6
7	2007	7 and 7	30	2,400	114.1	908,883	Lower	1	7
8	2004	1 and 1	30	2,000	95.1	7,000,000	Runout	2	9
9	2017	1 and 1	40	2,400	114.1	7,000,000	Runout	2	11
10	2017	2 and 2	40	2,800	133.2	7,000,000	Runout	2	13
11	2017	3 and 3	30	3,200	152.2	688,965	Lower	1	14
12	2017	4 and 4	40	2,800	133.2	7,000,000	Runout	2	16
13	2017	5 and 5	40	3,200	152.2	1,573,809	Lower	1	17
14	2017	6 and 6	40	2,800	133.2	7,000,000	Runout	2	19
15	2018	1 and 1	40	3,200	152.2	377,378	Lower	1	20
16	2018	2 and 2	40	2,800	133.2	531,843	Lower	1	21
17	2018	3 and 3	40	2,400	114.1	7,000,000	Runout	2	23
18	2018	4 and 4	40	2,800	133.2	7,000,000	Runout	2	25
19	2018	5 and 5	40	3,200	152.2	331,803	Lower	1	26
20	2018	6 and 6	40	2,800	133.2	7,000,000	Runout	2	28

Table 8 STF results of P/M-4680-HF-Ausf gears

Test #	Gear #	Tooth # Upper/Lower	Frequency hz	Load (lbs)	Stress (Std) (ksi)	Cycles	Points	Cum
1	8038	1 and 1	40	2,800	133.2	241,000	1	1
2	8038	2 and 2	40	2,400	114.1	7,000,000	2	3
3	8038	3 and 3	40	2,800	133.2	536,866	1	4
4	8038	4 and 4	40	2,400	114.1	7,000,000	2	6
5	8038	5 and 5	40	2,800	133.2	7,000,000	2	8
6	8038	6 and 6	40	3,200	152.2	109,498	1	9
7	8035	1 and 1	40	2,800	133.2	186,212	1	10
8	8035	2 and 2	40	2,400	114.1	7,000,000	2	12
9	8035	3 and 3	40	2,800	133.2	7,000,000	2	14
10	8035	4 and 4	40	3,200	152.2	58,406	1	15
11	8035	5 and 5	40	3,200	152.2	89,511	1	16
12	8035	6 and 6	40	3,200	152.2	132,979	1	17
13	8038	7 and 7	40	3,200	152.2	125,384	1	18
14	8038	8 and 8	40	2,800	133.2	7,000,000	2	20
15	8038	9 and 9	40	2,800	133.2	7,000,000	2	22
16	8035	7 and 7	40	2,800	133.2	338,245	1	23
17	8035	8 and 8	40	2,400	114.1	7,000,000	2	25
18	8035	9 and 9	40	2,400	114.1	407,331	1	26

Table 9 Baseline wrought steel gear STF test results sorted by loads showing failure rates and normal probability variate

Load lbs	Number Tests	Number Breaks	Failure Rate	Probability Variate	Low Limit Variant	High Limit Variant
4000	7	5	0.7143	0.5663	0.1397	0.6745
3600	9	3	0.3333	-0.4307	-0.6047	-0.2534
3200	8	0	0.0000	-3.0000	-3.0000	-1.1503

Table 10 P/M-4620-HF-Ausf gear STF test results sorted by loads showing failure rates and normal probability variate

Load	Number	Number	Failure		Low Limit	High Limit
lbs	Tests	Breaks	Rate	Variate	Variant	Variant
3600	6	6	1.0000	3.0000	0.6745	3.0000
3200	9	3	0.3333	-0.4307	-0.6047	-0.2529
2800	11	1	0.0909	-1.3352	-1.4263	-0.9673

Table 11 Preausform P/M-4620-HF gear STF test results sorted by loads showing failure rates and normal probability variate

Load	Number	Number	Failure		Low Limit	High Limit
lbs	Tests	Breaks	Rate	Variate	Variant	Variant
3200	5	5	1.0000	3.0000	0.5658	3.0000
2800	12	2	0.1667	-0.9673	-1.0676	-0.7362
2400	5	1	0.2000	-0.8418	-1.0676	-0.4307

Table 12 P/M-4680-HF-Ausf STF test results sorted by loads showing failure rates and normal probability variate

Load	Number	Number	Failure		Low Limit	High Limit
lbs	Tests	Breaks	Rate	Variate	Variant	Variant
3200	5	5	1.0000	3.0000	0.5658	3.0000
2800	12	4	0.3333	-0.4307	-0.5658	-0.2934
2400	9	1	0.1111	-1.2205	-1.3352	-0.8418

Table 13 PC surface durability RSF test results for baseline wrought steel gears

Test # #	Gear ID #	Mate Gear	Machine ID #	Load lbs	Torque lb-in	Contact in	Stress ksi	RPM	Total Hours	Cycles (Millions)	Comment
1	B-1 R	M-1 R	PC-2	96	2400	0.47	304	1800	229.0	24,678,000	Surface Origin Pitting
2	B-1 L	M-1 L	PC-2	96	2400	0.47	304	1800	234.9	25,315,200	Surface Origin Pitting
3	B-3 R	M-3	PC-1	96	2400	0.47	304	1795	252.6	27,151,170	Surface Origin Pitting
4	B-2 R	M-2	PC-2	96	2400	0.47	304	1800	192.2	20,289,528	Severe Pitting - Probably Surface Origin
5	B-4 B	M-6 B	PC-2	128	3200	0.5	335	1800	5.1	496,800	All teeth scored. Auto stop
6	B-4 A	M-7 B	PC-1	112	2830	0.5	320	1795	269.5	28,971,300	Surface Origin Pitting
7	B-5 A	M-8 B	PC-2	96	2400	0.47	304	1800	230.4	24,829,200	Surface Origin Pitting
8	B-5 B	M-9 B	PC-1	96	2400	0.47	304	1795	363.8	39,176,569	Surface Origin Pitting
9	B-10 A	M-11 B	PC-2	96	2400	0.47	304	1800	243.2	26,211,600	Surface Origin Pitting

Table 14 PC surface durability RSF test results for P/M-4620-HF-Ausf gears

Test # #	Gear ID #	Mate Gear	Machine ID #	Load lbs	Torque lb-in	Contact in	Stress ksi	RPM	Total Hours	Cycles (Millions)	Comment
1	2033	M-2	PC-2	83	2075	0.37	294	1800	278.3	30,002,400	Ran out - 30 MC
2	2022	M-3	PC-1	83	2075	0.37	294	1795	278.3	29,919,060	Ran out - 30 MC
3	2050	M-4	PC-2	117	2925	0.405	335	1800	16.1	1,684,800	Mate gear pitted
4	2046	M-4	PC-2	91	2275	0.37	304	1800	281	30,294,000	Ran out - 30 MC
5	2054	M-5 A	PC-1	91	2275	0.37	304	1795	285.6	30,705,270	Ran out - 30 MC
6	2055	M-6 A	PC-2	91	2275	0.37	304	1800	286.6	30,898,800	Ran out - 30 MC
7	2034	M-5 B	PC-1	91	2275	0.37	304	1795	279.8	30,080,610	Ran out - 30 MC
8	2045	M-7 A	PC-1	117	2925	0.405	335	1795	4.7	452,340	3 teeth scored - stopped by Mike
9	2052	M-8 A	PC-2	103	2575	0.38	320	1800	304.1	33,116,688	Surface Origin Pitting
10	2051	M-9 A	PC-1	91	2275	0.37	304	1795	567	61,012,050	Ran out - 60 MC
11	2036	M-11A	PC-2	91	2275	0.37	304	1800	547.1	59,032,800	Surface Origin Pitting
12	2039	M-16 A	PC-1	91	2275	0.37	304	1795	74.8	8,002,110	Testing

Table 15 Scoring resistance test results for baseline wrought steel gears

Test # #	Gear ID #	Mate Gear	Start (hrs)	End (hrs)	Machine ID #	Load lbs	Torque lb-in	Contact in	Stress ksi	RPM	Oil Temp Start	Oil Temp End	Comment
1	B-6 A	M-10 B	0.0	3.0	PC-3	80	2000	0.5	278	2600	100	260	Scored
2	B-7 A	M-12 A	0.0	2.9	PC-3	80	2000	0.5	278	2600	100	260	Scored
3	B-8 A	M-12 B	0.0	3.2	PC-3	80	2000	0.5	278	2600	100	270	Scored
4	B-9 A	M-13 A	0.0	3.3	PC-3	80	2000	0.5	278	2600	100	270	Scored

Table 16 Scoring resistance test results for P/M-4620-HF-Ausf gears

Test # #	Gear ID #	Mate Gear	Start (hrs)	End (hrs)	Machine ID #	Load lbs	Torque lb-in	Contact in	Stress ksi	RPM	Oil Temp Start	Oil Temp End	Comment
1	2037	M-10 A	0.0	4.6	PC-3	80	2000	0.36	285	2600	100	300	No scoring.
2			4.6	8.2	PC-3	88	2200	0.37	299	2600	100	300	No scoring.
3			8.2	11.4	PC-3	96	2400	0.38	312	2600	100	300	No scoring.
4	2028	M-13 B	0.0	4.1	PC-3	80	2000	0.36	285	2600	100	300	No scoring.
5			4.1	7.2	PC-3	88	2200	0.37	299	2600	100	300	No scoring.
6			7.2	10.4	PC-3	96	2400	0.38	312	2600	100	300	No scoring.
7	2044	M-14 A	0.0	3.4	PC-3	80	2000	0.36	285	2600	100	300	Scored
8	2038	M-14 B	0.0	3.6	PC-3	80	2000	0.37	299	2600	100	300	No scoring.
9				7.1	PC-3	88	2200	0.37	299	2600	100	300	No scoring.
10				10.3	PC-3	88	2200	0.38	312	2600	100	300	No scoring.

Table 17 Scoring resistance test results for preausform P/M-4620-HF gears

Test # #	Gear ID #	Mate Gear	Machine ID #	Load lbs	Torque lb-in	Contact in	Stress ksi	RPM	Oil Temp Start	Oil Temp End	Comment
1	2101-A	M-15 A	PC-3	72	1800	0.5	263	2600	100	300	Scored
2	2101-B		PC-3	72	1800	0.5	263	2600	100	220	Scored

Table 18 Gear tooth impact test results for baseline wrought steel gears

#	Gear #	Tooth #	Drop Ht	Peak Load (N)	Mean Peak Load (N)	Energy (N.m)	Mean Energy (N.m)
1	Baseline Gear B-102	5	5"	48843	48032	41.18	39.37
2	Baseline Gear B-102	6	5"	49190		42.91	
3	Baseline Gear B-102	7	5"	46062		34.01	
4	Baseline Gear B-102	10	10"	47626	46989	39.22	39.30
5	Baseline Gear B-102	9	10"	46236		37.73	
6	Baseline Gear B-102	8	10"	47105		40.95	
7	Baseline Gear B-101	1	20"	47626	47974	43.43	44.21
8	Baseline Gear B-101	2	20"	47626		44.07	
9	Baseline Gear B-101	3	20"	48669		45.12	

Table 19 Gear tooth impact test results for P/M-4620-HF-Ausf gears

#	Gear #	Tooth #	Drop Ht	Peak Load (N)	Mean Peak Load (N)	Energy (N.m)	Mean Energy (N.m)
1	Ausformed Gear PM-2031	2	5"	44497	43107	43.71	40.28
2	Ausformed Gear PM-2031	10	5"	43281		43.58	
3	Ausformed Gear PM-2031	9	5"	41542		33.54	
4	Ausformed Gear PM-2027	1	10"	43454	43107	51.14	51.87
5	Ausformed Gear PM-2027	2	10"	42759		52.6	
6	Ausformed Gear PM-2027	10	20"	39084	40748	37.81	44.70
7	Ausformed Gear PM-2027	9	20"	42412		51.59	

Table 20 Gear tooth impact test results for preausform P/M-4620-HF gears

#	Gear #	Tooth #	Drop Ht	Peak Load (N)	Mean Peak Load (N)	Energy (N.m)	Mean Energy (N.m)
1	Preausform Gear PM-2006	1	5"	51972	51711	45.57	44.73
2	Preausform Gear PM-2006	2	5"	51450		43.88	
3	Preausform Gear PM-2006	10	10"	53362	52406	49.36	47.00
4	Preausform Gear PM-2006	9	10"	51450		44.64	

Table 21 Manufacturing process cost comparison for wrought steel gears and P/M steel gears

Process Summary	Cost / Unit	Annual Cost*	% Cost Avoidance	
			Current NPG Process	"Modified" NPG Process
NPG current wrought steel gears process (Figure 4)	\$2.41	\$23.1 M		37%
"Modified" NPG process for ground wrought steel gears (Figure 75)	\$3.80	\$36.5 M	-37%	
High Strength P/M 4620 C/H Steel Gears (Figure 12)	\$2.16	\$20.7 M	10%	43%
High Strength P/M 4680 Steel Gears (Figure 13)	\$2.15	\$20.6 M	11%	44%
"Modified" High Strength P/M 4620 C/H Steel Gears (Figure 76)	\$1.86	\$17.9 M	23%	51%
"Modified" High Strength P/M 4680 Steel Gears (Figure 77)	\$1.85	\$17.8 M	23%	51%

* Annual costs based on a daily production of 40,000 parts

Table 22 Manufacturing process cycle time comparison for wrought steel and P/M steel gears

Process Summary	Process Cycle Time (hr/piece)	%Reduction (vs. NPG Process)
NPG current wrought steel gears process (Figure 4)	14.08	
"Modified" NPG process for ground wrought steel gears (Figure 75)	14.09	
High Strength P/M 4620 C/H Steel Gears (Figure 12)	5.13	64%
High Strength P/M 4680 Steel Gears (Figure 13)	16.12	-14%
“Modified” High Strength P/M 4620 C/H Steel Gears (Figure 76)	5.12	63%
“Modified” High Strength P/M 4680 Steel Gears (Figure 77)	16.10	-14%

Figures

Figure 1 Baseline wrought steel gear: 8 DP, 24 teeth, 18.65° pressure angle, 0.5" face width spur gear

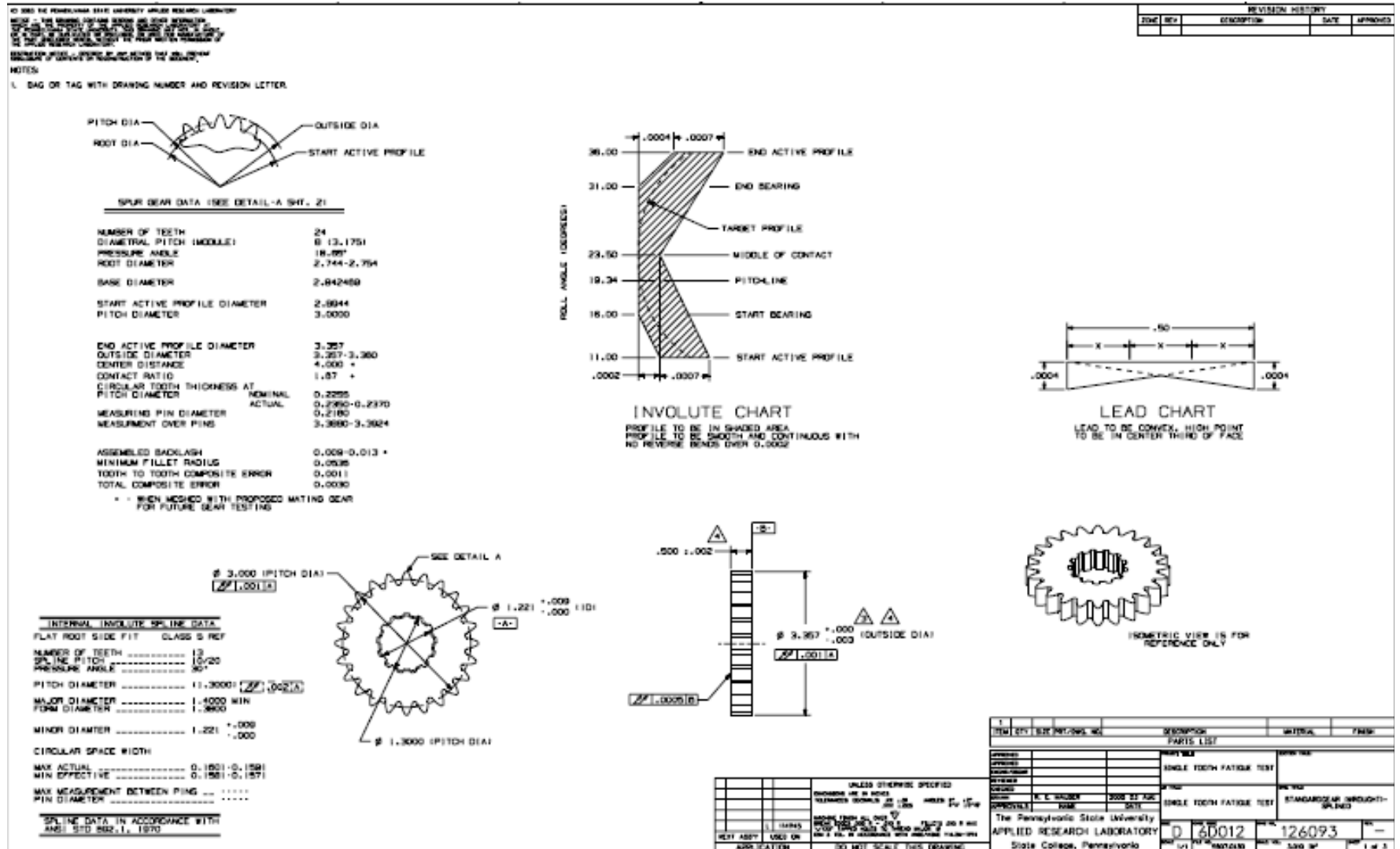


Figure 2 Mate gear for surface durability tests: 8 DP, 40 teeth, 18.65° pressure angle, 1.0" face width spur gear

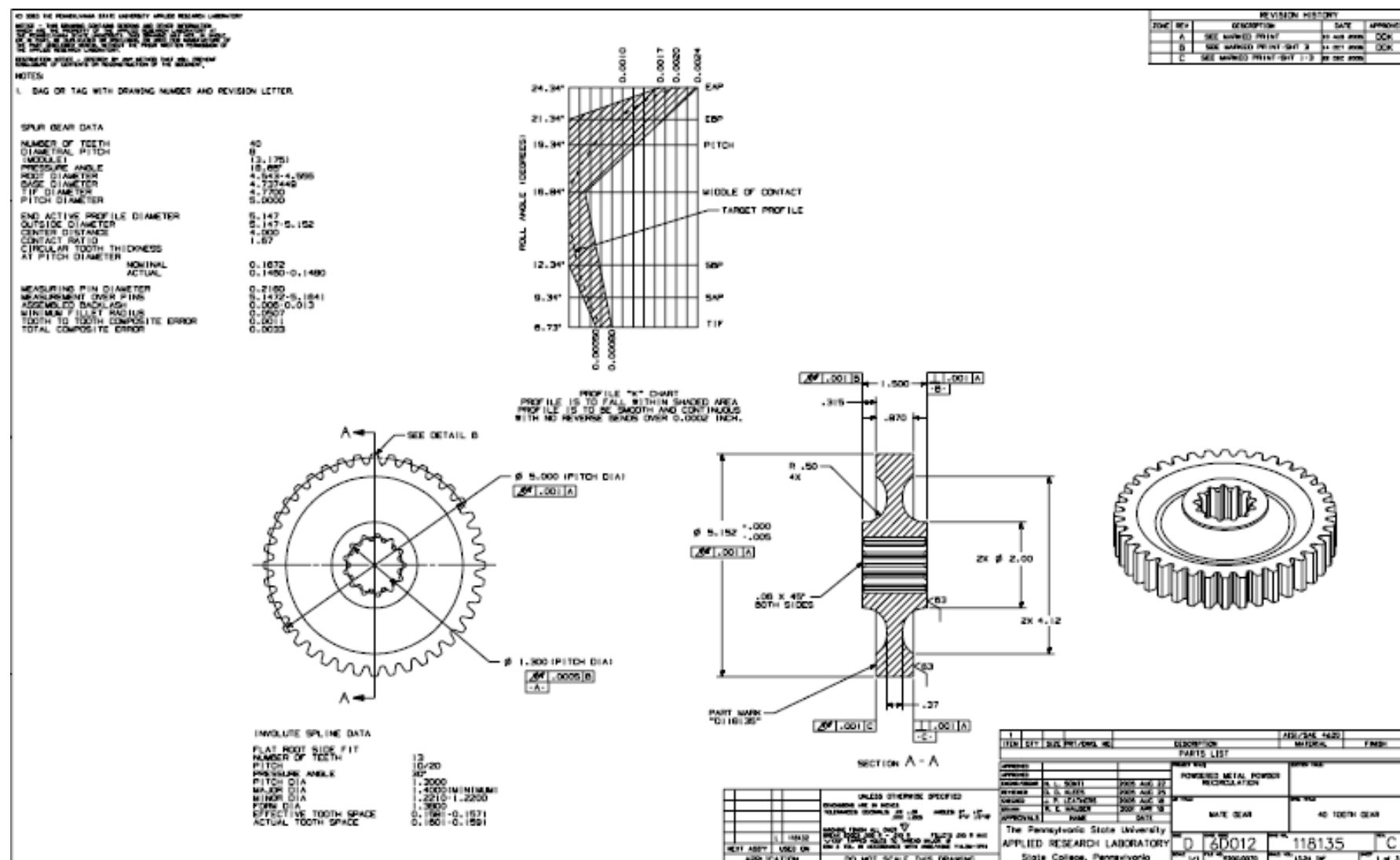


Figure 3 Focus planetary helical pinion: 19 teeth, 16 TDP, 17.5° normal pressure angle, 1.4" face width, 19° helix angle

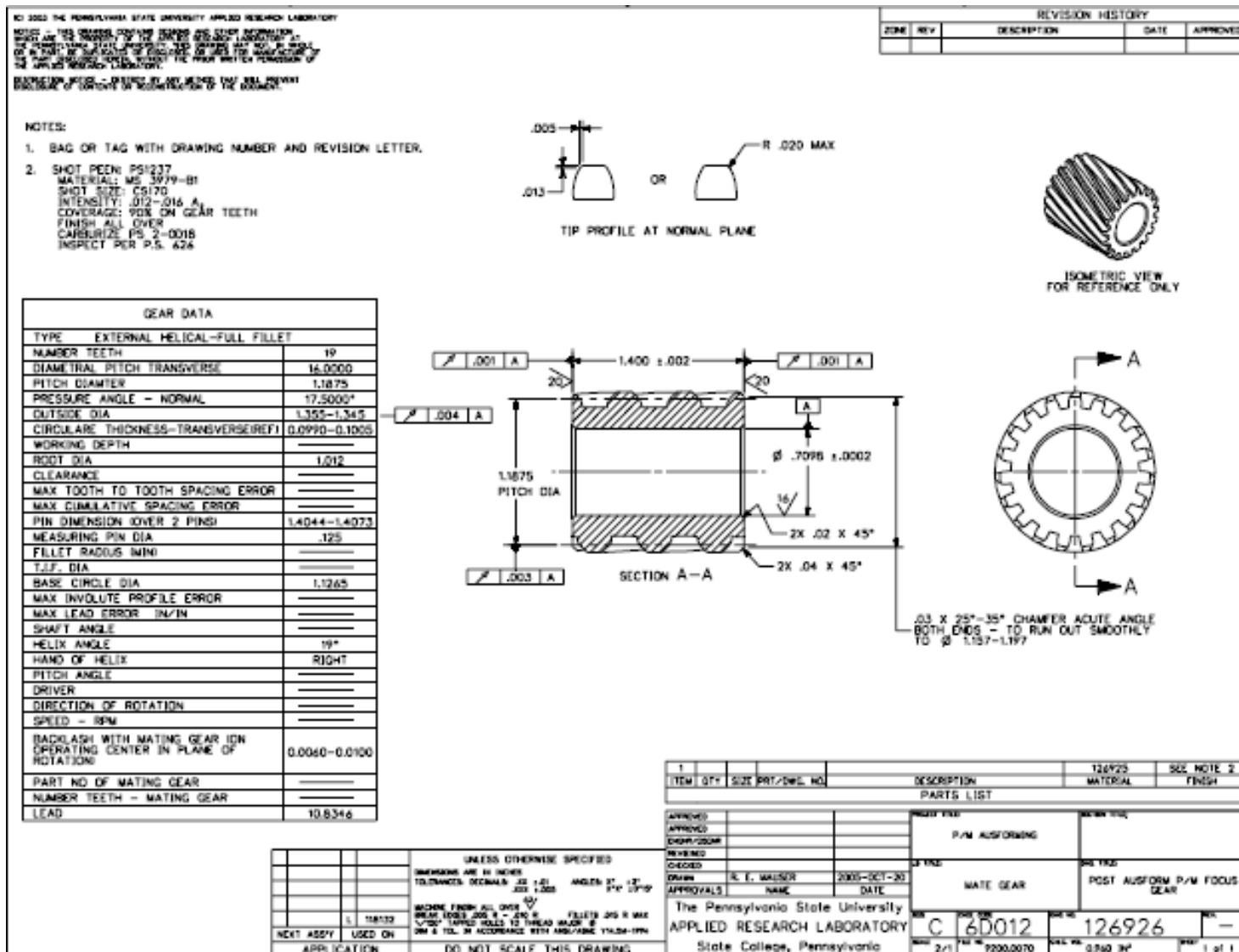
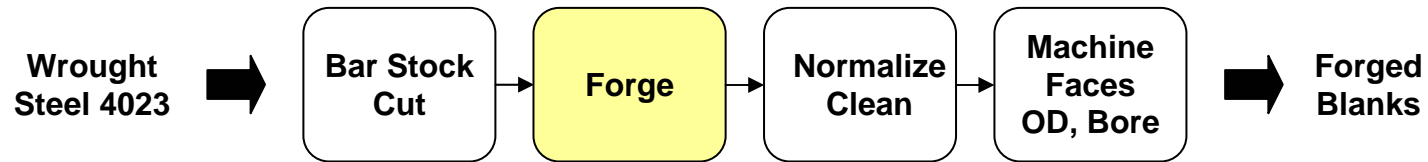


Figure 4 **Current NPG manufacturing process sequence to produce focus gears (planetary helical pinions)**

a. Forged Blanks Procured from



b. NPG Manufacturing Process

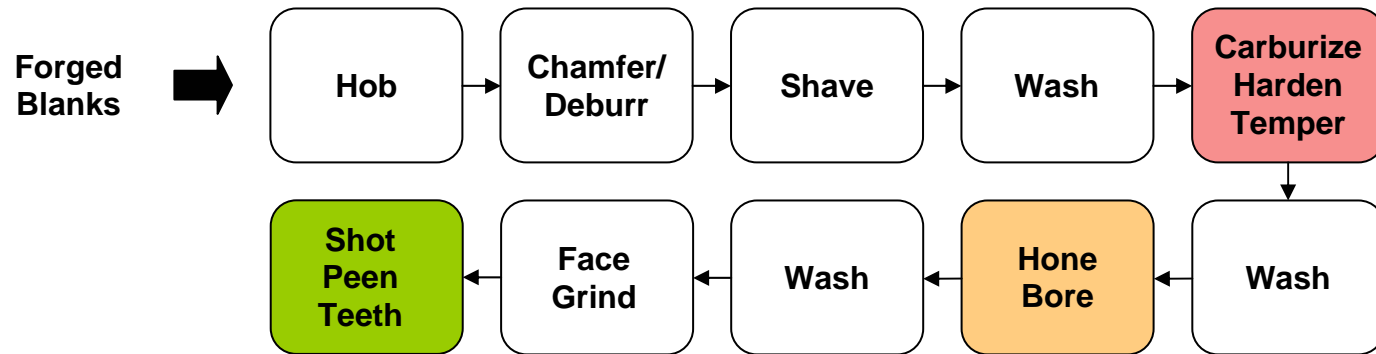


Figure 5 Ausforming process depicted on a typical Time-Temperature-Transformation diagram

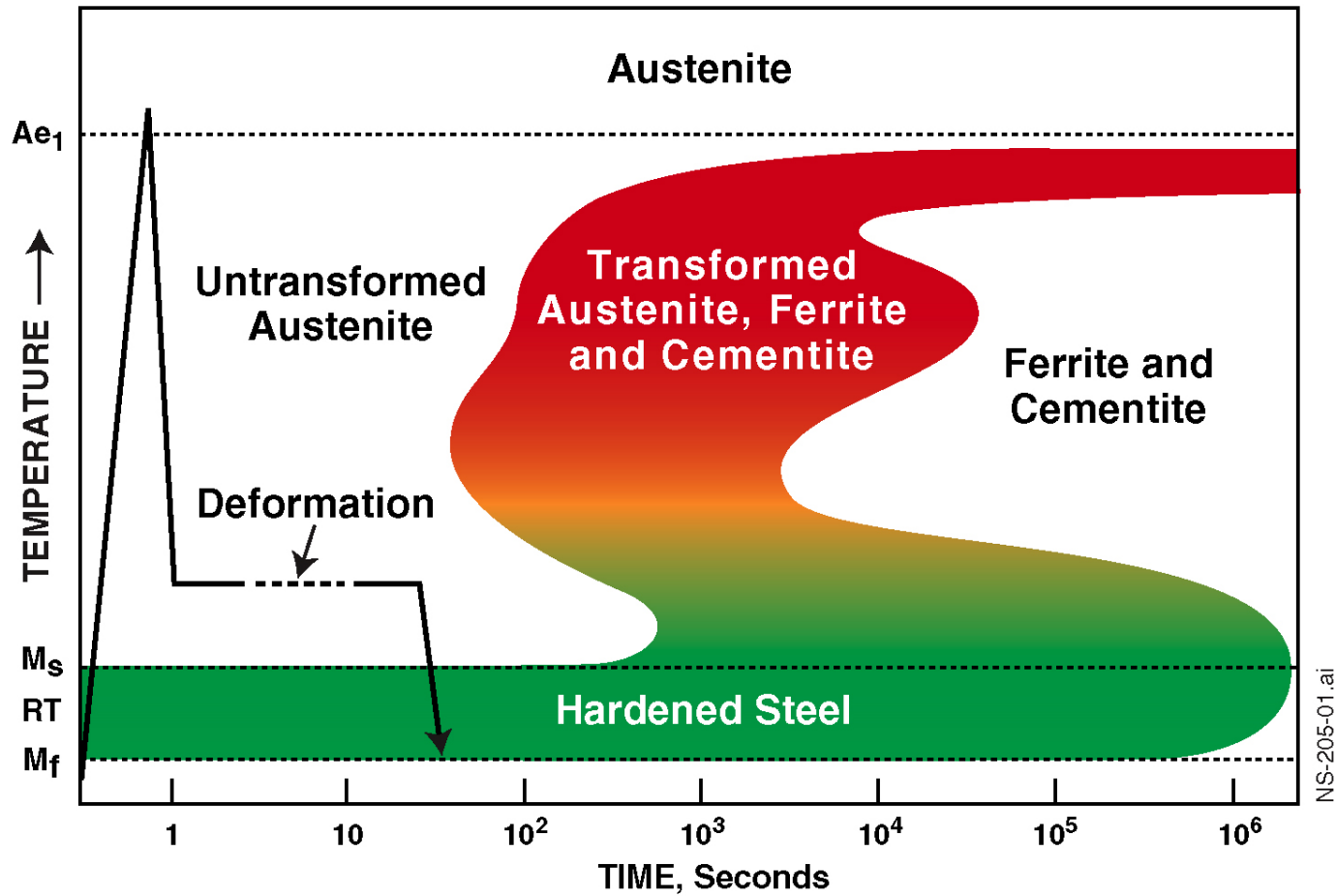


Figure 6 **Examples of increase in strength due to ausforming**

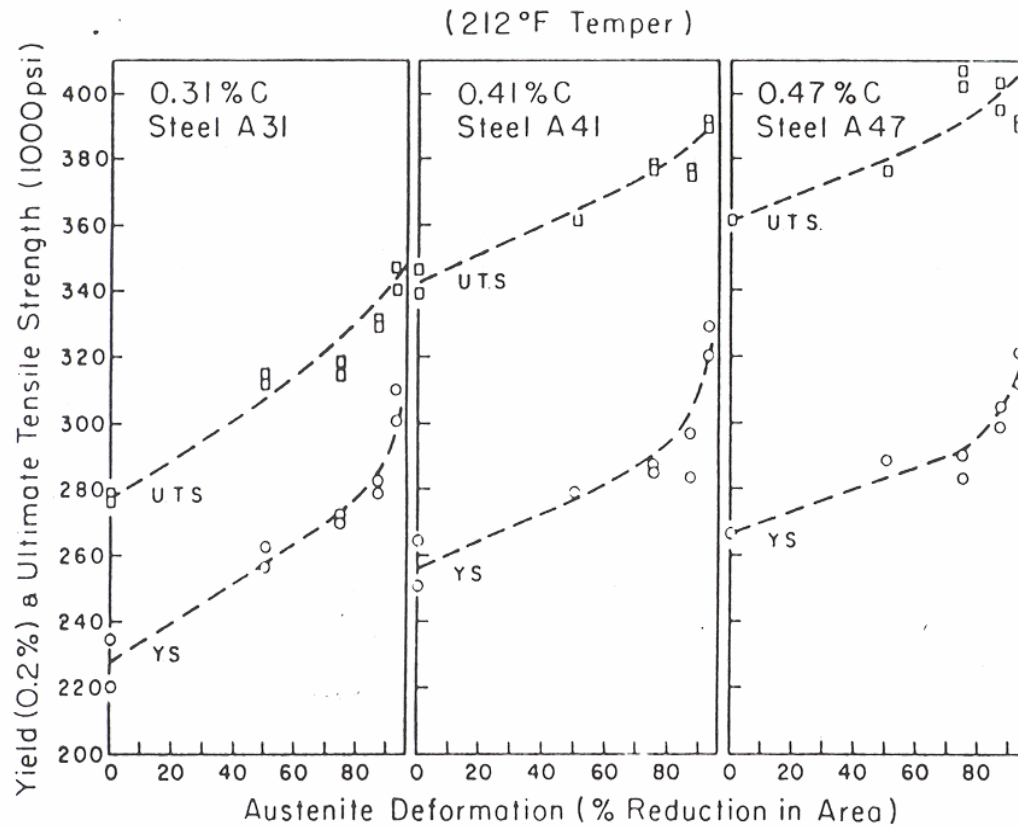


Fig. 2—Yield and Ultimate Tensile Strength as Influenced by Deformation of Meta-stable Austenite. These data refer to air melted steels tempered at 212 °F.

Figure 7 **Rolling contact fatigue life of ausformed RCF balls as compared to conventionally processed parts**

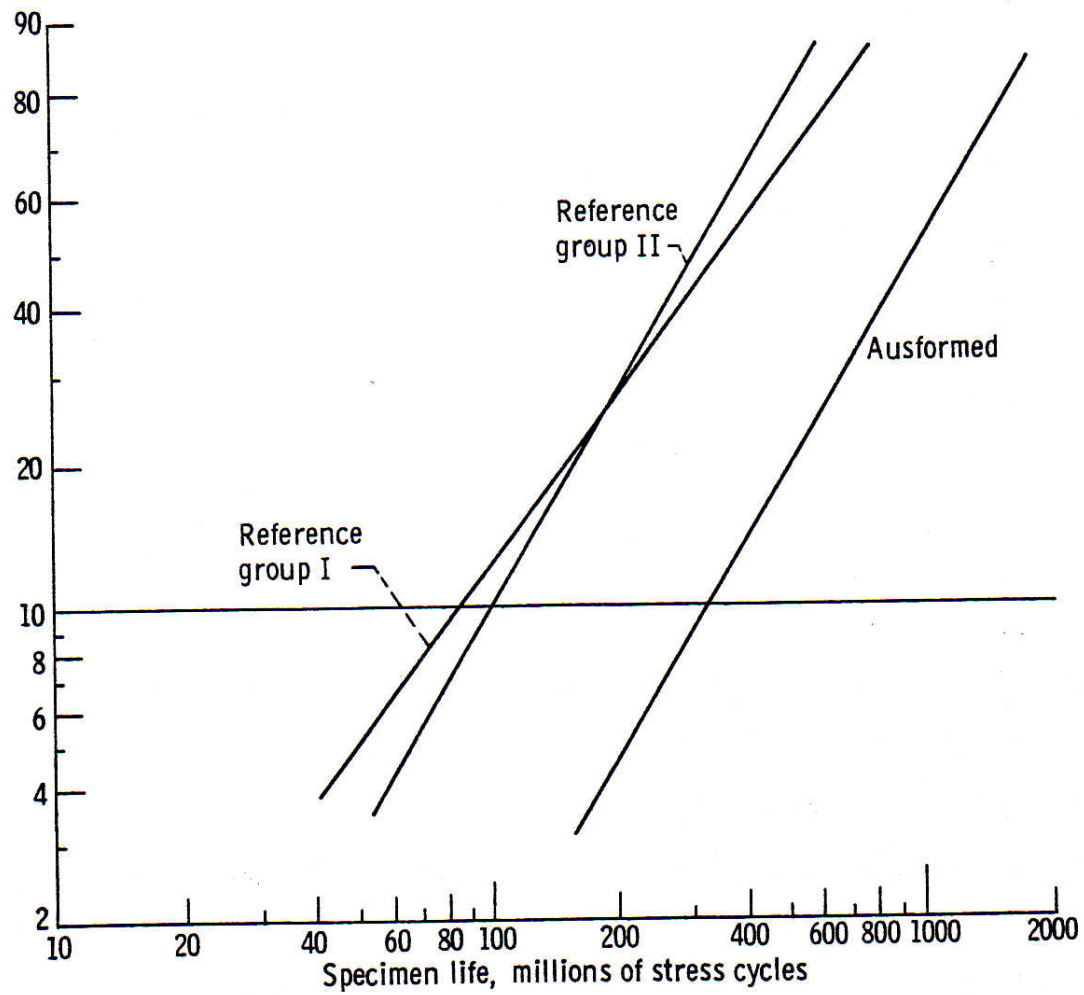


Figure 8 Increase in B_{10} life as a function of amount of plastic deformation of metastable austenite during ausforming

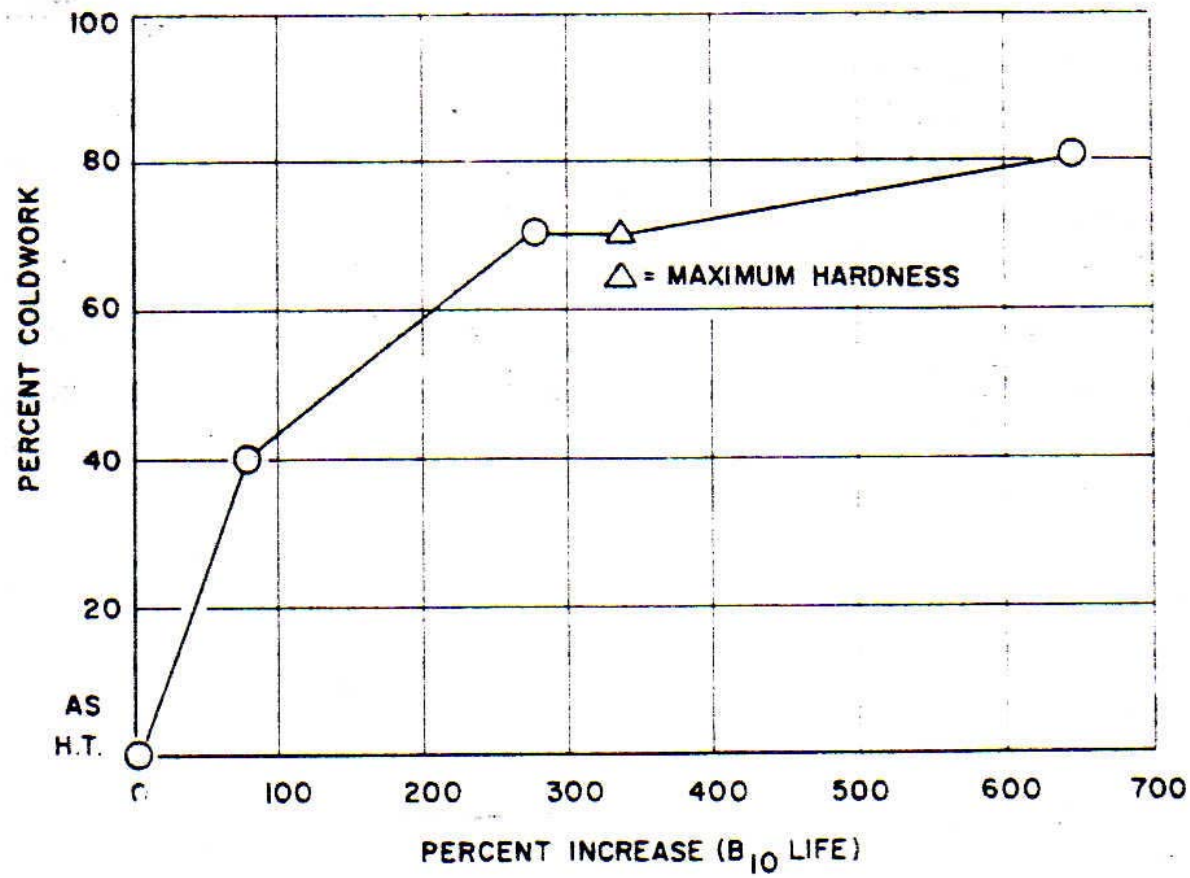


Figure 9 **Performance of ausformed bearings relative to conventional bearings**

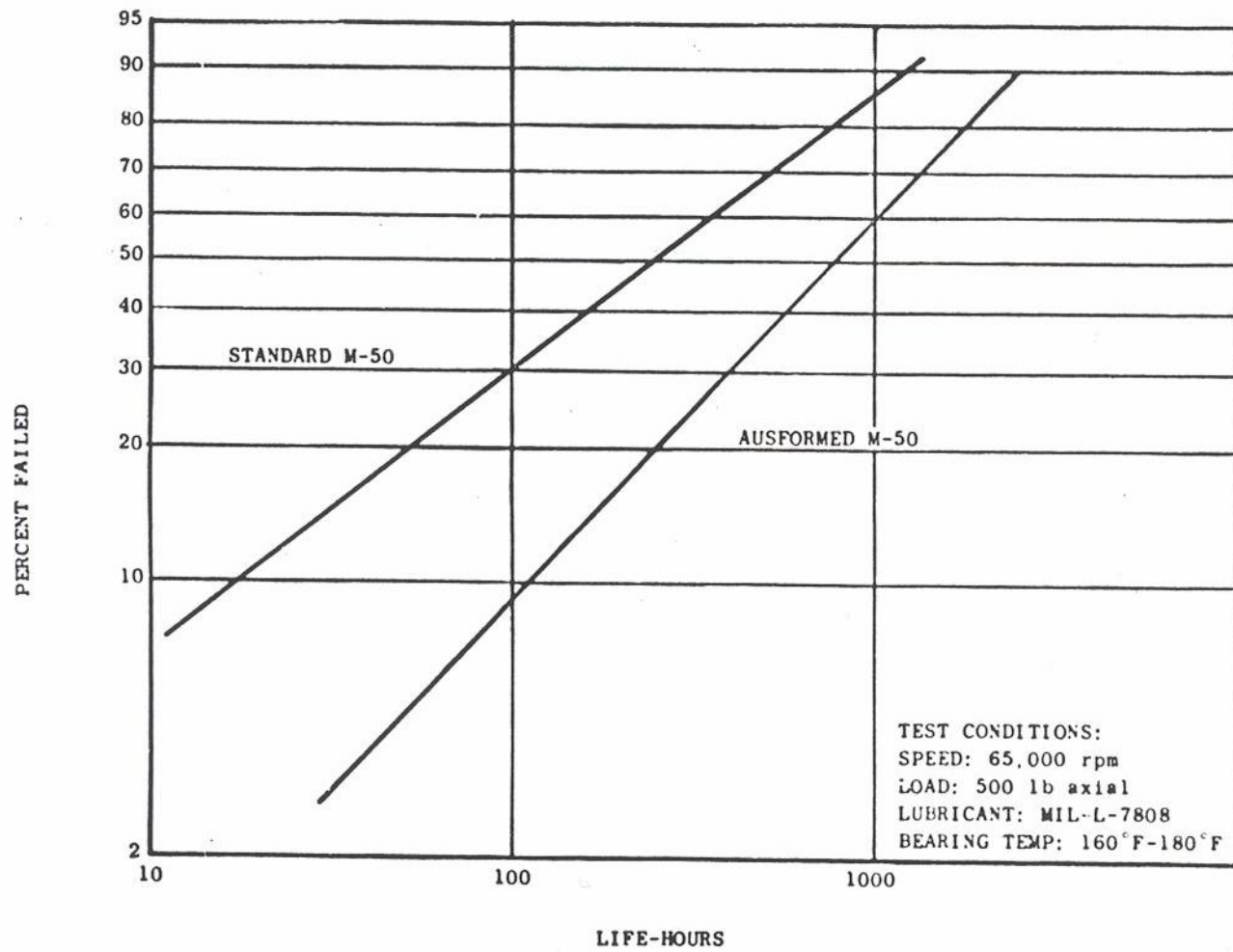


Figure 10 Schematic of ausform gear finishing process

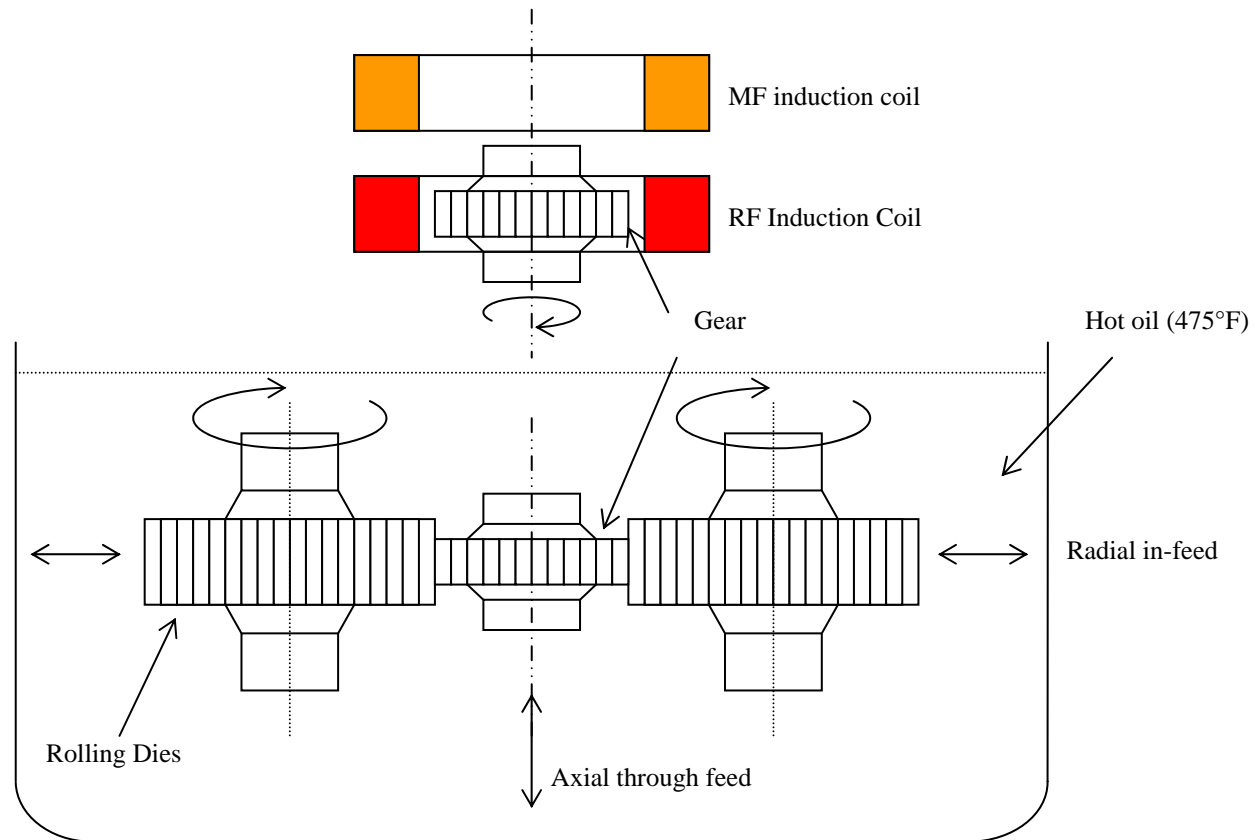


Figure 11 Double die ausform gear finishing machine, and views of induction heating and gear roll finishing equipment

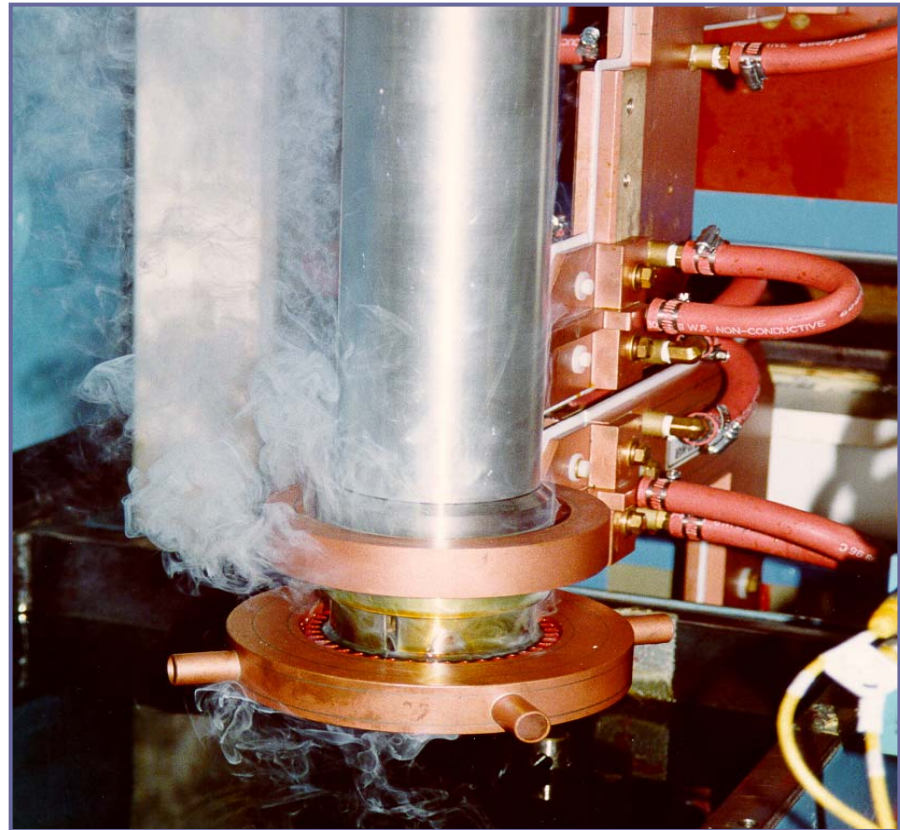
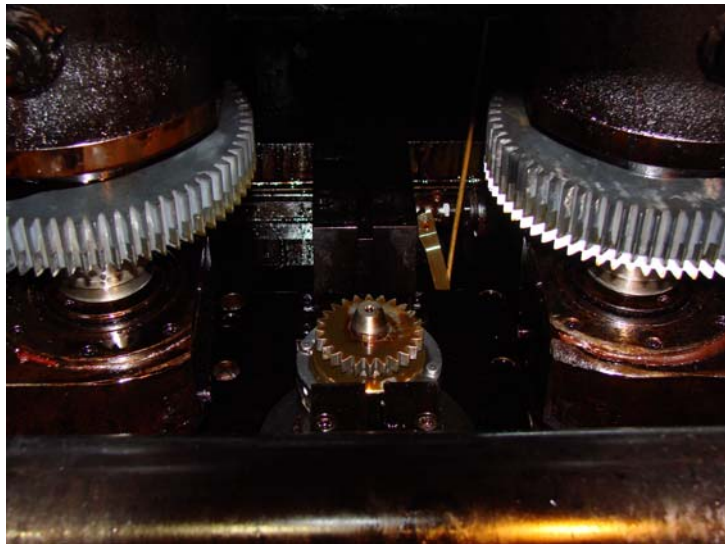
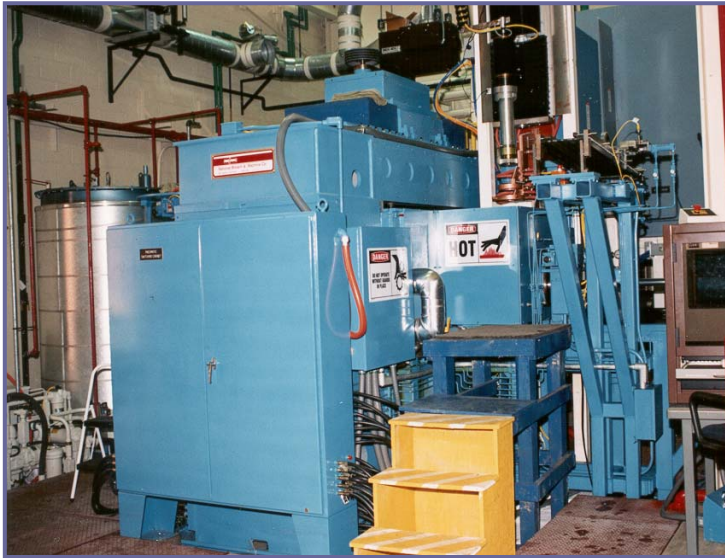


Figure 12 **Process sequence for P/M-4620-HF-Ausf gears**

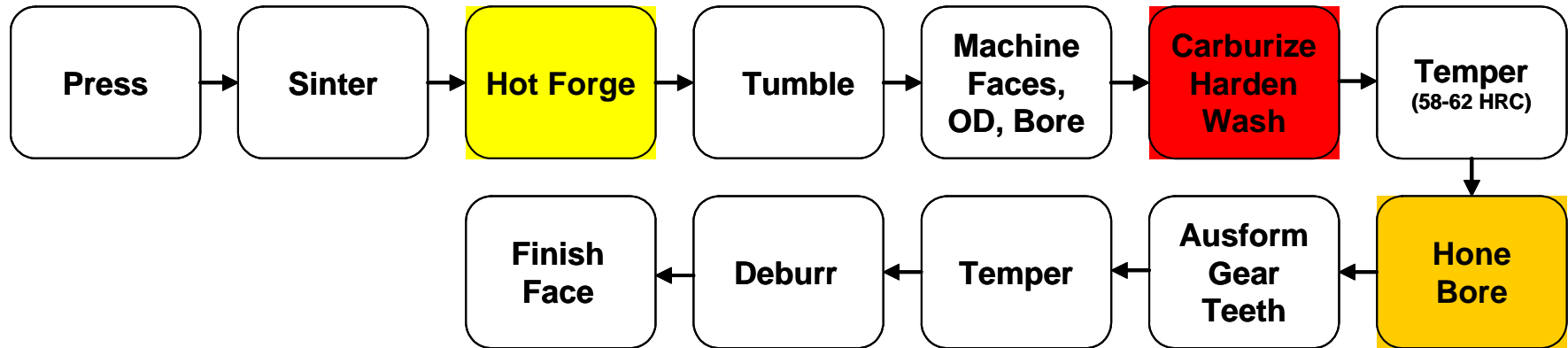


Figure 13 Process sequence for P/M-4680-HF-Ausf gears

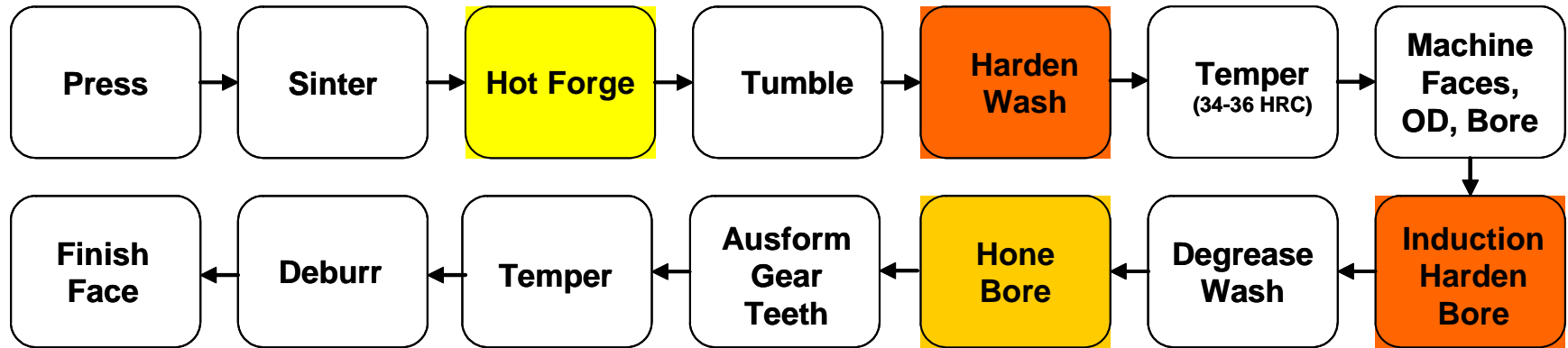


Figure 14 Preausform P/M steel Standard gear design: 8 DP, 24 teeth, 18.65° pressure angle, 0.5” face width spur gear

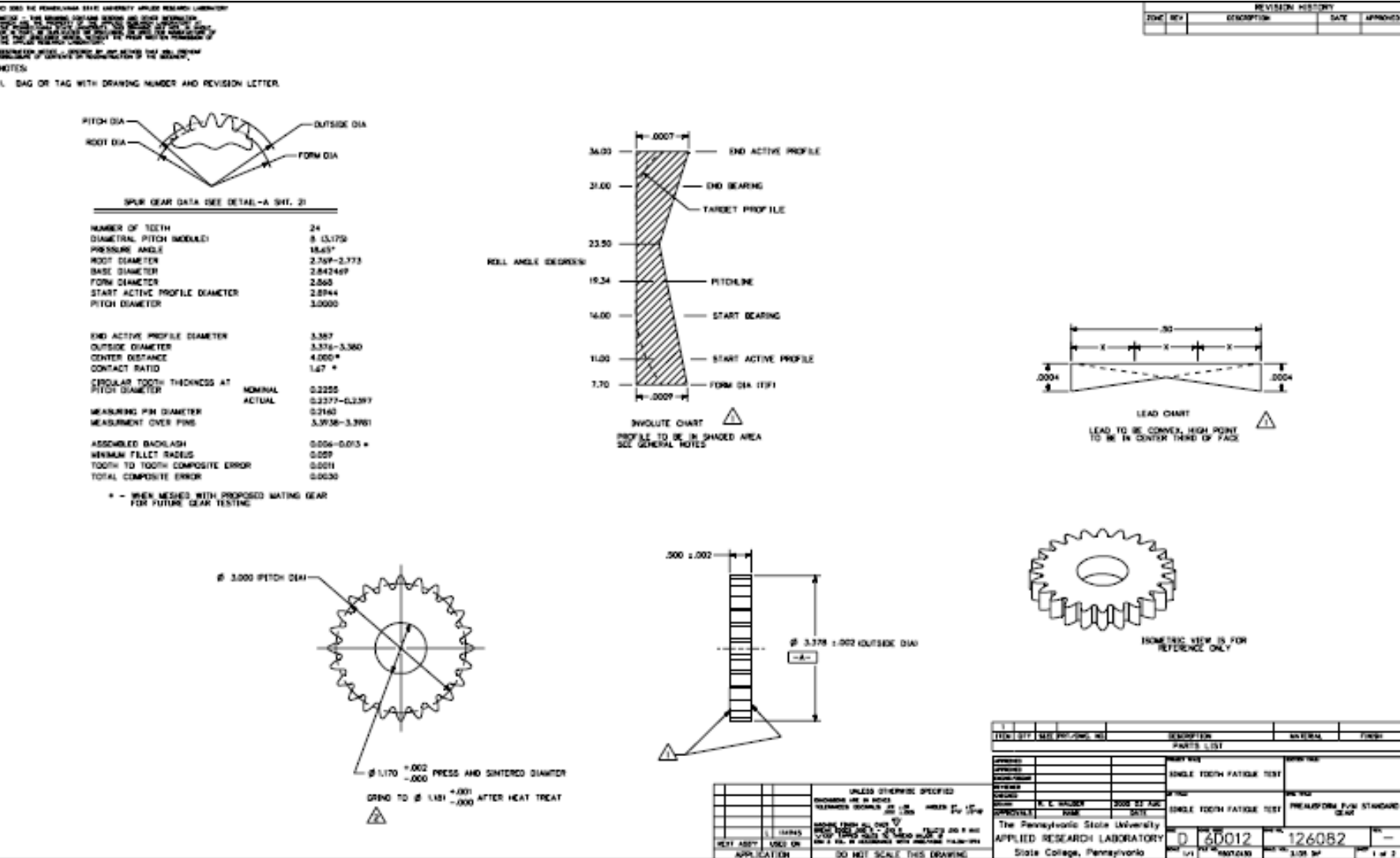


Figure 15 Heat treat specifications for P/M-4620-HF-Ausf gear

- **Process sequence**

Press and sinter

Hot forge and air cool

Carburize, direct quench and temper

- **Metallurgical specifications in the preausform as-hardened condition**

Surface hardness

58-63 HRC

Surface carbon

0.80% \pm 0.05%

Surface microstructure

Tempered martensite

Retained austenite

<15%

Effective case depth to 50 HRC

@ tooth half height

0.030"-0.040" (aim middle)

45° to root fillet

0.015" minimum

Tooth centerline @ half height

34 HRC (minimum)

Tooth centerline @ root diameter

27 HRC (minimum)

Tooth centerline 1/8" below root

23 HRC (minimum)

Inter-granular oxides

0.0002" (maximum)

Figure 16 Heat treat specifications for P/M-4620-HF-Ausf gear

- **Prior processing**

Press and sinter

Hot forge and air cool

Reheat and oil quench

Temper to achieve 34-36 HRC in case

- Metallurgical specifications in the preausform Q&T condition

Surface hardness 34-36 HRC

Surface microstructure Tempered martensite

Tooth centerline @ half height 30 HRC (minimum)

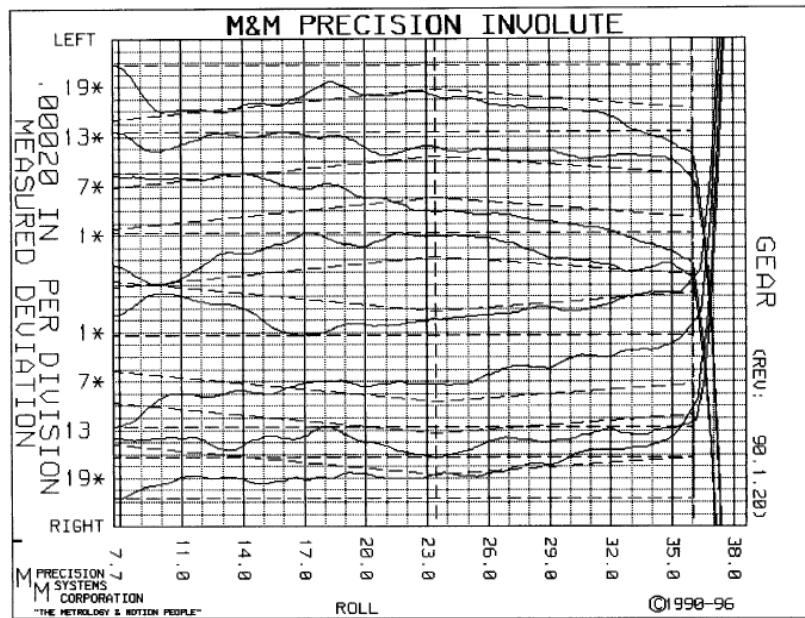
Tooth centerline @ root diameter 30 HRC (minimum)

Tooth centerline 1/8" below root 30 HRC (minimum)

(Final surface hardness and desired effective case depth with tempered martensitic microstructure will be achieved during the ausforming operation.)

Figure 17 Profile inspection charts for preausform P/M-4620-HF and P/M-4680-HF gears

a. Preausform P/M-4620-HF gear



b. Preausform P/M-4680-HF gear

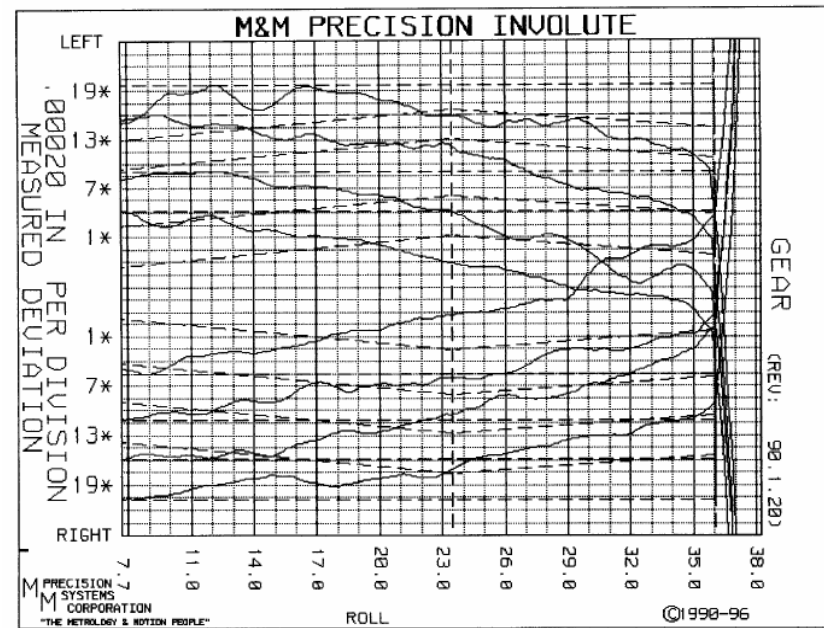
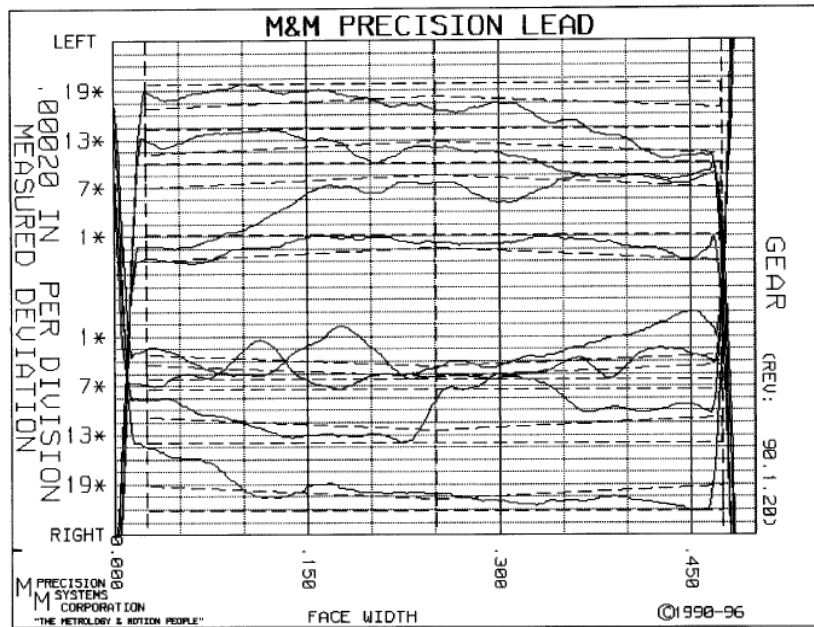


Figure 18 Profile inspection charts for preausform P/M-4620-HF and P/M-4680-HF gears

a. Preausform P/M-4620-HF gear



b. Preausform P/M-4680-HF gear

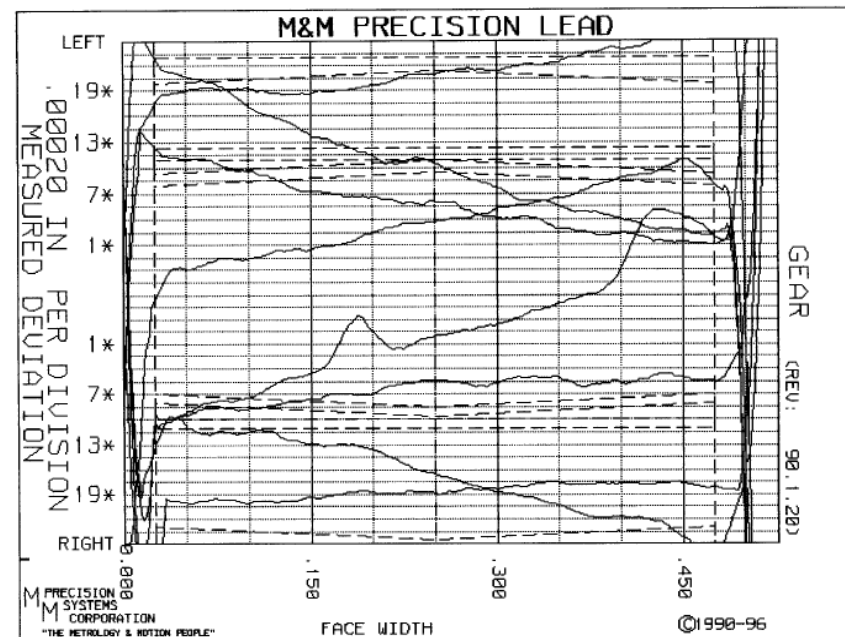
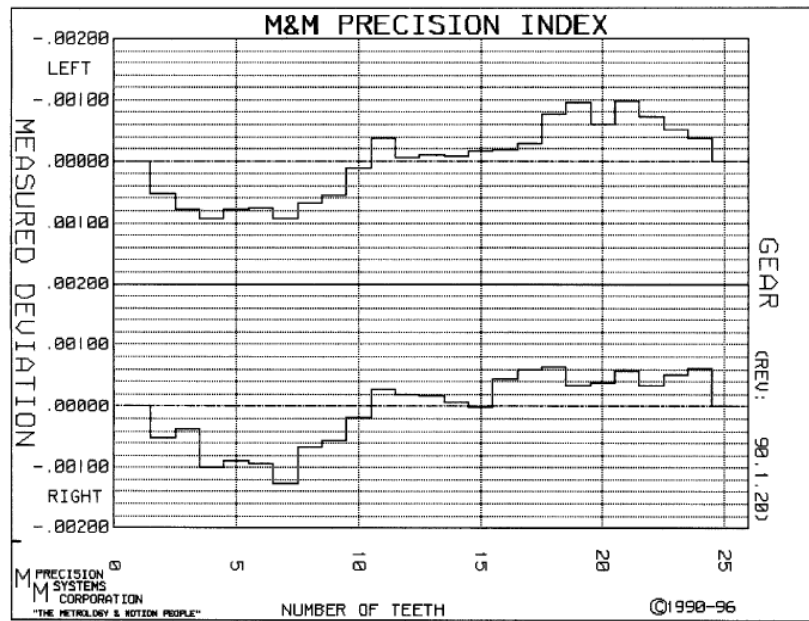


Figure 19 Profile inspection charts for preausform P/M-4620-HF and P/M-4680-HF gears

a. Preausform P/M-4620-HF gear



b. Preausform P/M-4680-HF gear

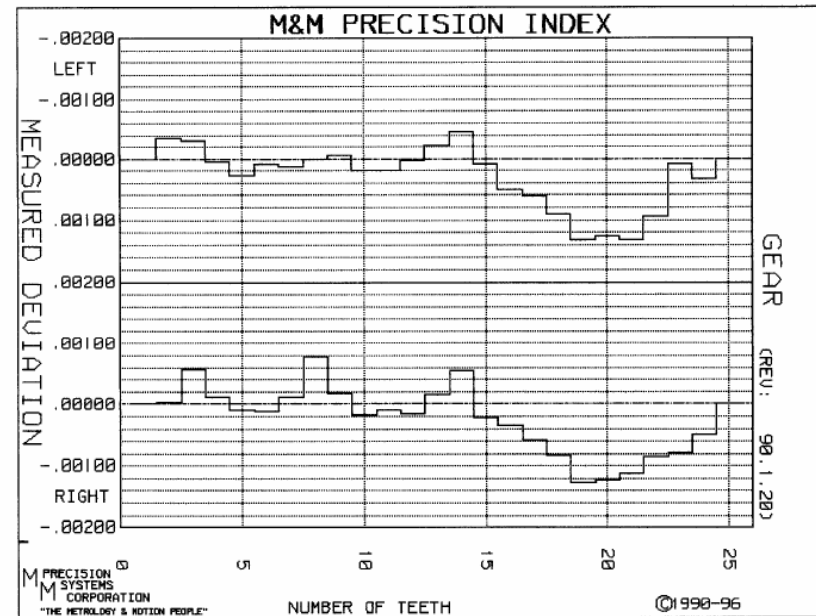


Figure 20 **Comparison of preausform P/M-4620-HF and P/M-4680-HF gear tooth geometry**

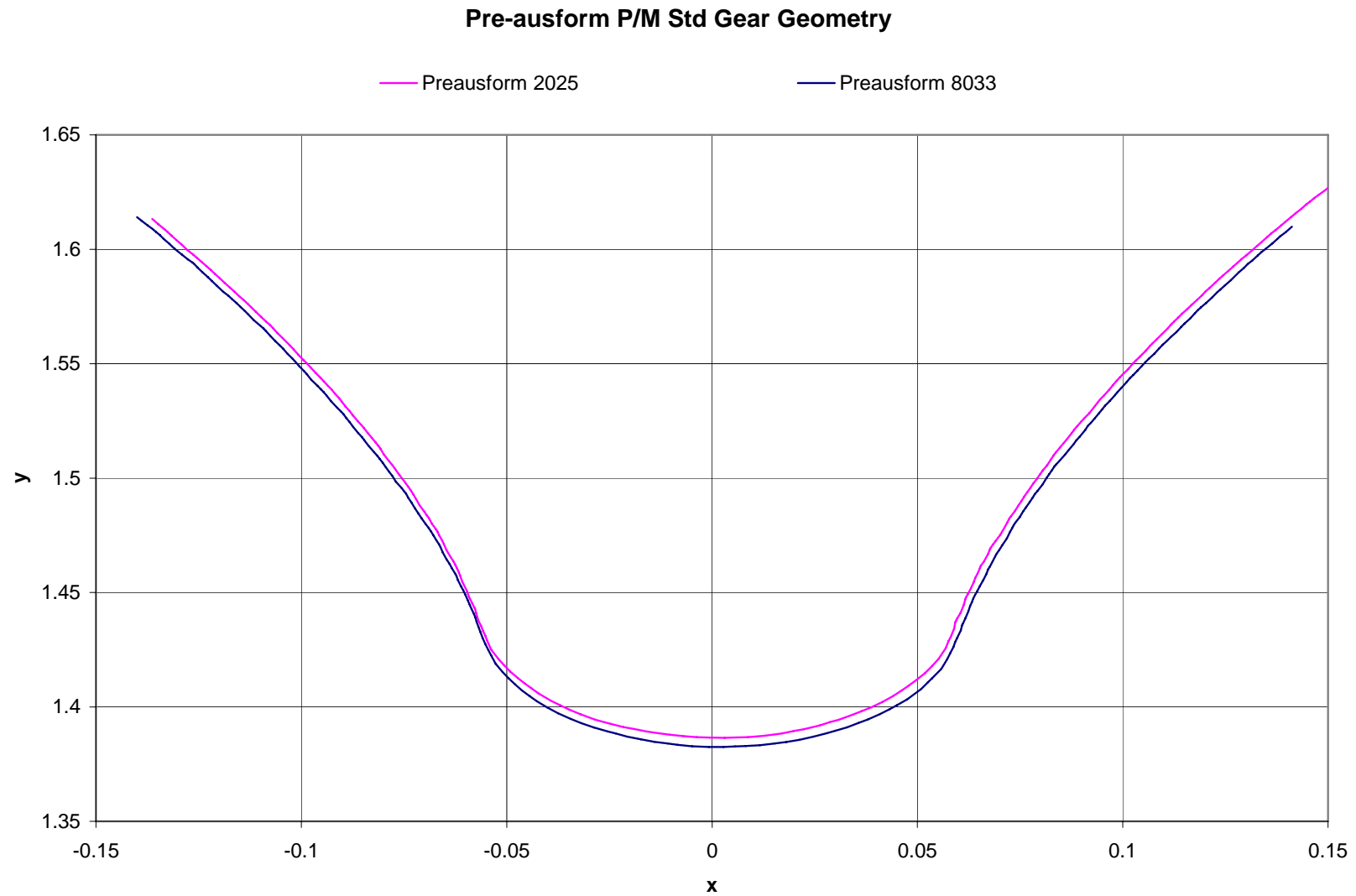
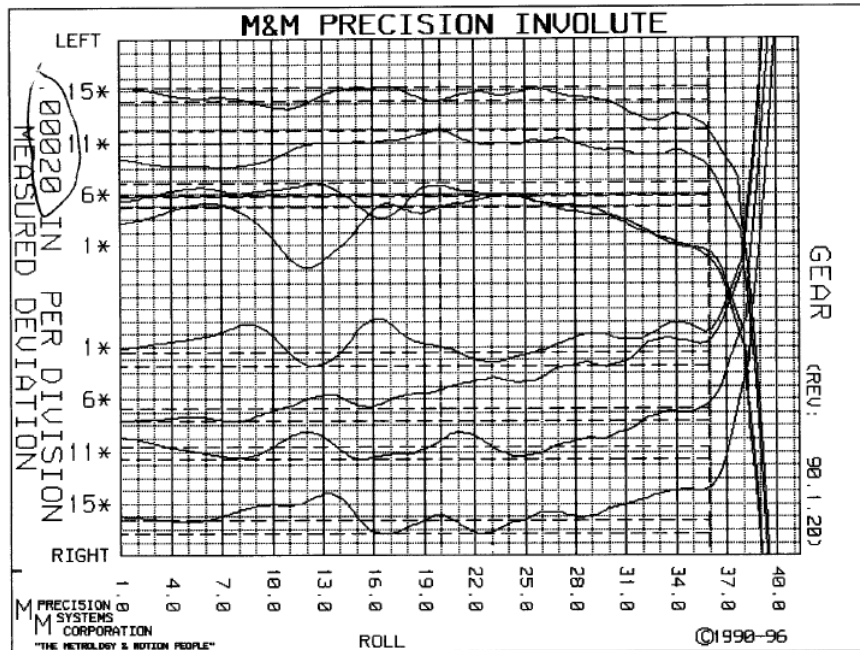


Figure 21 Preausform P/M focus gear tooth profile charts

a. Preausform P/M-4620-HF focus gear



b. Preausform P/M-4680-HF focus gear

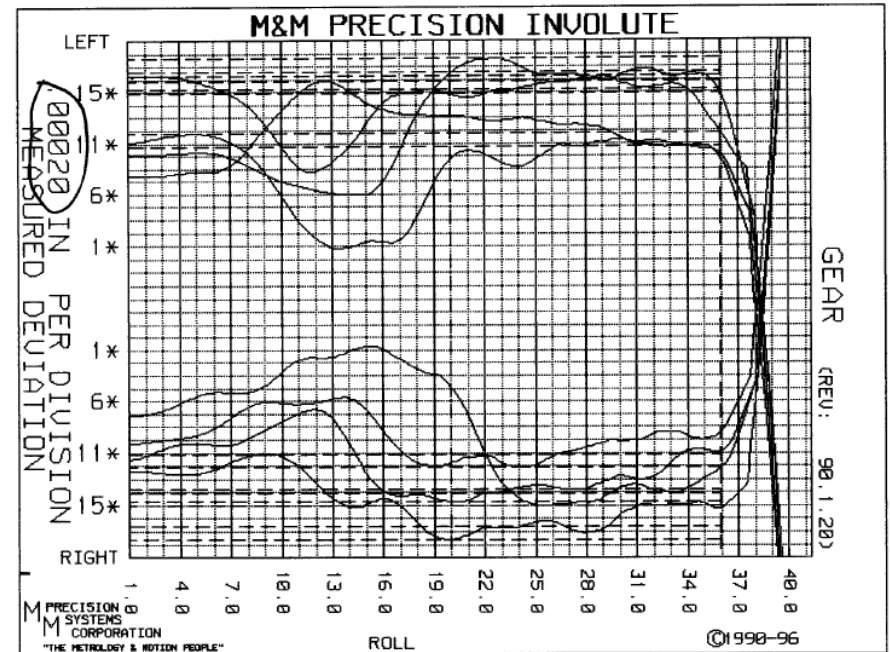


Figure 22 Preausform P/M focus gear lead charts

a. Preausform P/M-4620-HF focus gear

b. Preausform P/M-4680-HF focus gear

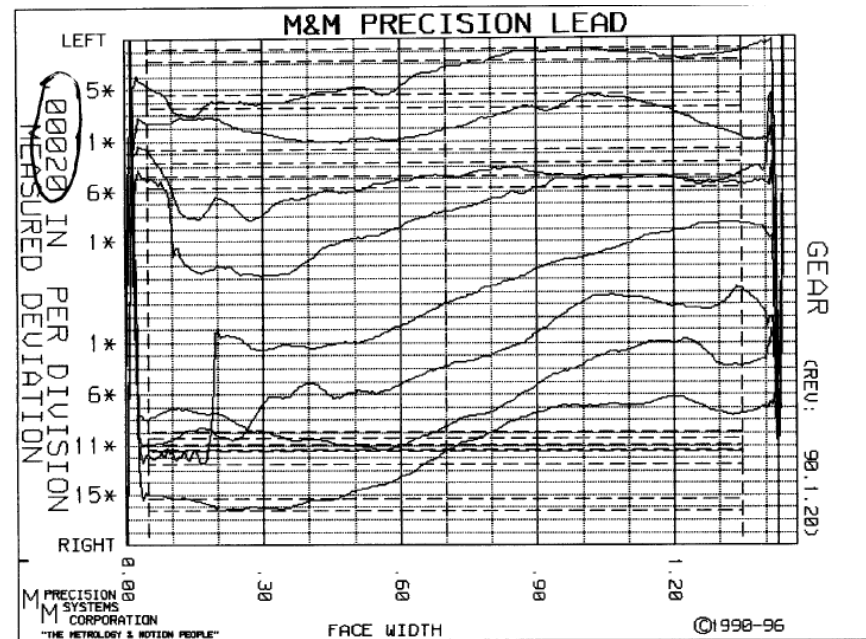
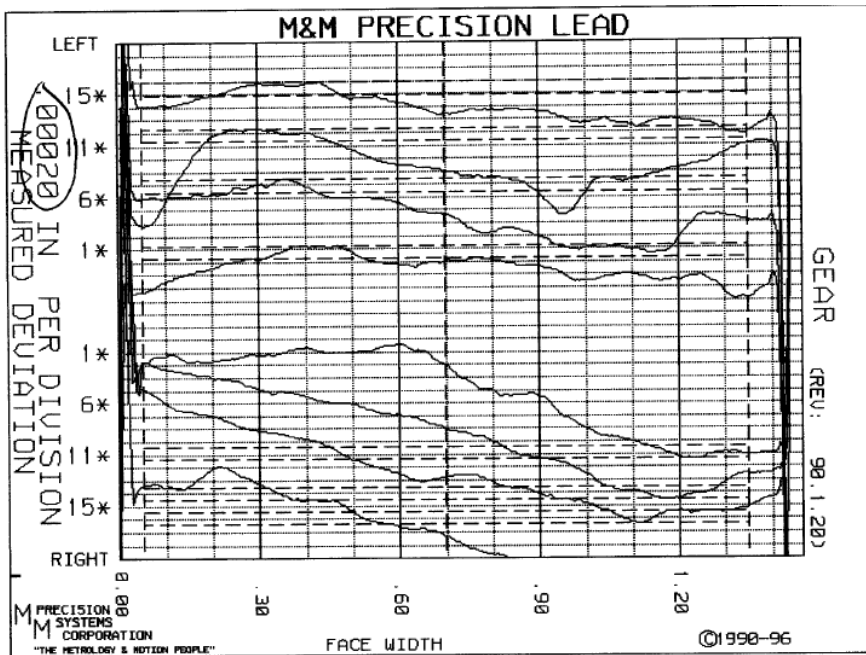


Figure 23 Preausform P/M focus gear tooth spacing chart

a. Preausform P/M-4620-HF focus gear

b. Preausform P/M-4680-HF focus gear

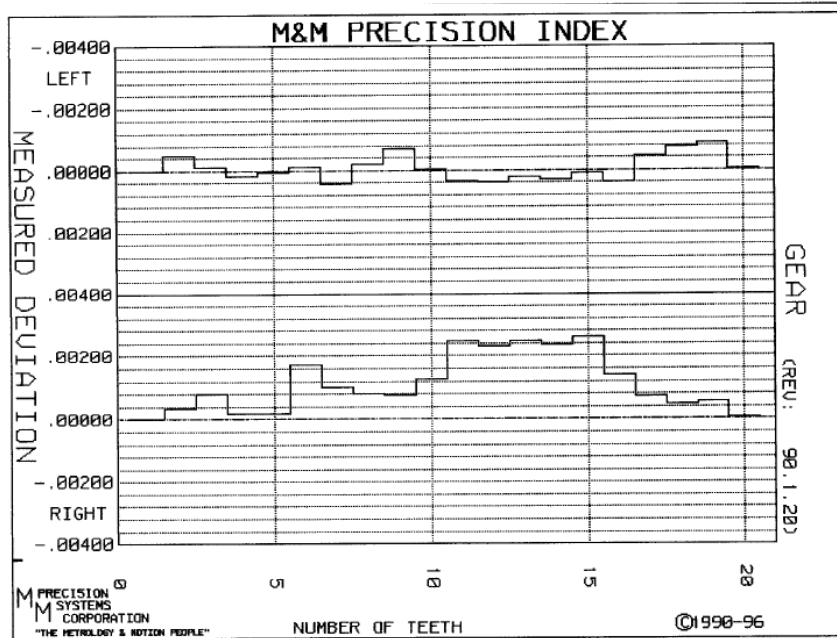


Figure 24 Zeiss CMM comparison of the root region of preausform P/M-4620-HF and P/M-4680-HF focus gears

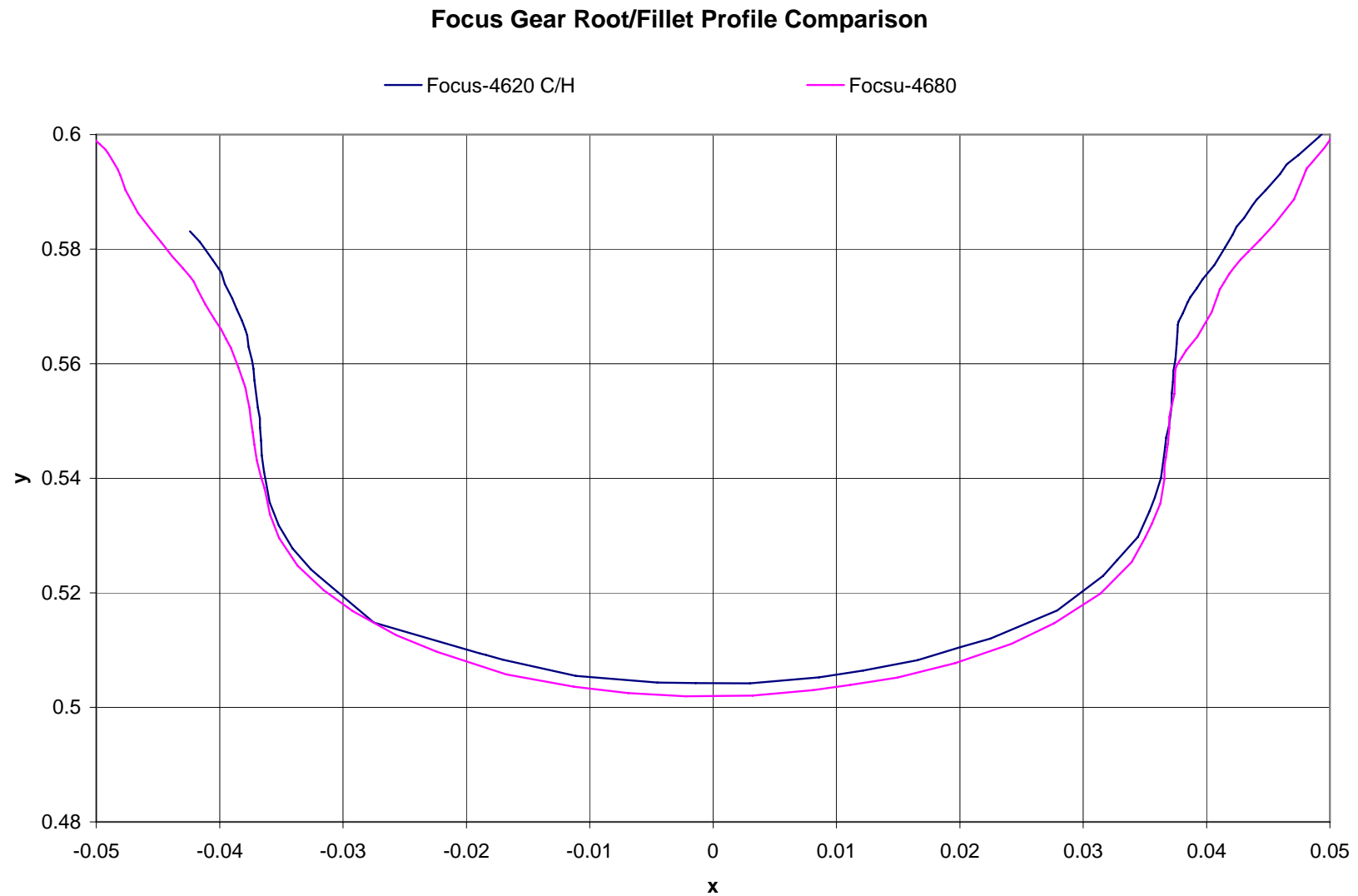


Figure 25 Baseline gear profile chart

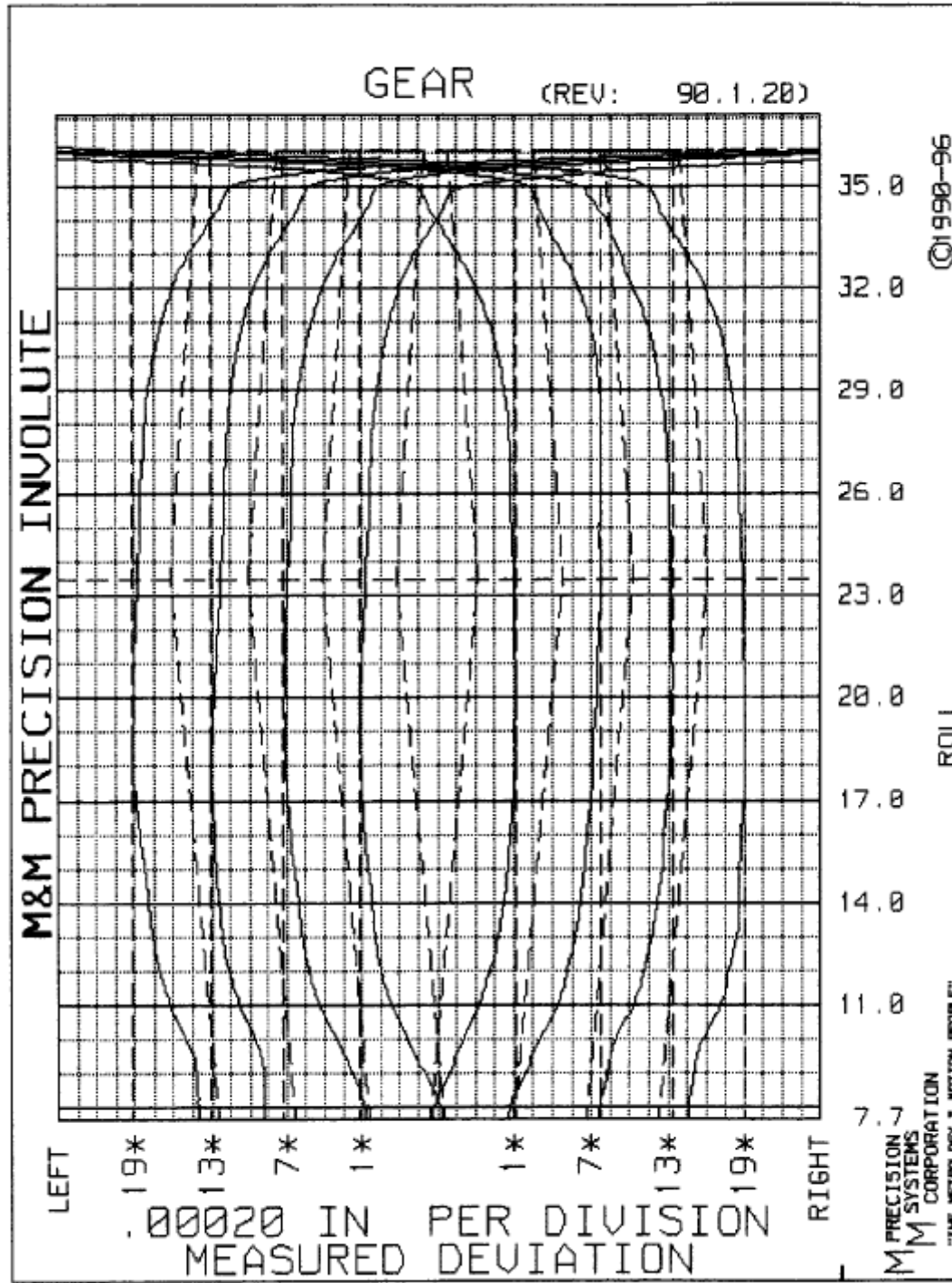


Figure 26 Baseline gear lead chart

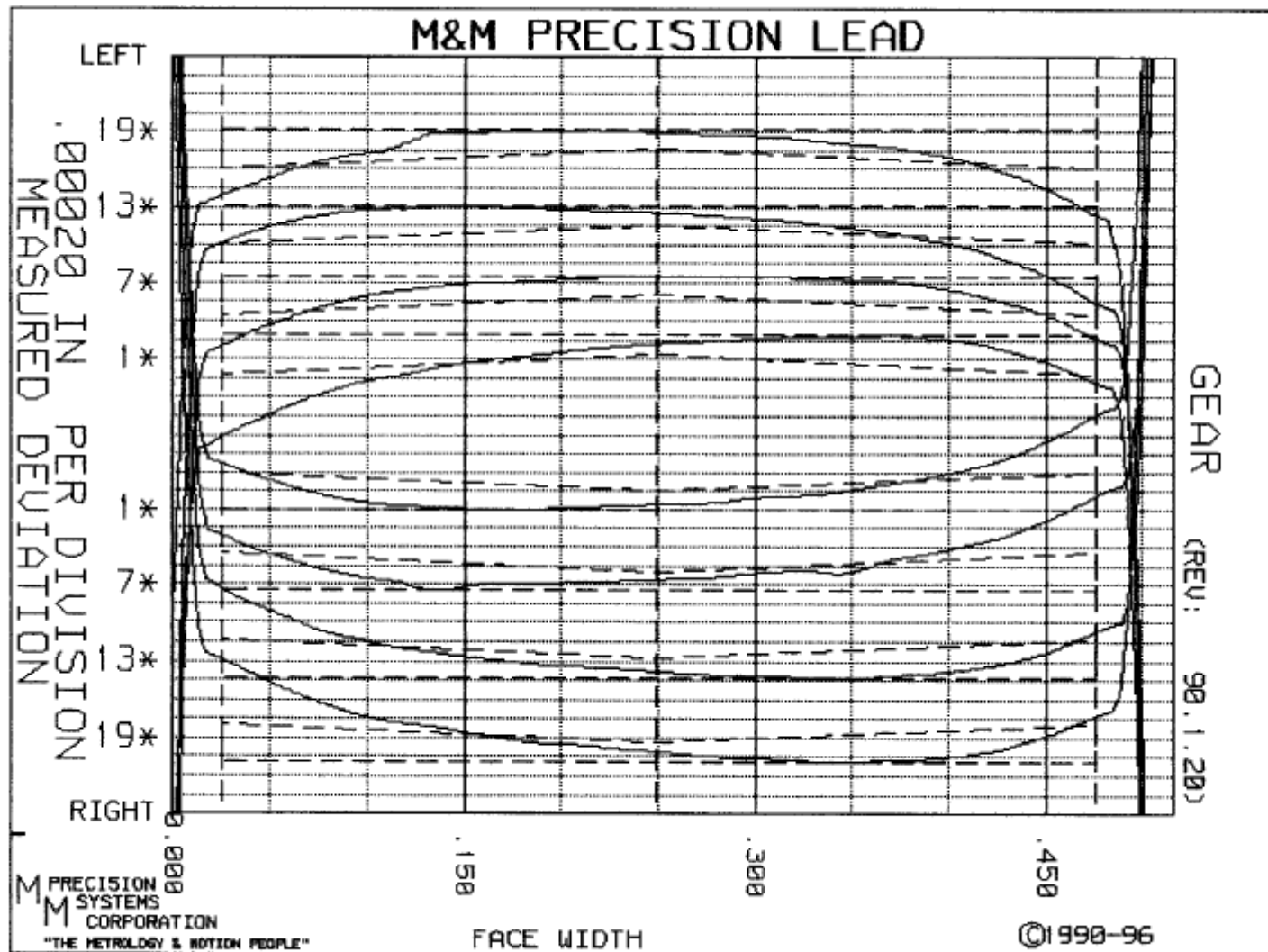


Figure 27 Baseline gear tooth spacing chart

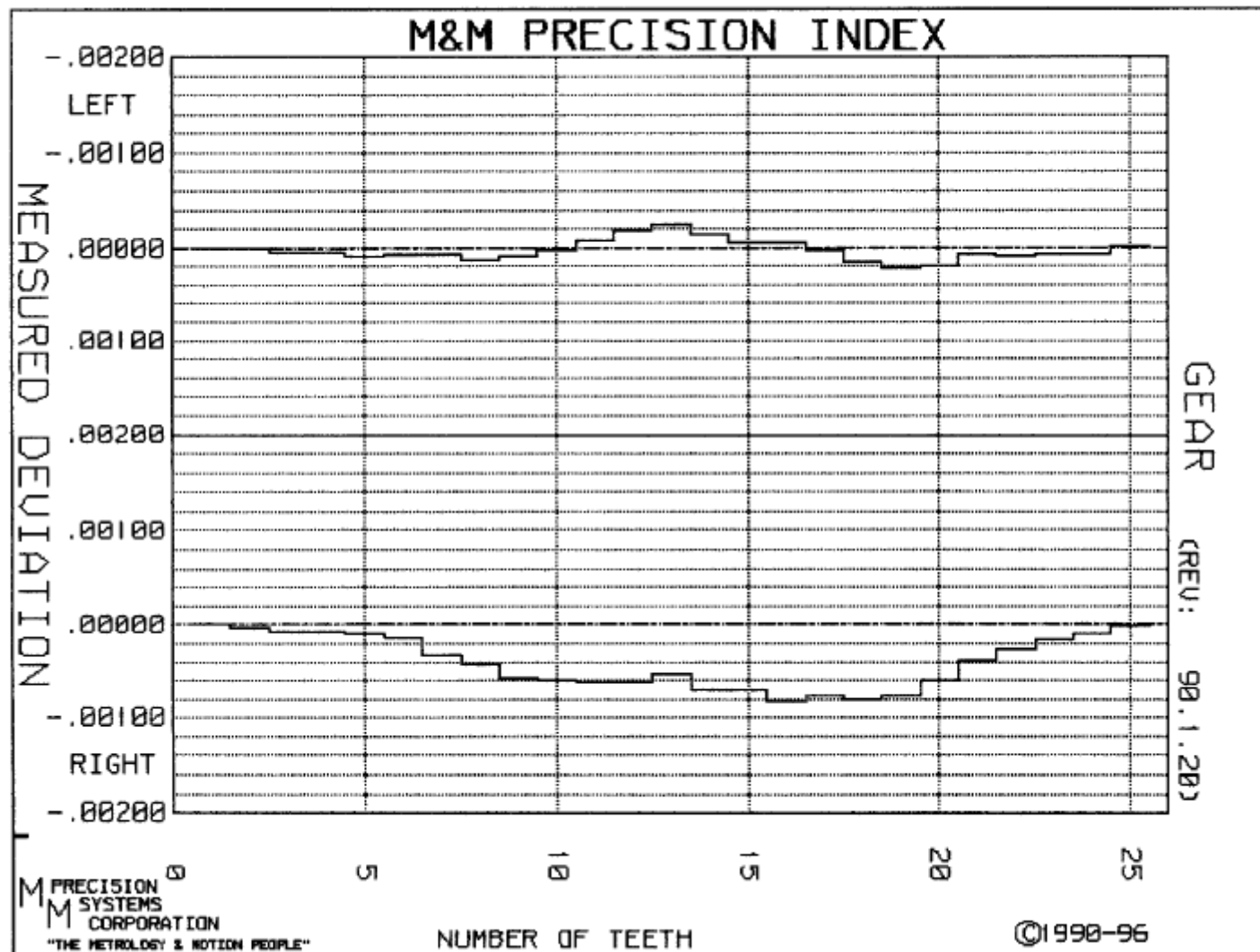


Figure 28 **PC Surface durability mate gear design**

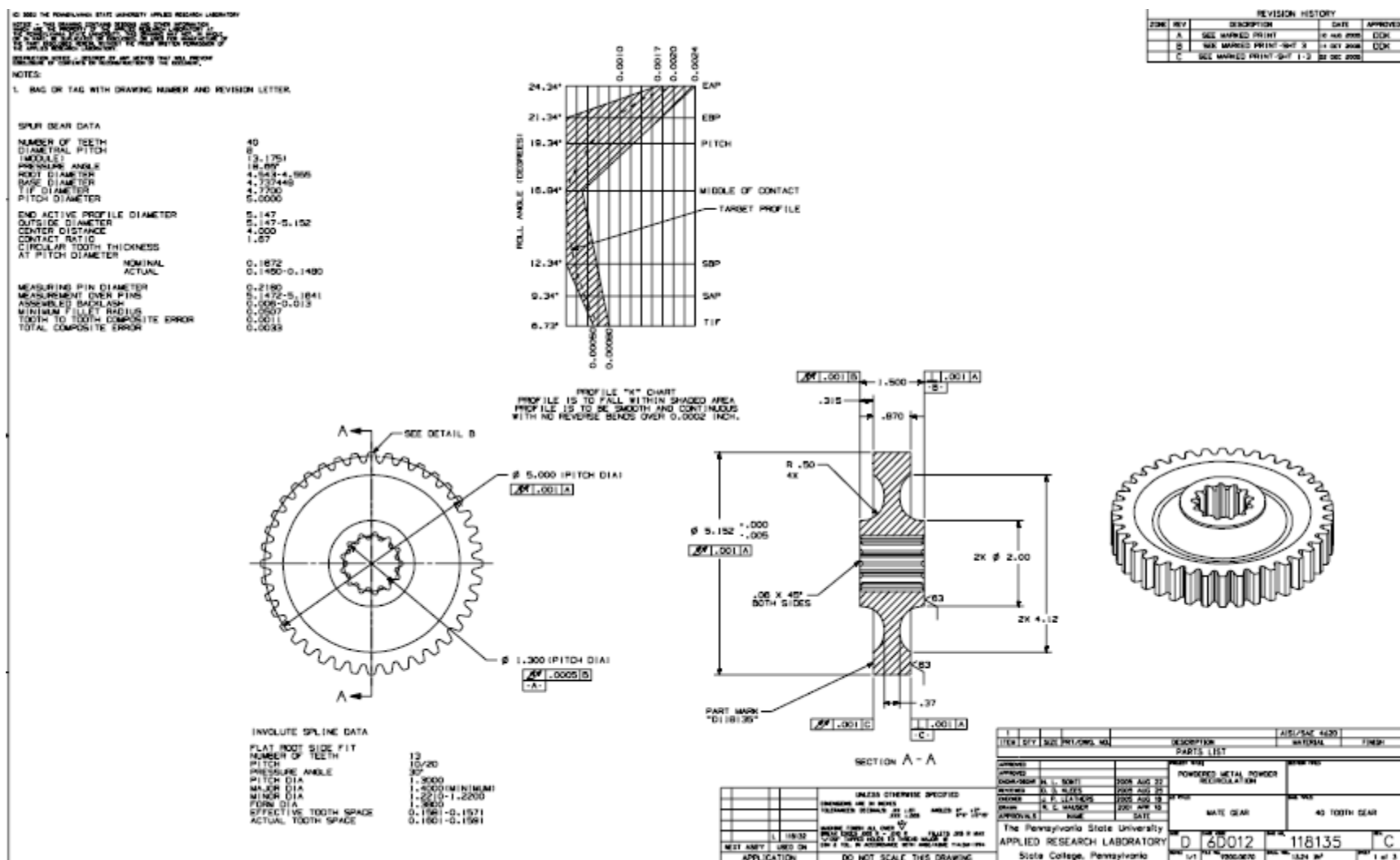
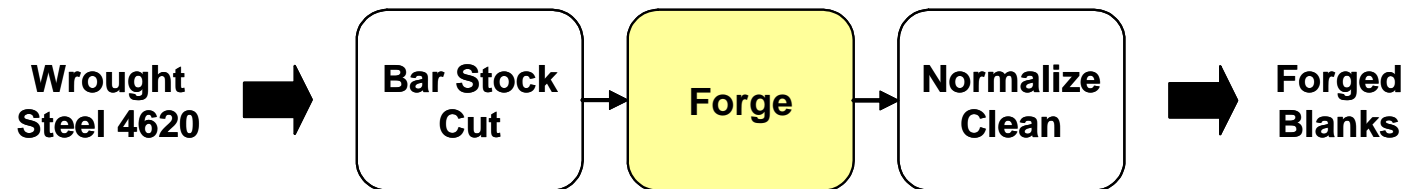


Figure 29 Manufacturing process use to produce mate gears at NPG

Forged Blanks Procured from Milwaukee Forge



NPG Manufacturing Process

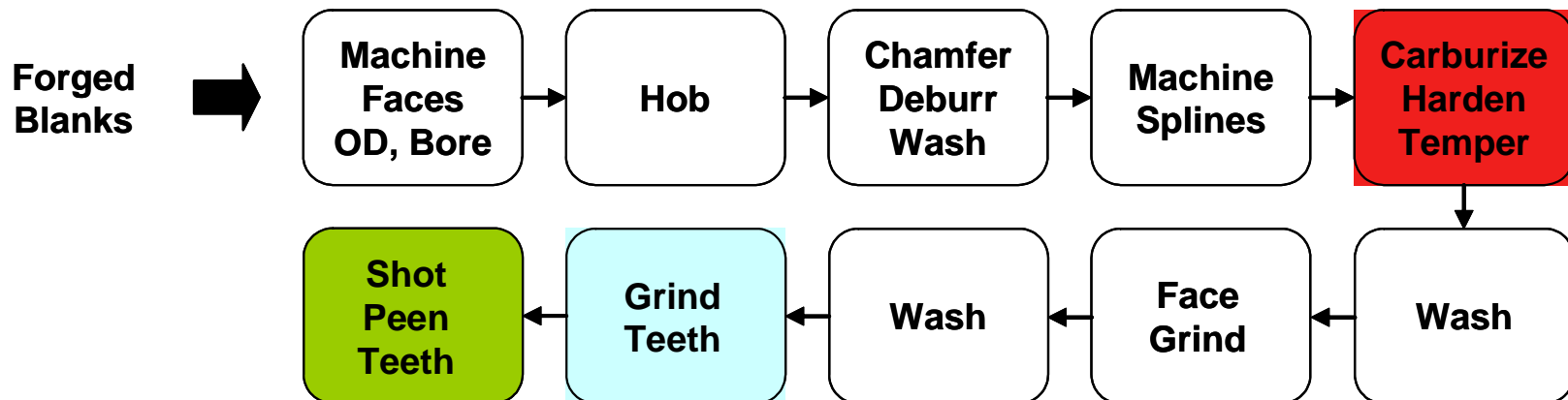


Figure 30 Mate gear profile chart

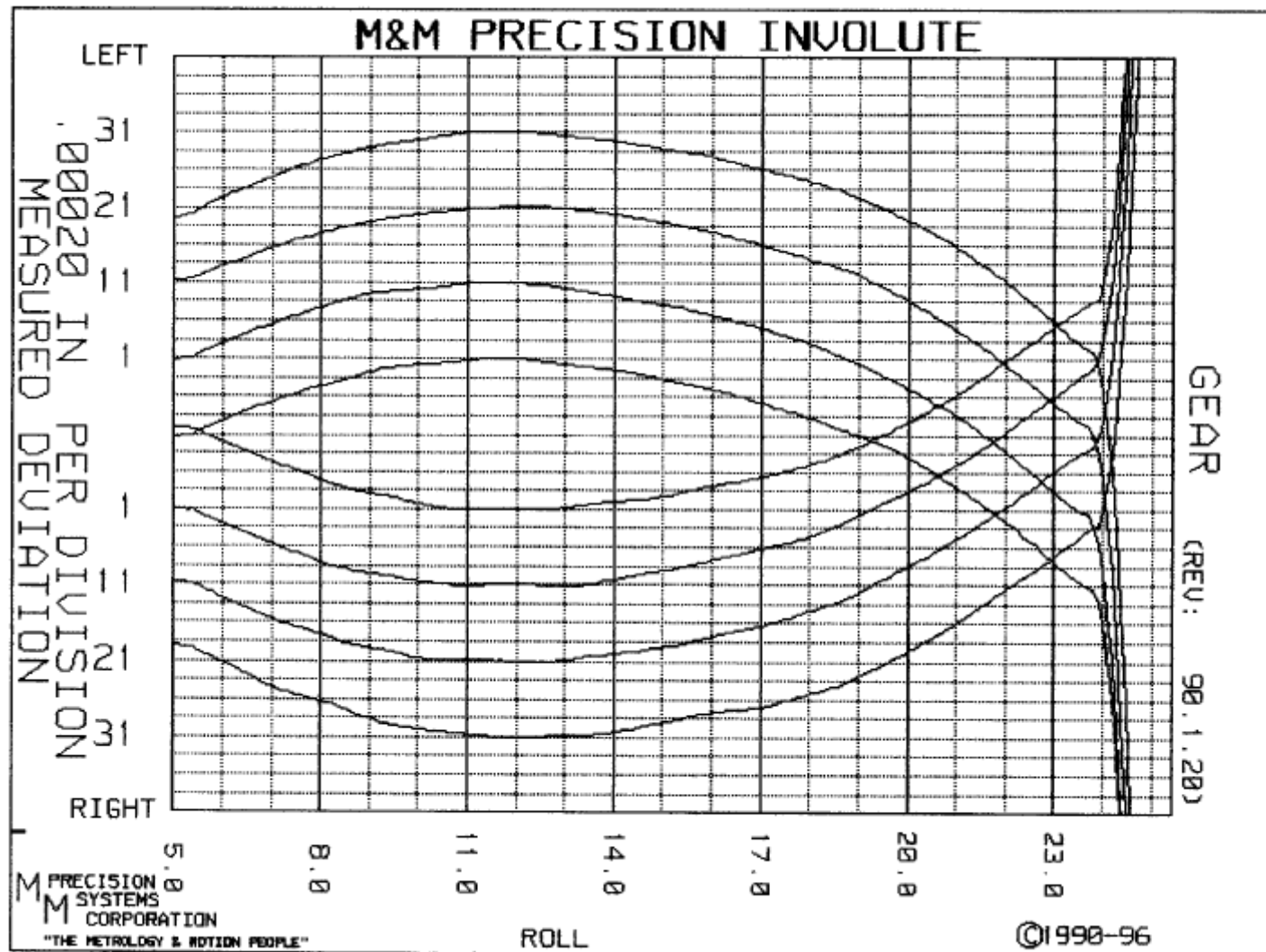


Figure 31 Mate gear lead chart

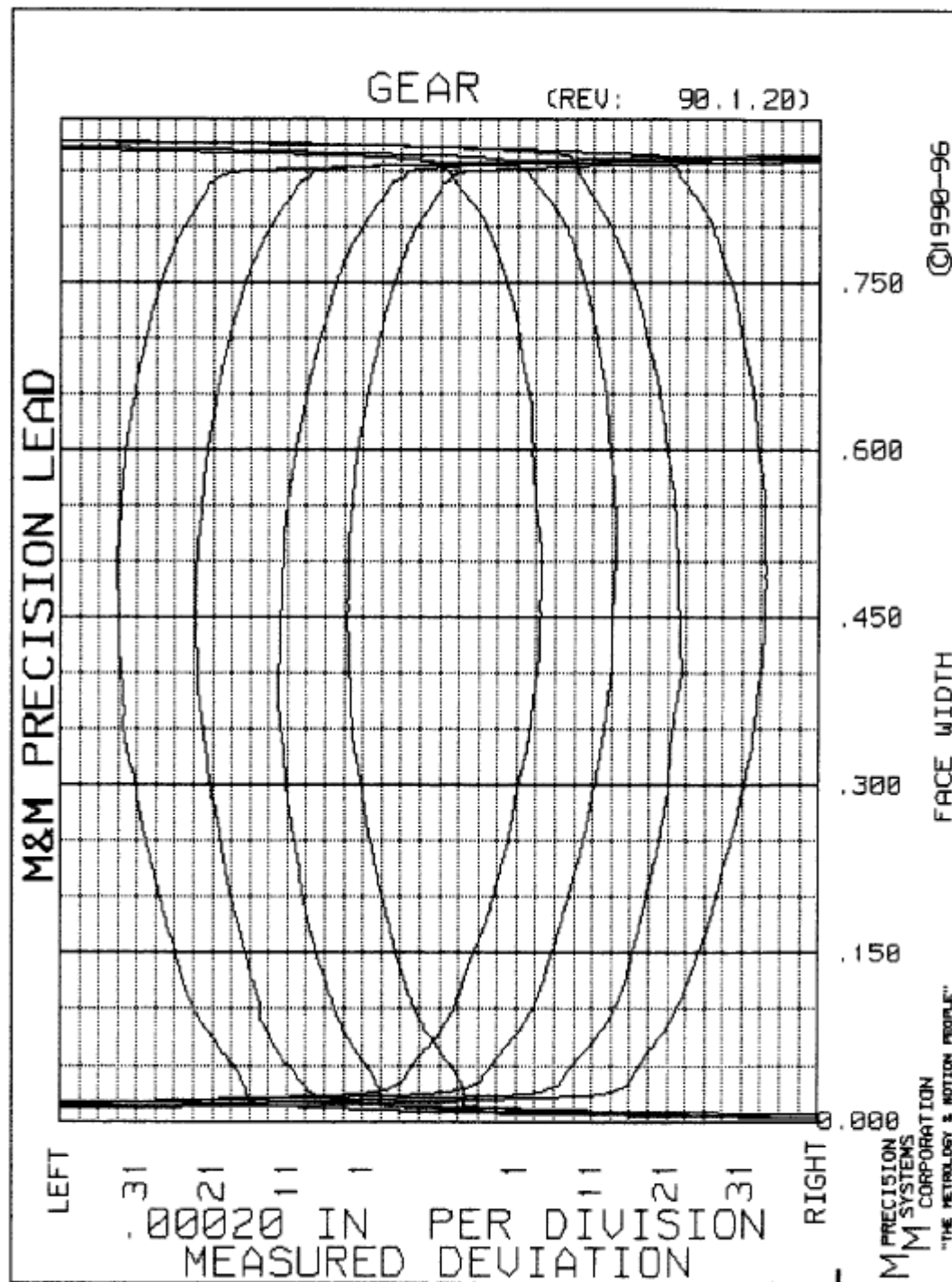


Figure 32 Mate gear tooth spacing chart

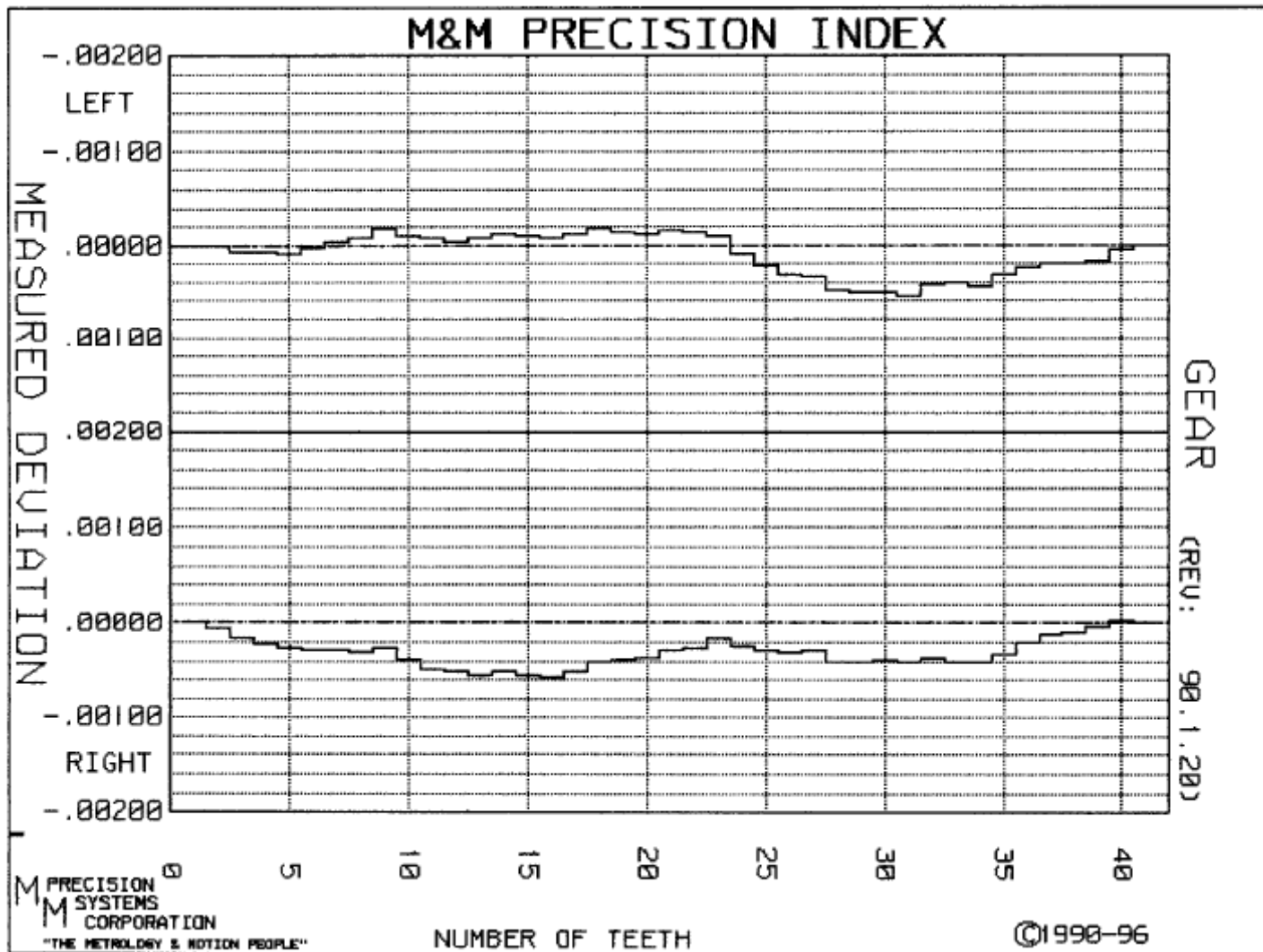


Figure 33 Mid tooth hardness profiles of ausform finished P/M gears (# 2003: P/M-4620-HF-Ausf; # 8019: P/M-4680-HF-Ausf)

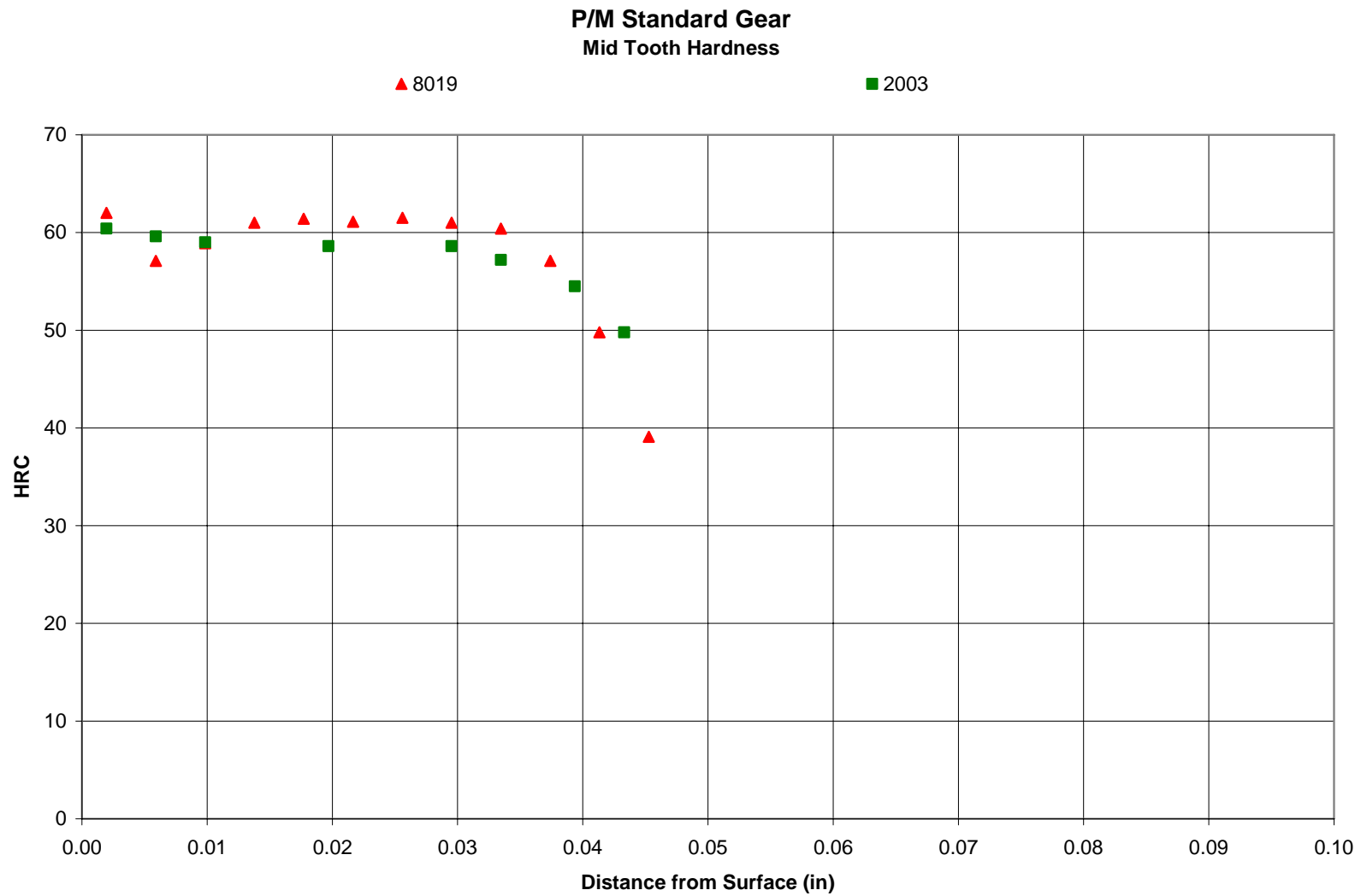


Figure 34 Fillet hardness profiles of ausform finished P/M gears (# 2003: P/M-4620-HF-Ausf; # 8019: P/M-4680-HF-Ausf)

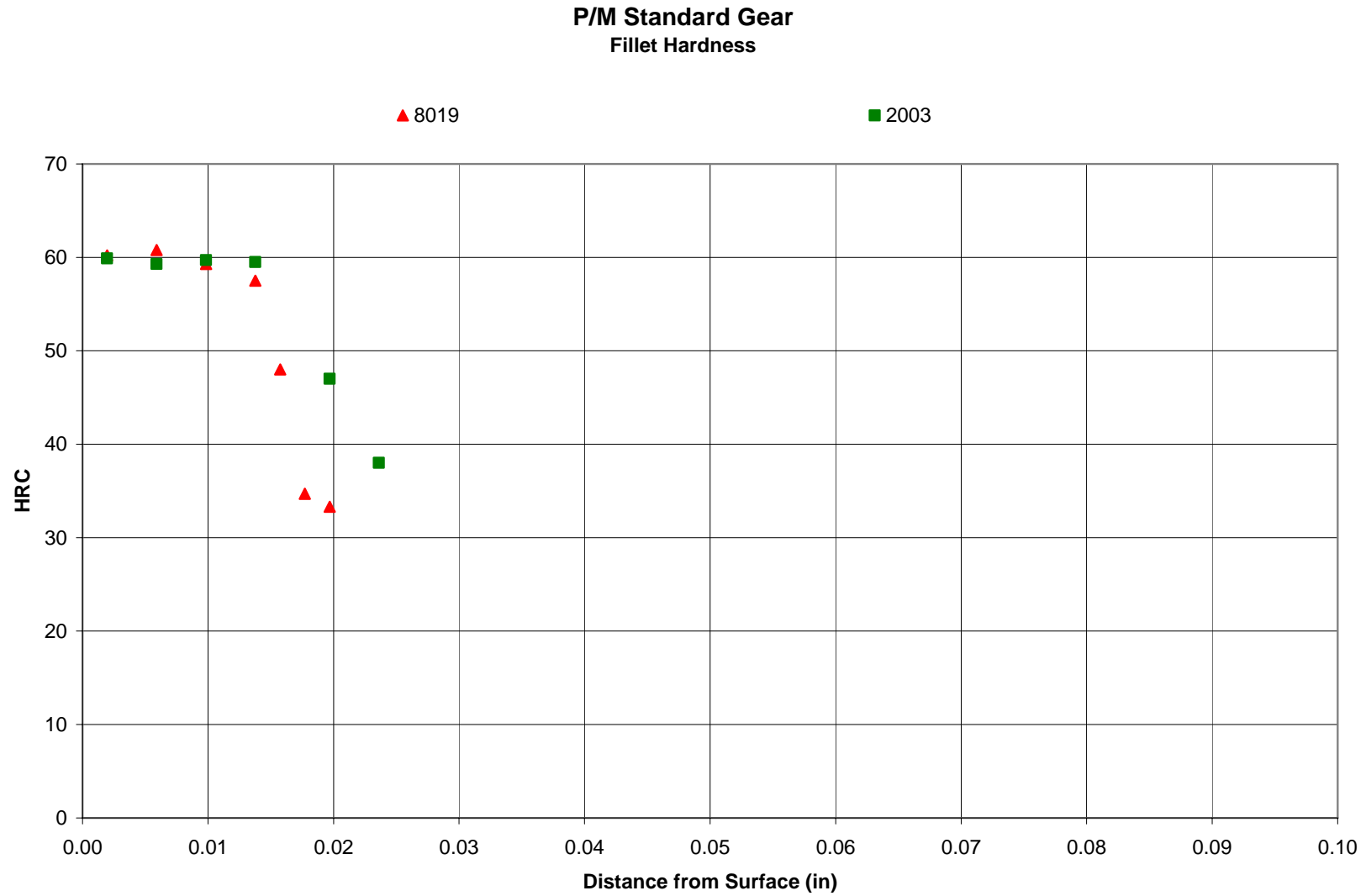


Figure 35 Mid tooth hardness profiles of ausform finished P/M focus gears
(# 207: P/M-4620-HF-Ausf; # 804: P/M-4680-HF-Ausf)

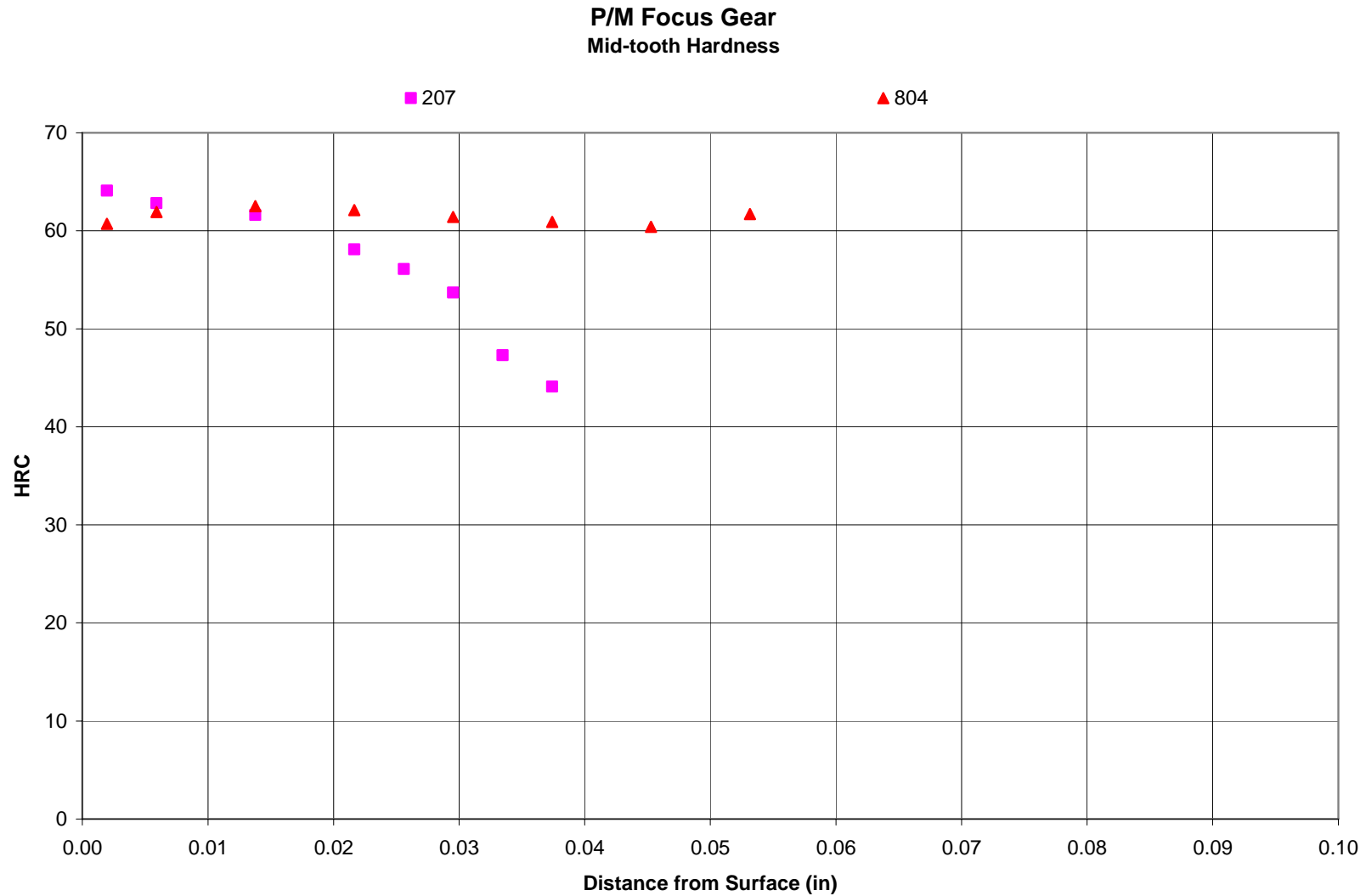


Figure 36 **Mid tooth hardness profiles of ausform finished P/M focus gears**
(# 207: P/M 4620 C/H steel; # 804: P/M 4680 steel)

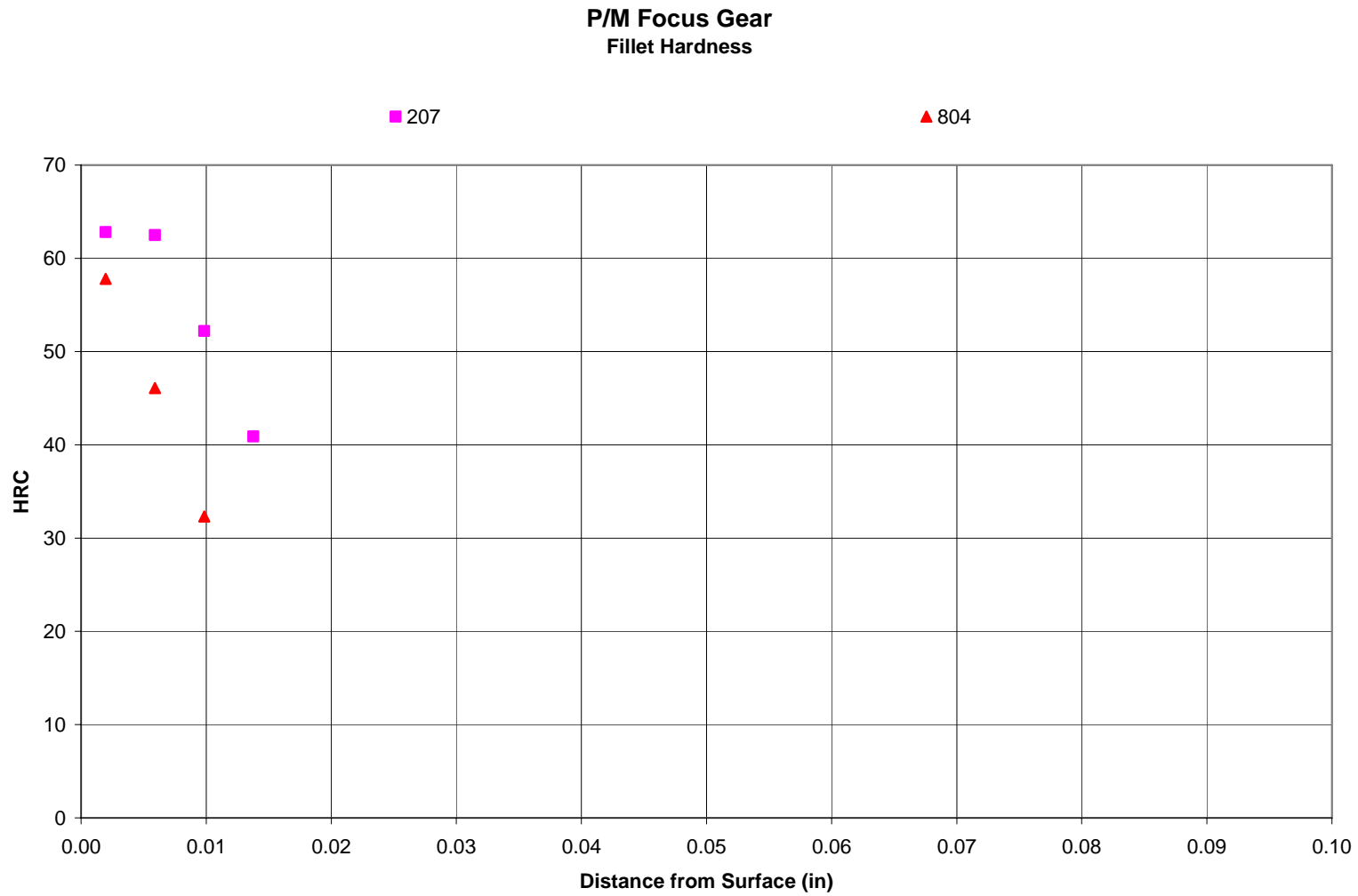


Figure 37 Rolling die tooth profile on drive side

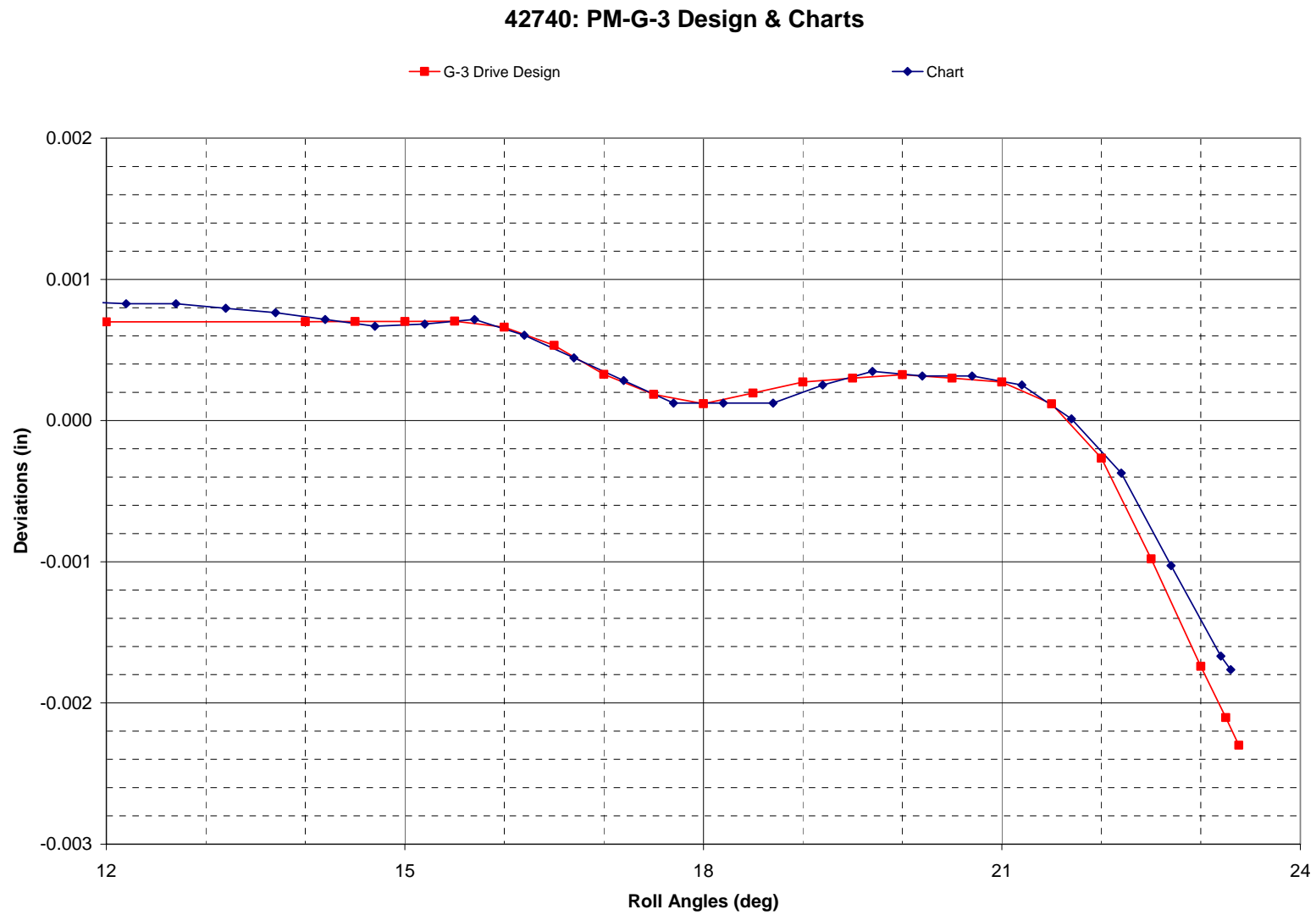


Figure 38 Rolling die tooth profile on coast side

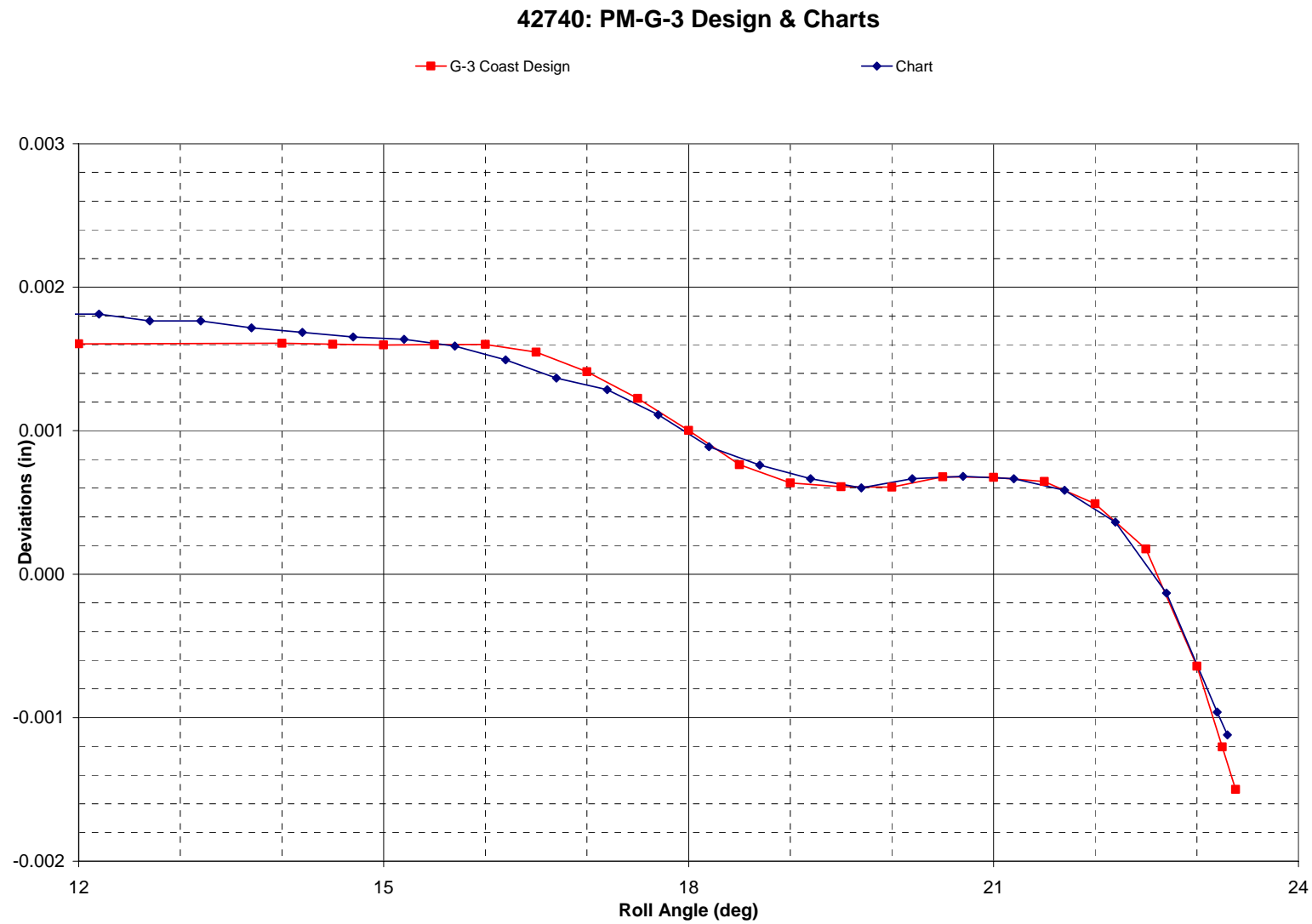


Figure 39 Drive side tooth profile chart for a representative P/M-4620-HF-Ausf gear

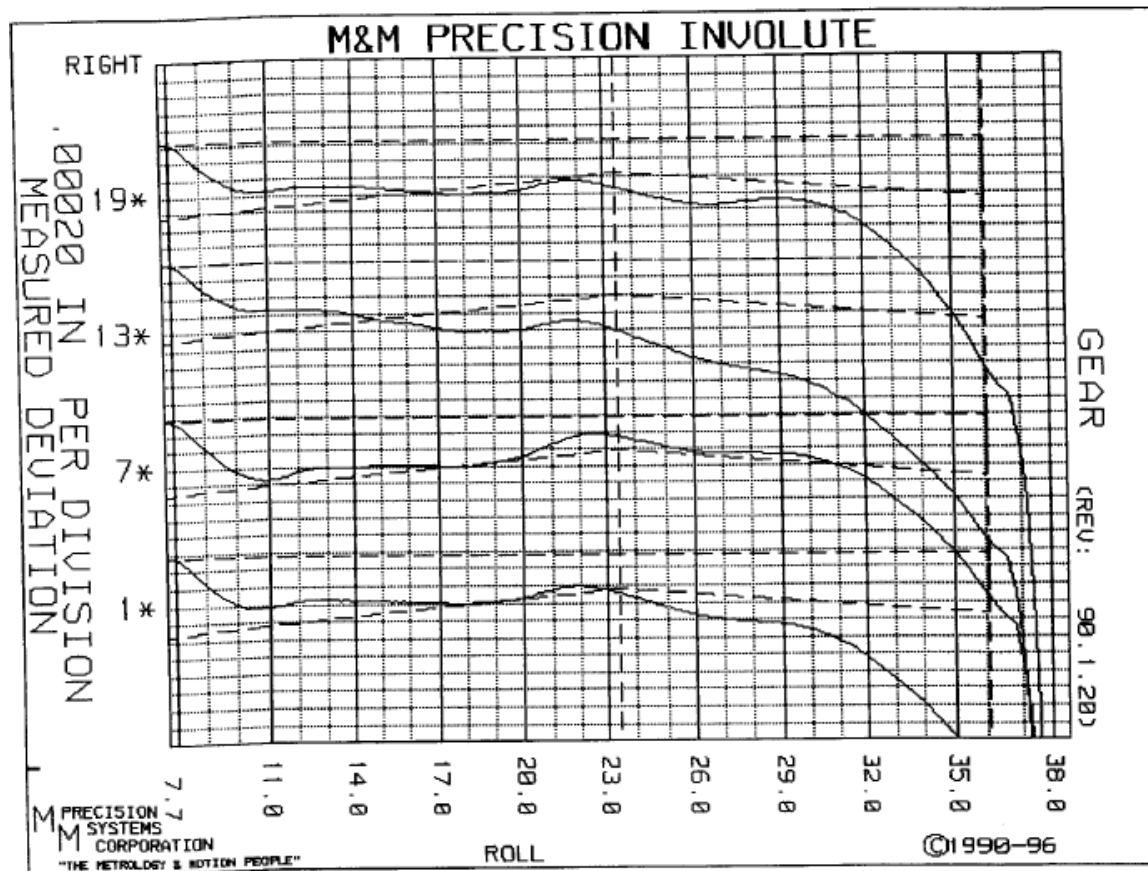


Figure 40 Lead chart for a representative P/M-4620-HF-Ausf gear

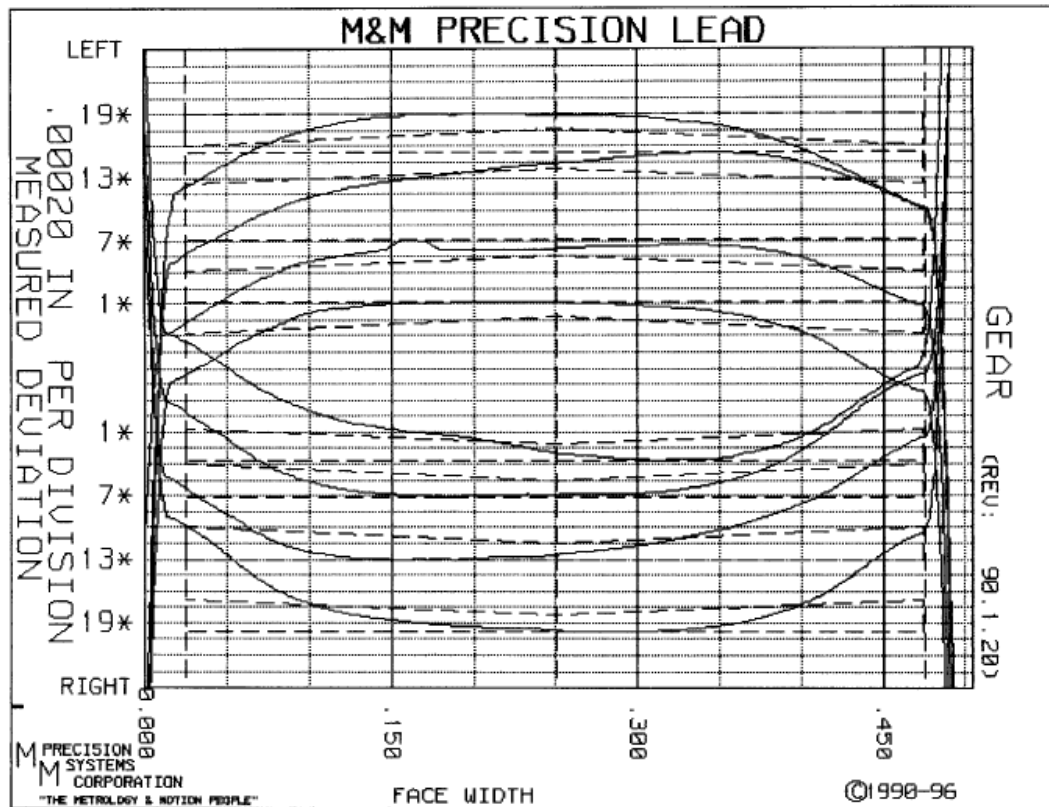


Figure 41 Tooth spacing chart for a representative P/M-4620-HF-Ausf gear

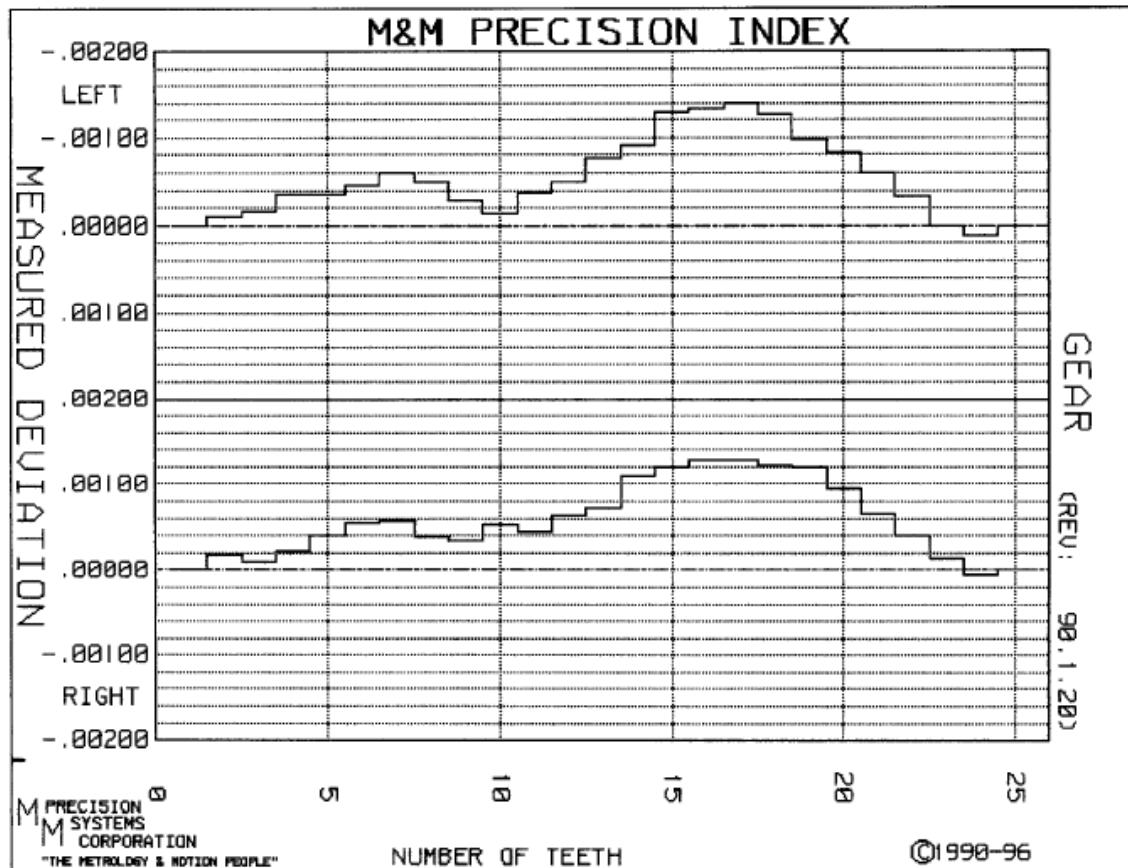


Figure 42 Tooth profile comparison using Zeiss CMM inspection for P/M-4620-HF-Ausf gear

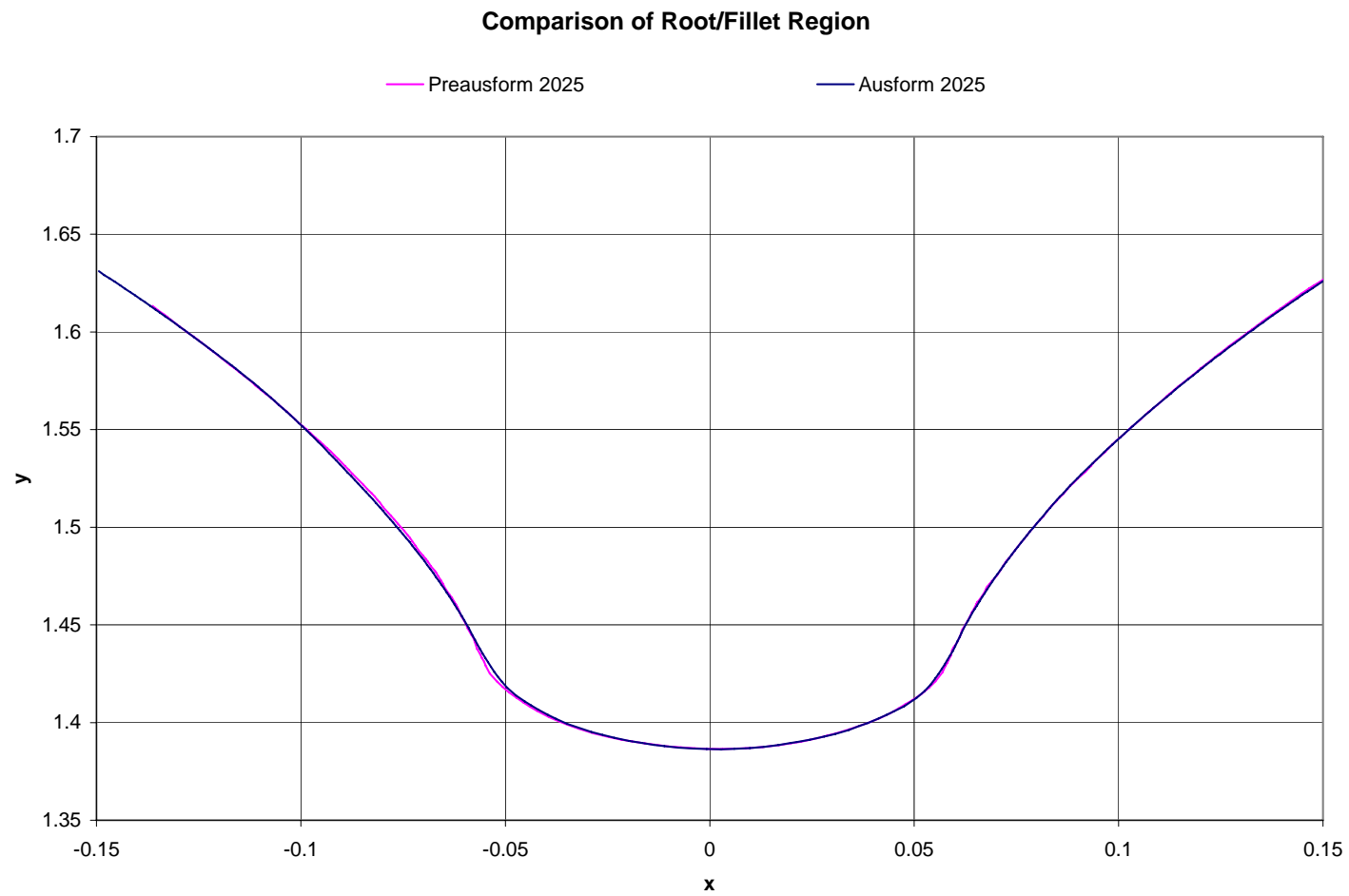


Figure 43 Residual stress depth profiles in root region of gear teeth

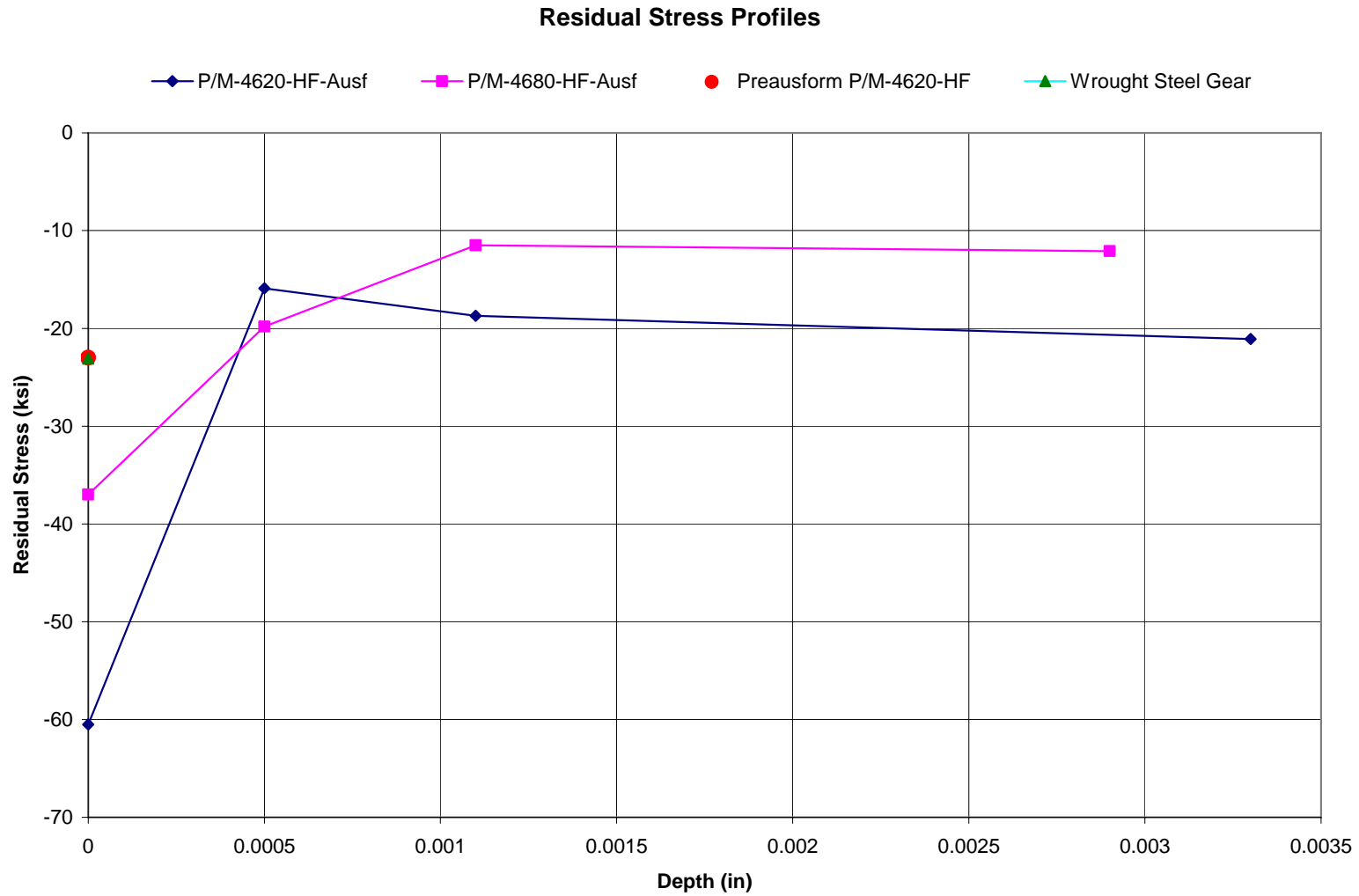


Figure 44 STF testing machine

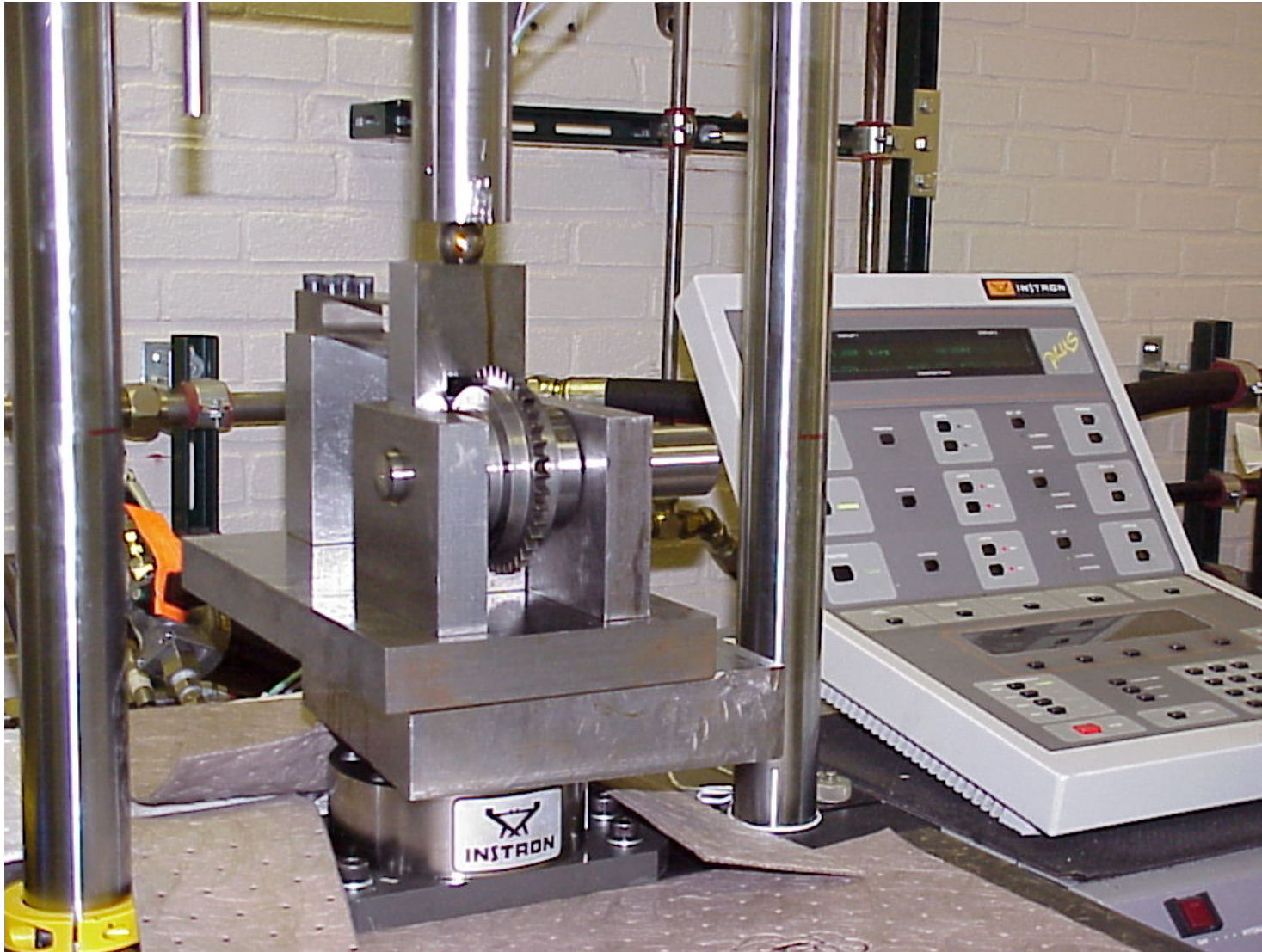


Figure 45 STF test tooth geometry details

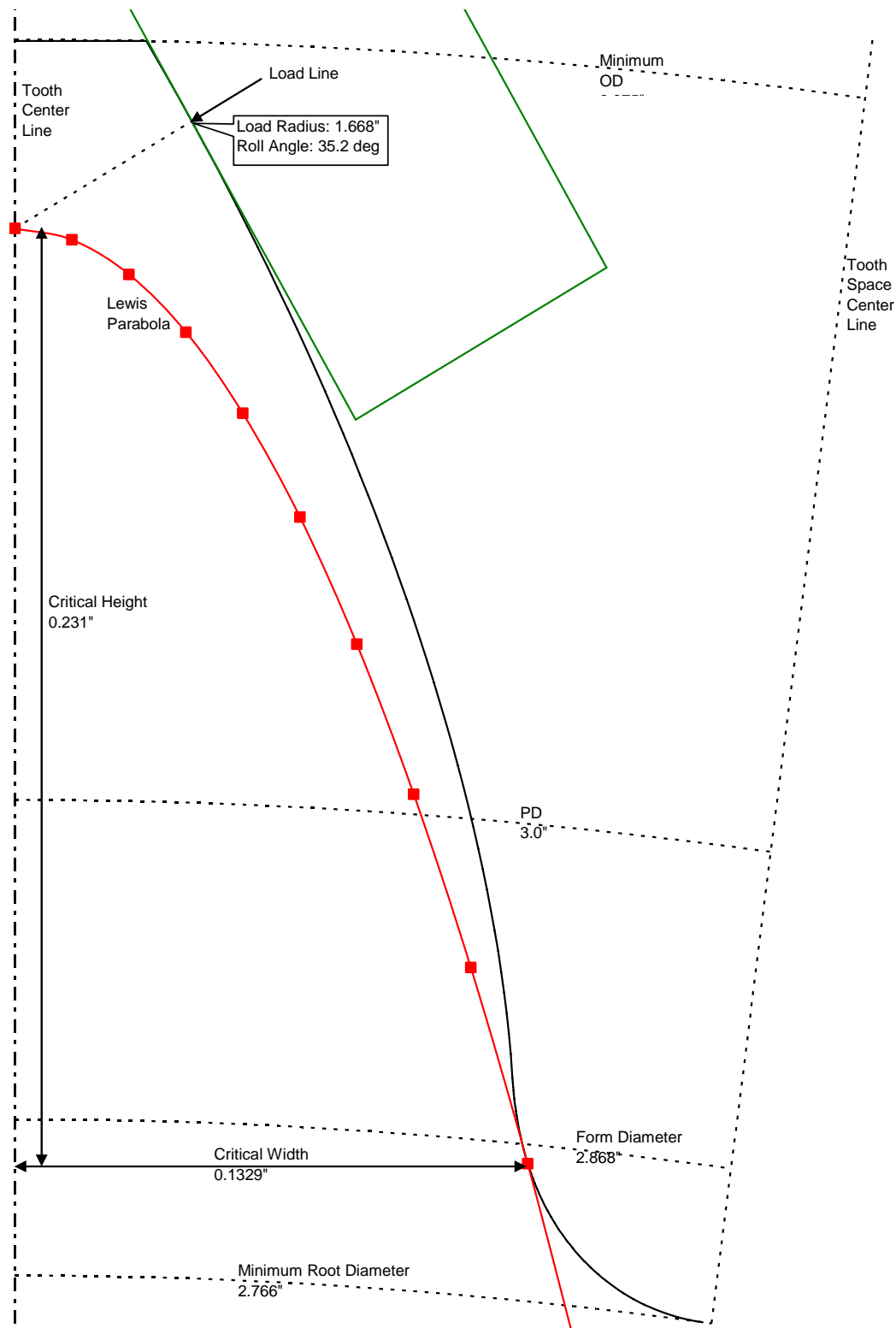


Figure 46 **STF test layout**

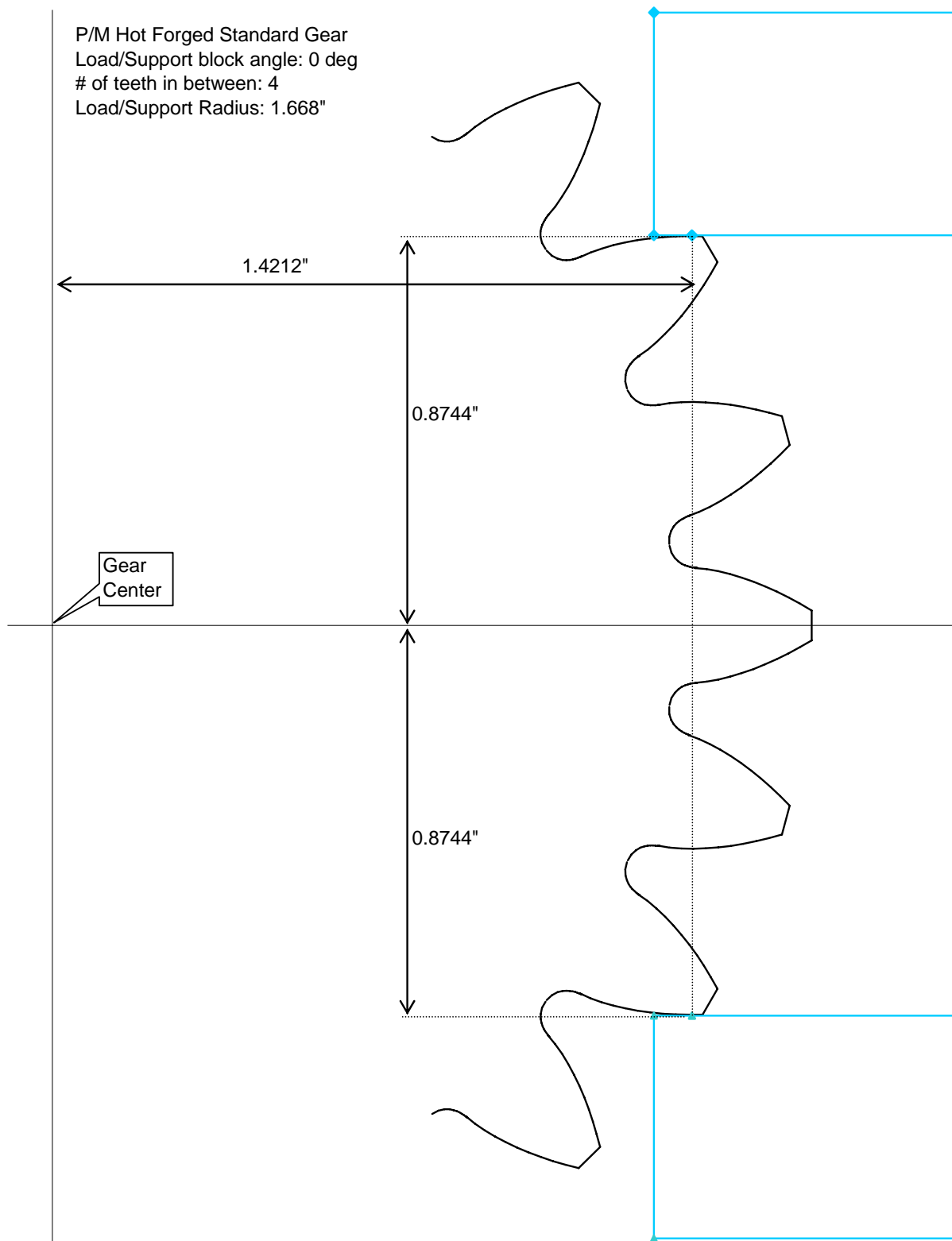


Figure 47 STF test fixture for P/M standard gear

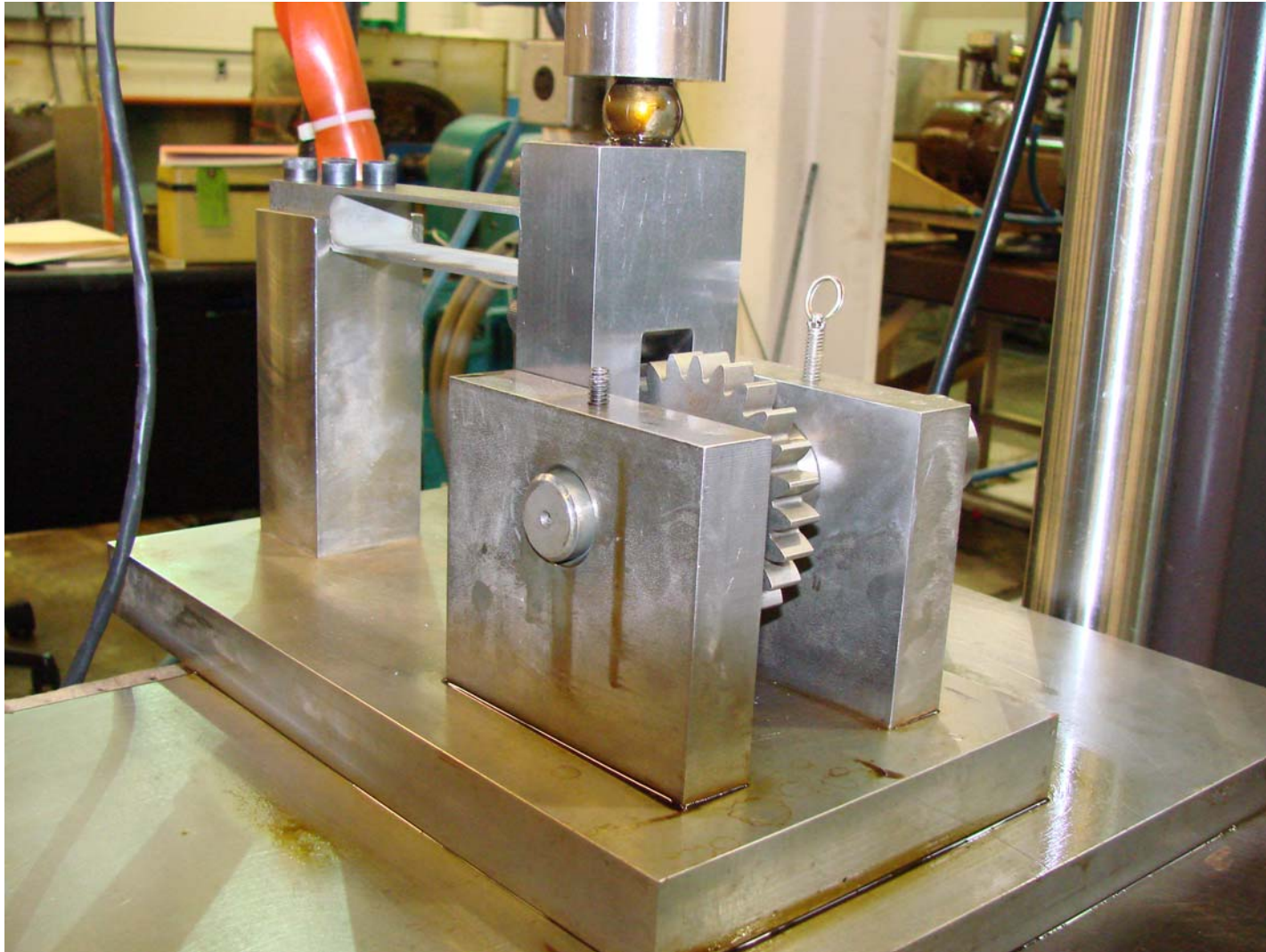


Figure 48 Typical bending fatigue failure of baseline wrought steel gear

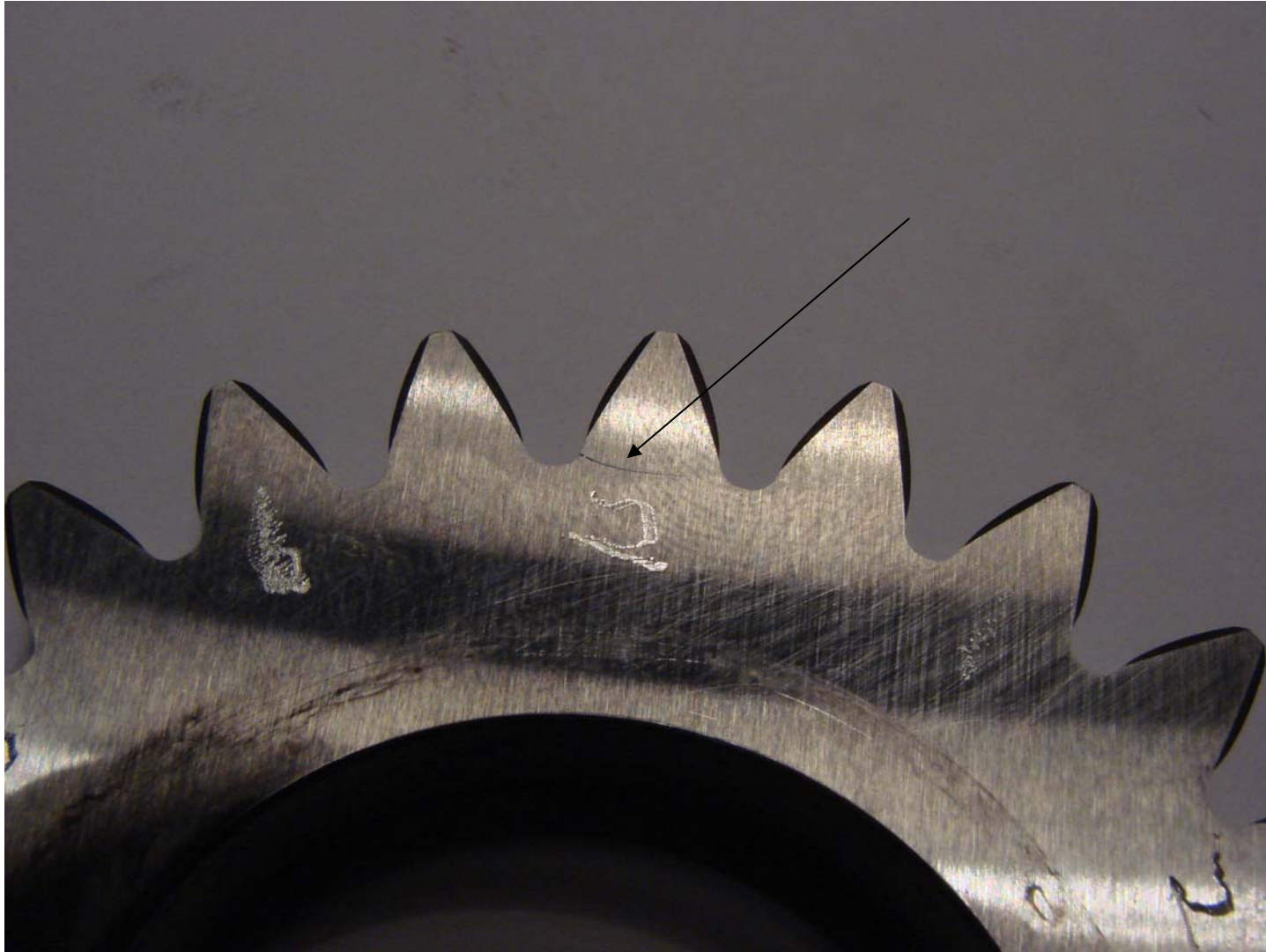


Figure 49 Typical bending fatigue fracture surface of P/M-4620-HF-Ausf and P/M-4680-HF-Ausf gears



Figure 50 STF test results: Maximum bending stress vs. cycles to failure

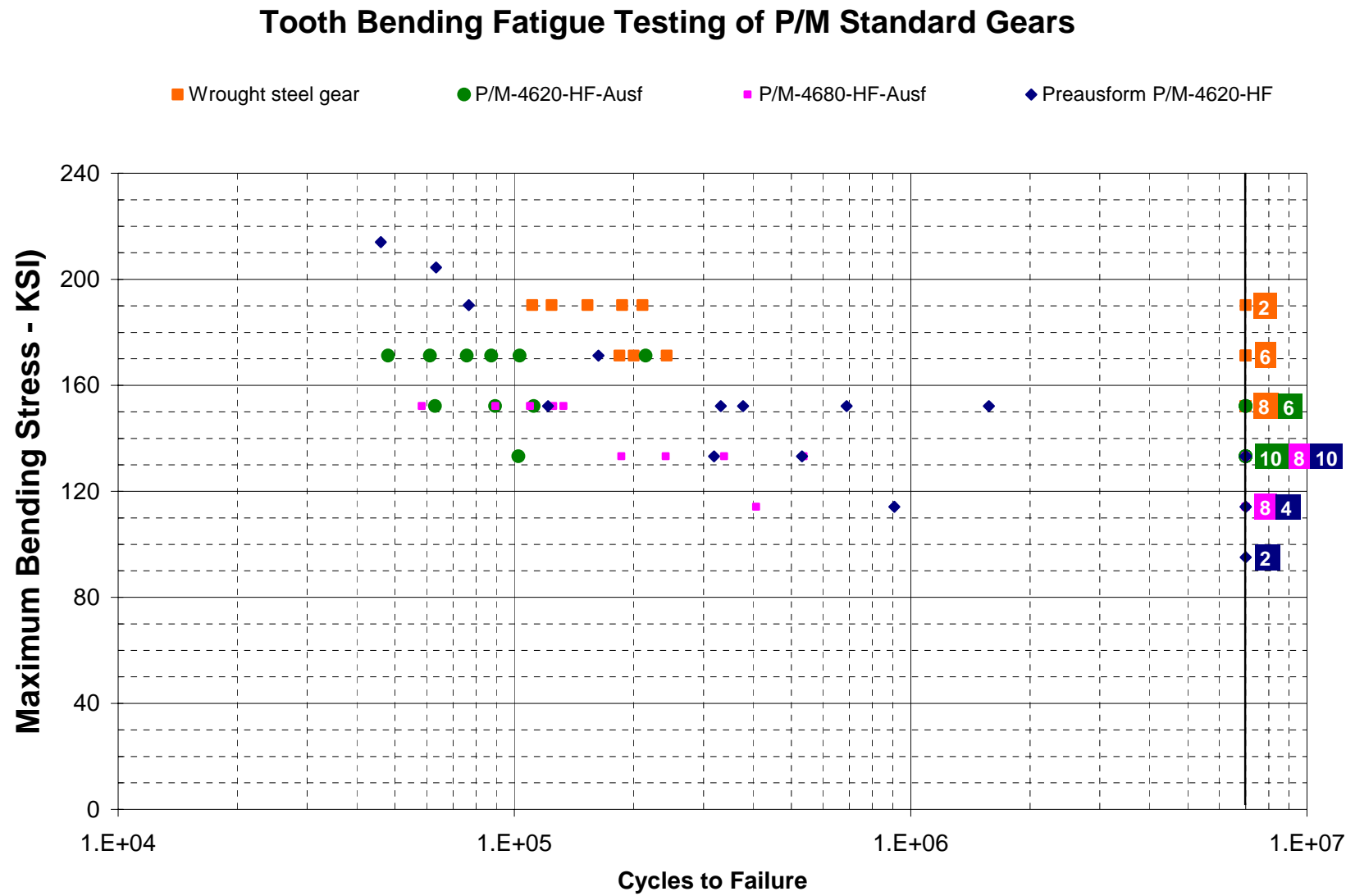


Figure 51 Test loads vs. normal probability variate for baseline gears

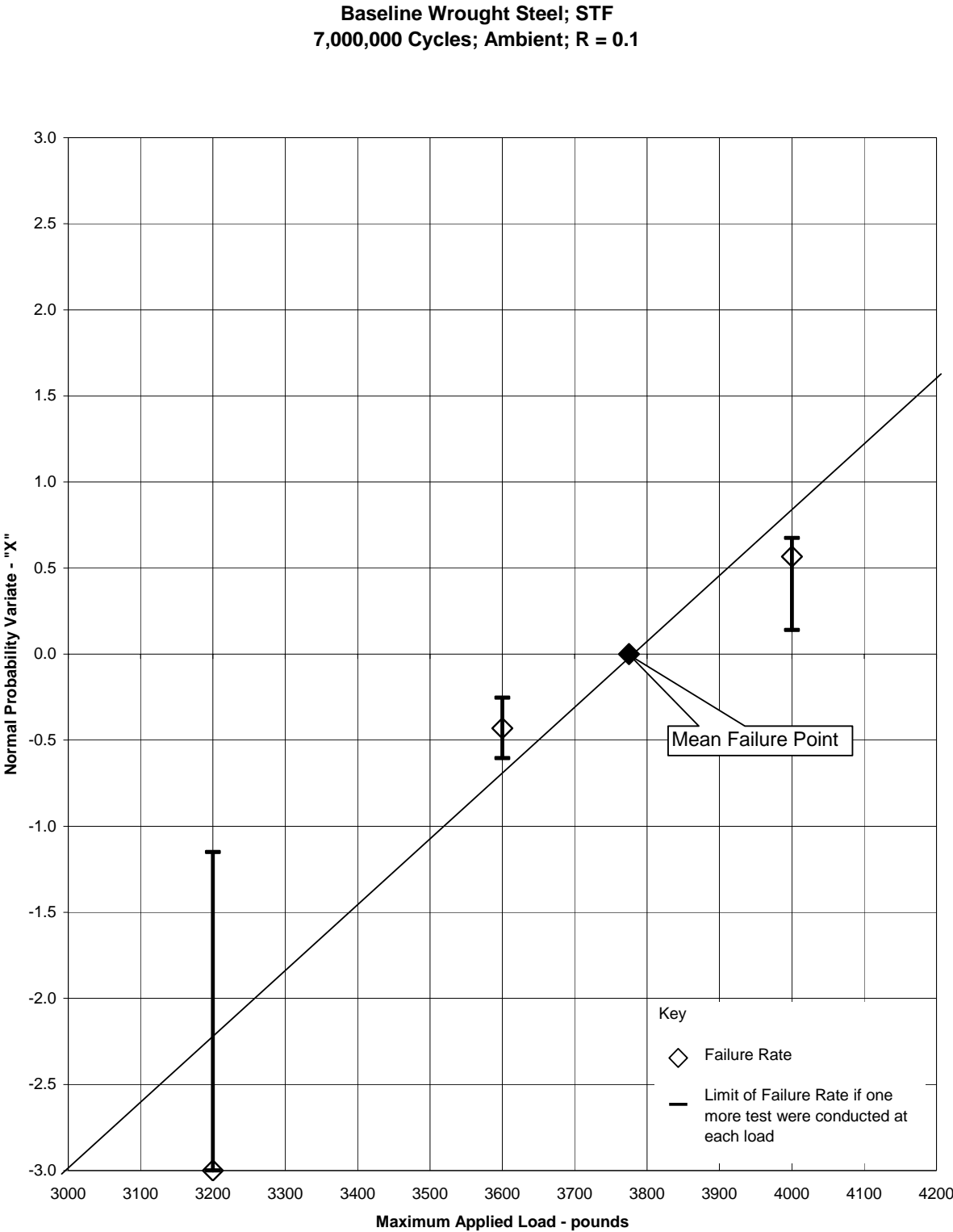


Figure 52 Test loads vs. normal probability variate for P/M-4620-HF-Ausf gears

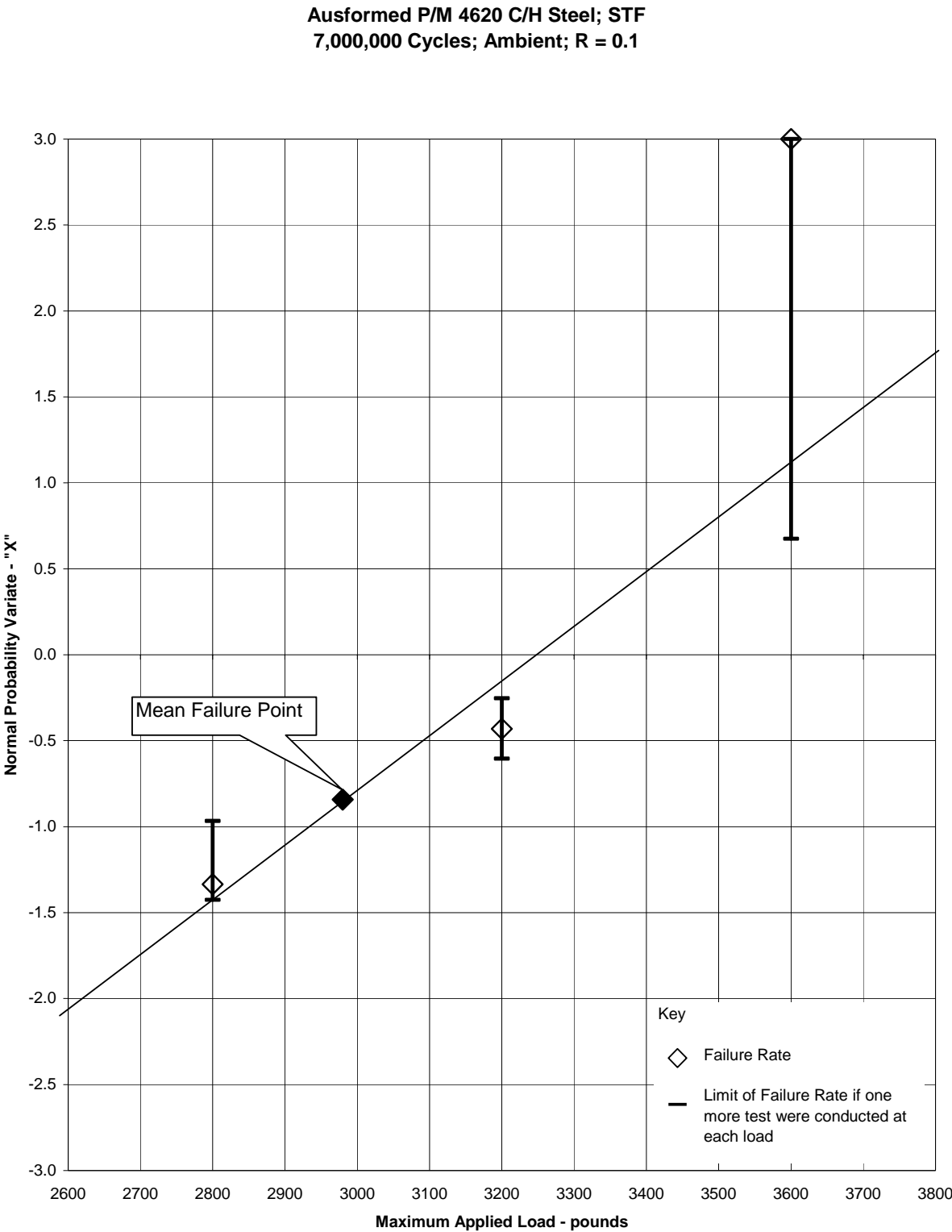


Figure 53 Test loads vs. normal probability variate for preausform P/M-4620-HF gears

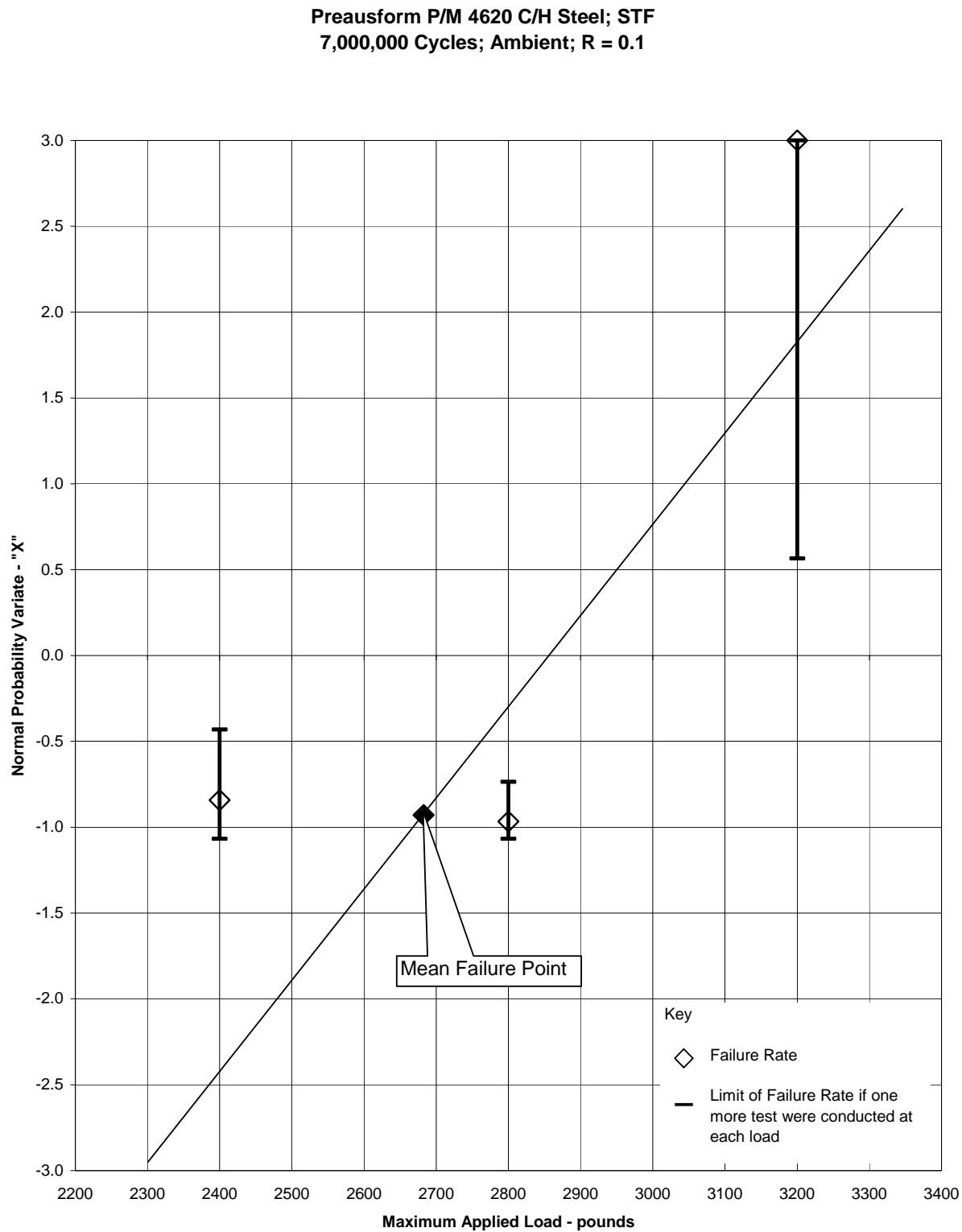


Figure 54 Test loads vs. normal probability variate for P/M-4680-HF-Ausf gears

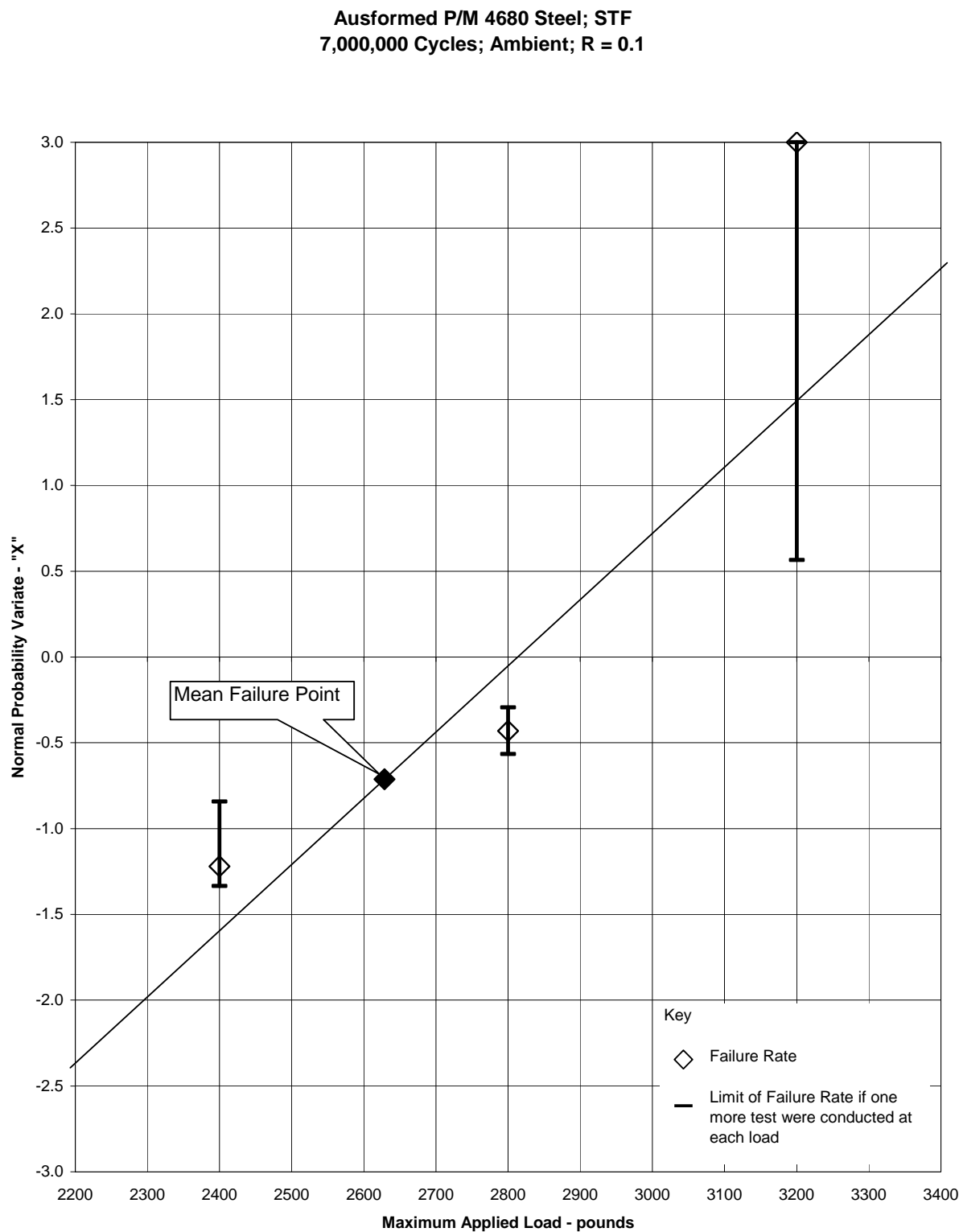


Figure 55 **Comparison of test load for 50% failures at seven million cycles**

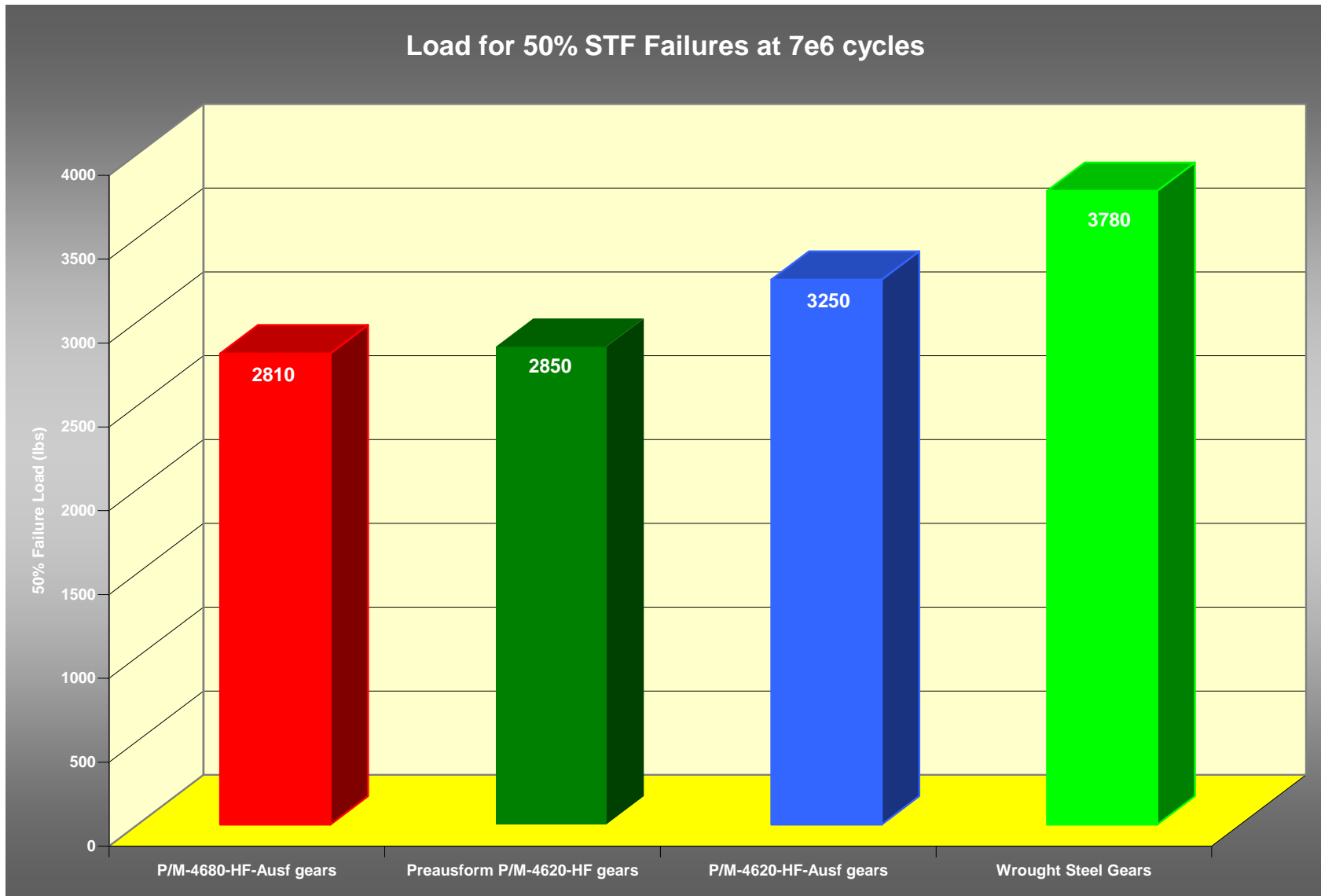


Figure 56 PC surface durability testing machine, and test loop arrangement

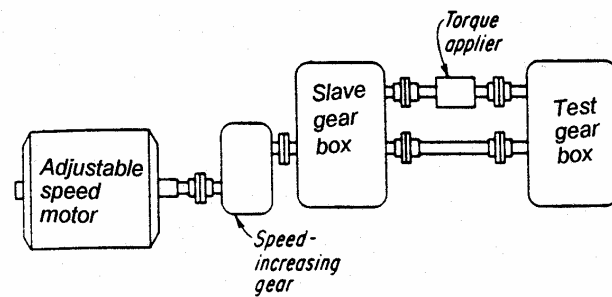
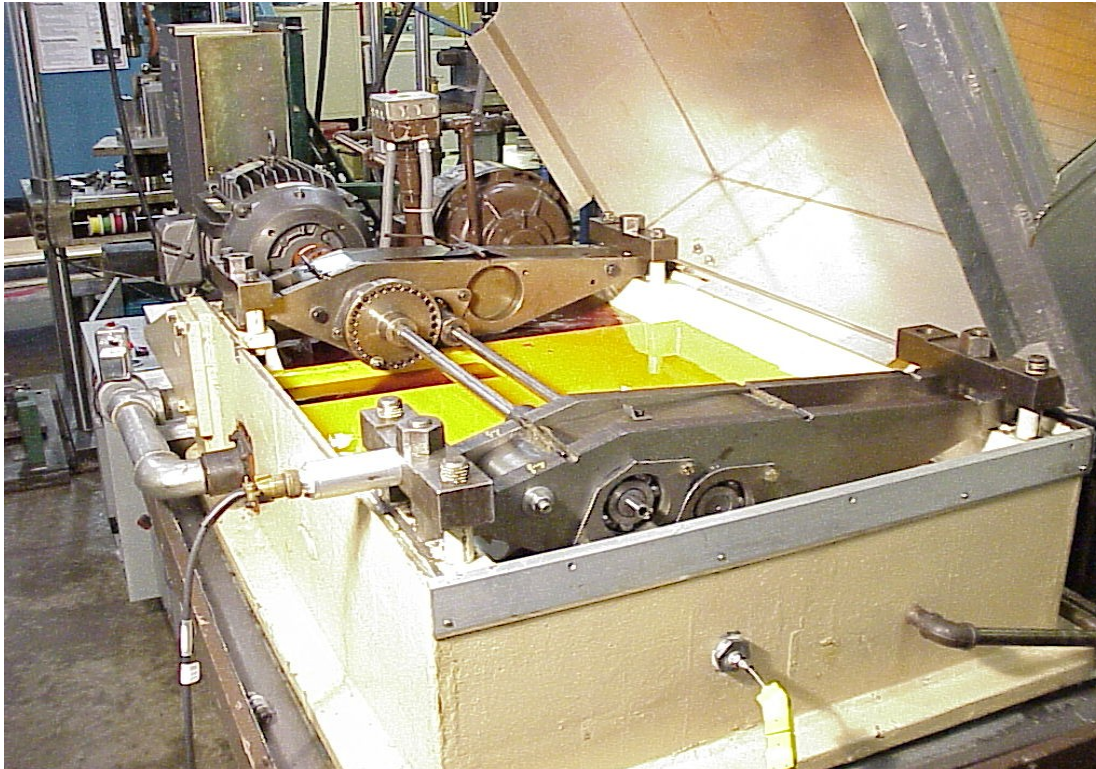


Figure 57 Typical pitting fatigue failure of baseline wrought steel gear

Lubricant		Havoline Dexron III Automatic transmission fluid	
Lubricant inlet temperature		140°F	
Lubricant filter		10 Micron (nominal)	
Lubricant change interval		1200 hours (approximately)	
Tooth Engagement		Full Face width	
Specimen Operating Speed		1800 RPM	
		Specimen	Mate
		(1800 RPM)	(1080 RPM)
Rolling Velocity	Pitch Line	475 in/sec	475 in/sec
	OBD	670 in/sec	540 in/sec
	MFCA	283 in/sec	409 in/sec
Roll/Slide Ratio	OBD	0.39	0.48
	MFCA	-0.91	-0.64
Run-in Procedure	Run ½ hour at ½ test load, starting with 80°F lubricant inlet temperature.		
Test Loads	Based on searching tests to result in average life to surface durability failure of 30 to 50 million cycles.		
Run-Out	Tests will be suspended after 30 million cycles with no failure.		
Failure Criterion	Surface origin pit 5% area on one tooth, several smaller pits (totaling slightly greater area), excess vibration, progressive scoring, tooth breakage, or 0.001" profile degradation		

Figure 58 Surface durability RSF Test results for baseline wrought steel gears and P/M-4620-HF-Ausf gears

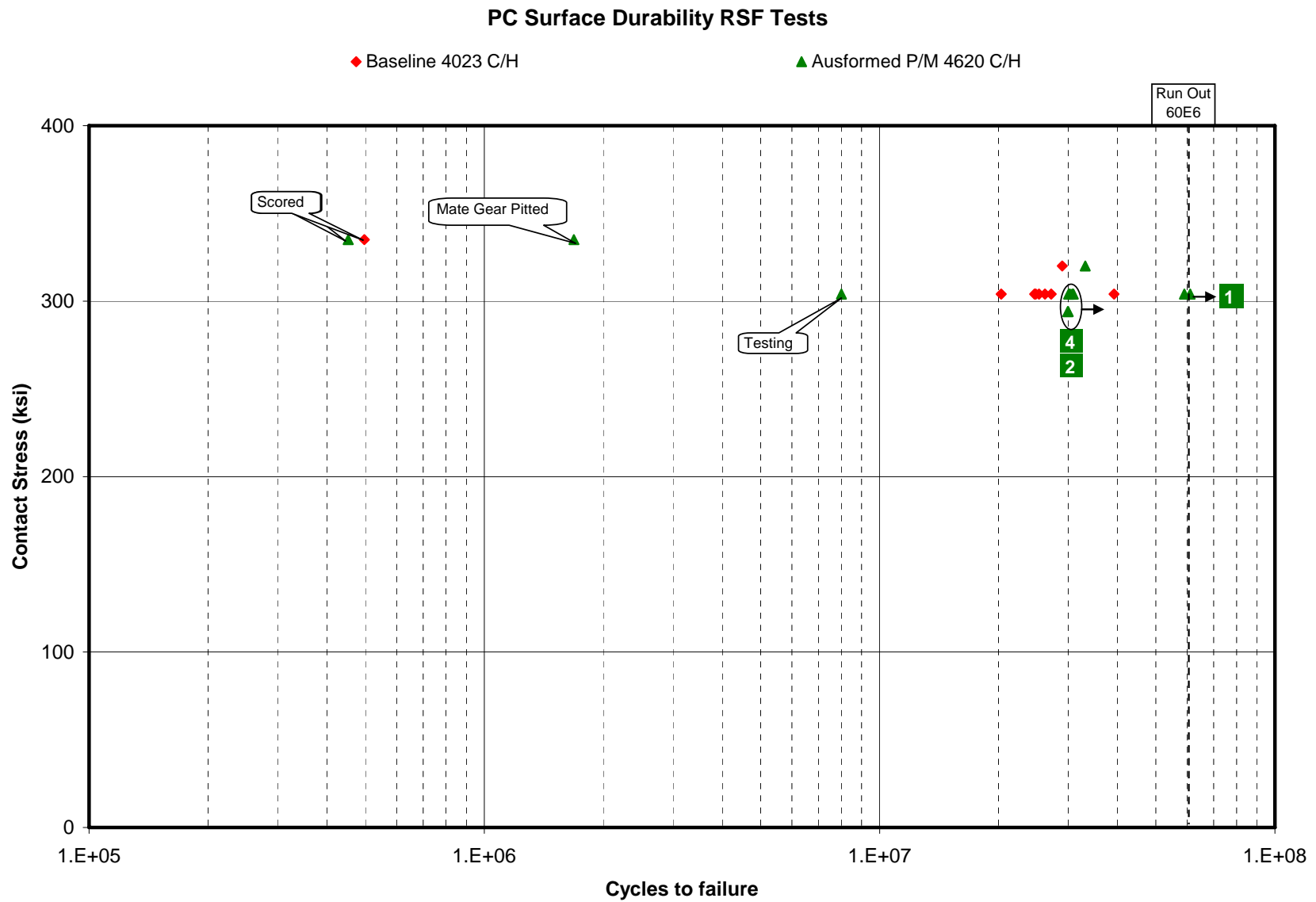


Figure 59 Typical pitted gear tooth surface for baseline wrought steel gears



Figure 60 **Mate gear pitted gear tooth**



Figure 61 **Pitted tooth surface of P/M-4620-HF-Ausf gear**

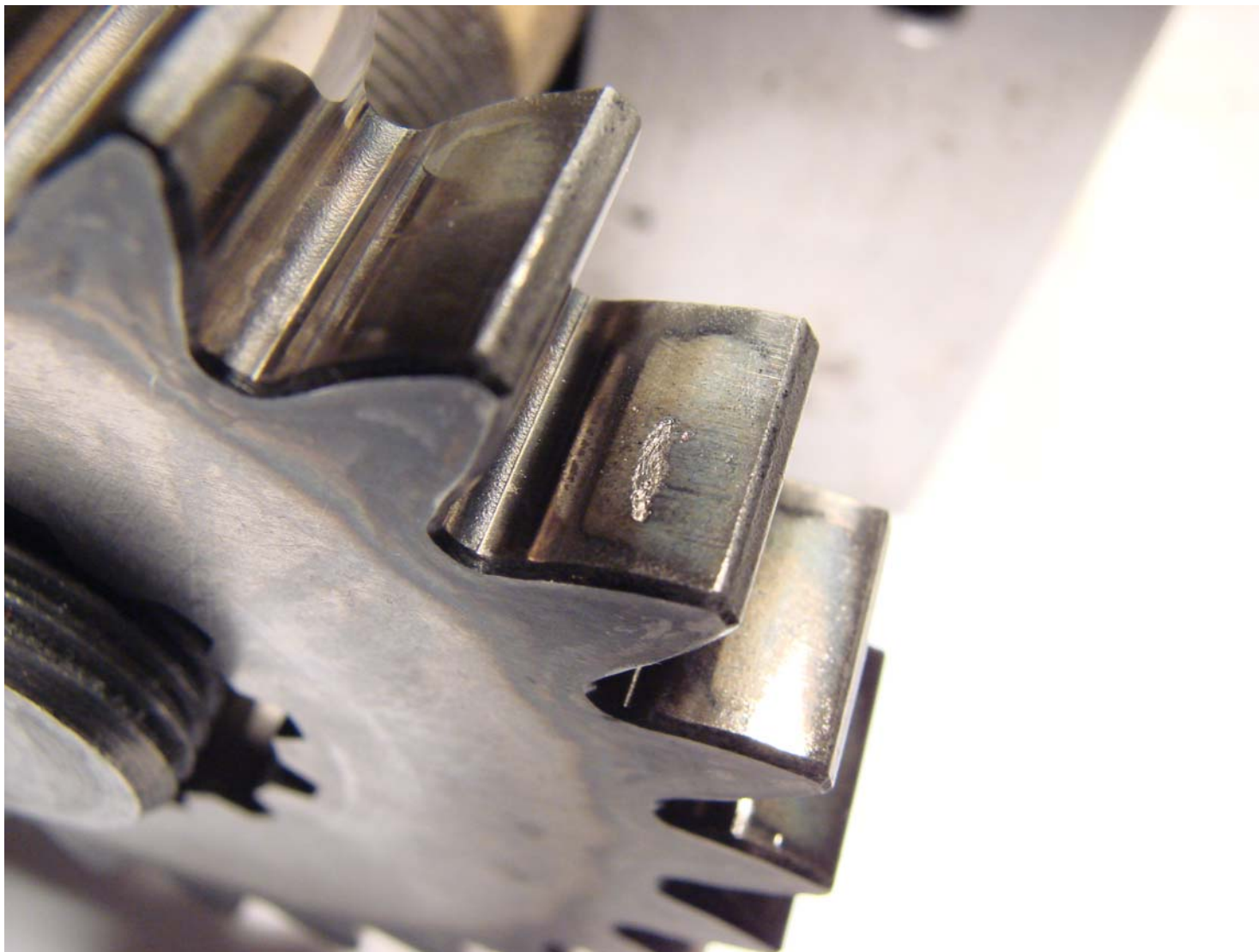


Figure 62 Weibul analysis of surface durability G-50 life for baseline wrought steel gears and P/M-4620-HF-Ausf gears

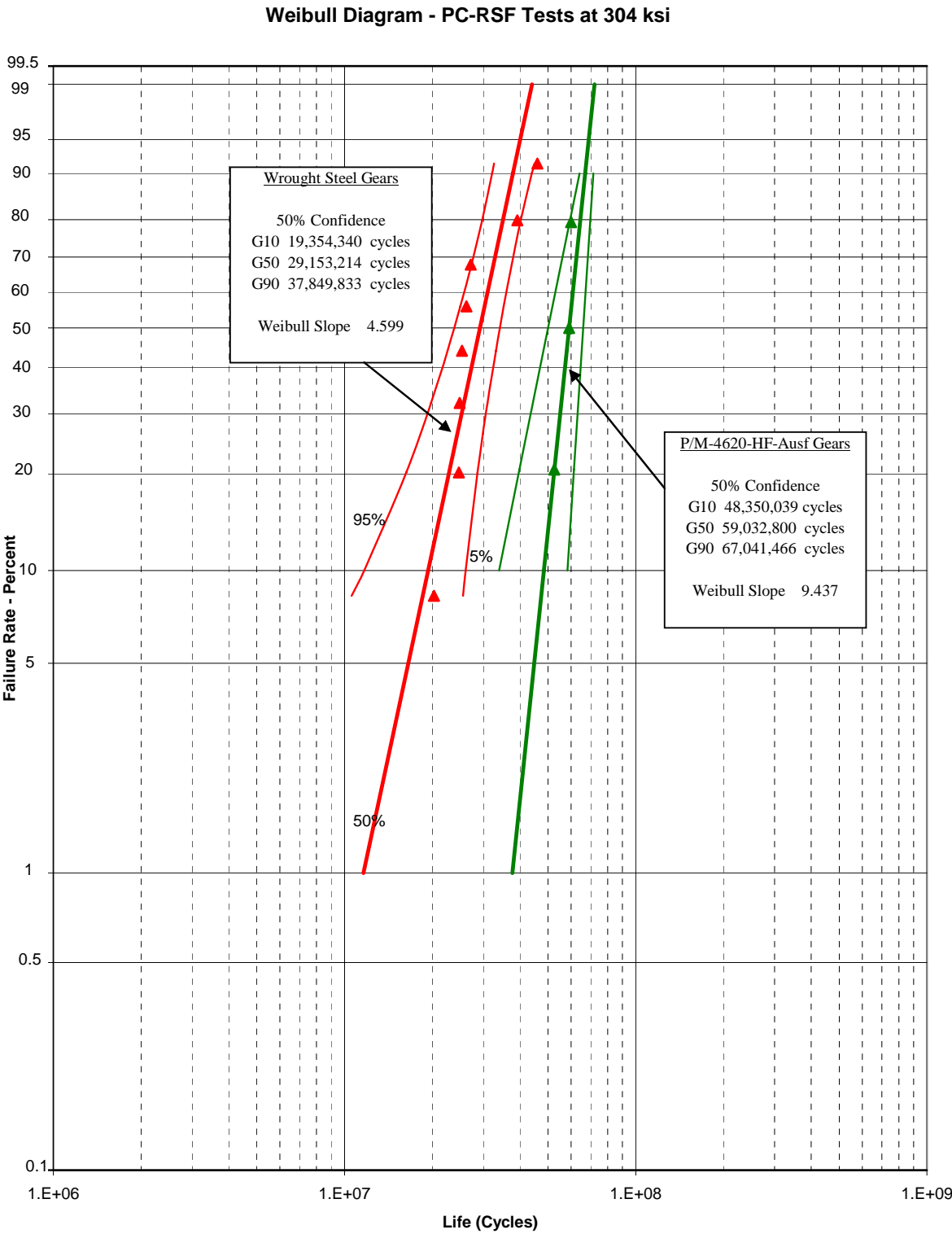


Figure 63 **Comparison of surface durability G-50 life**

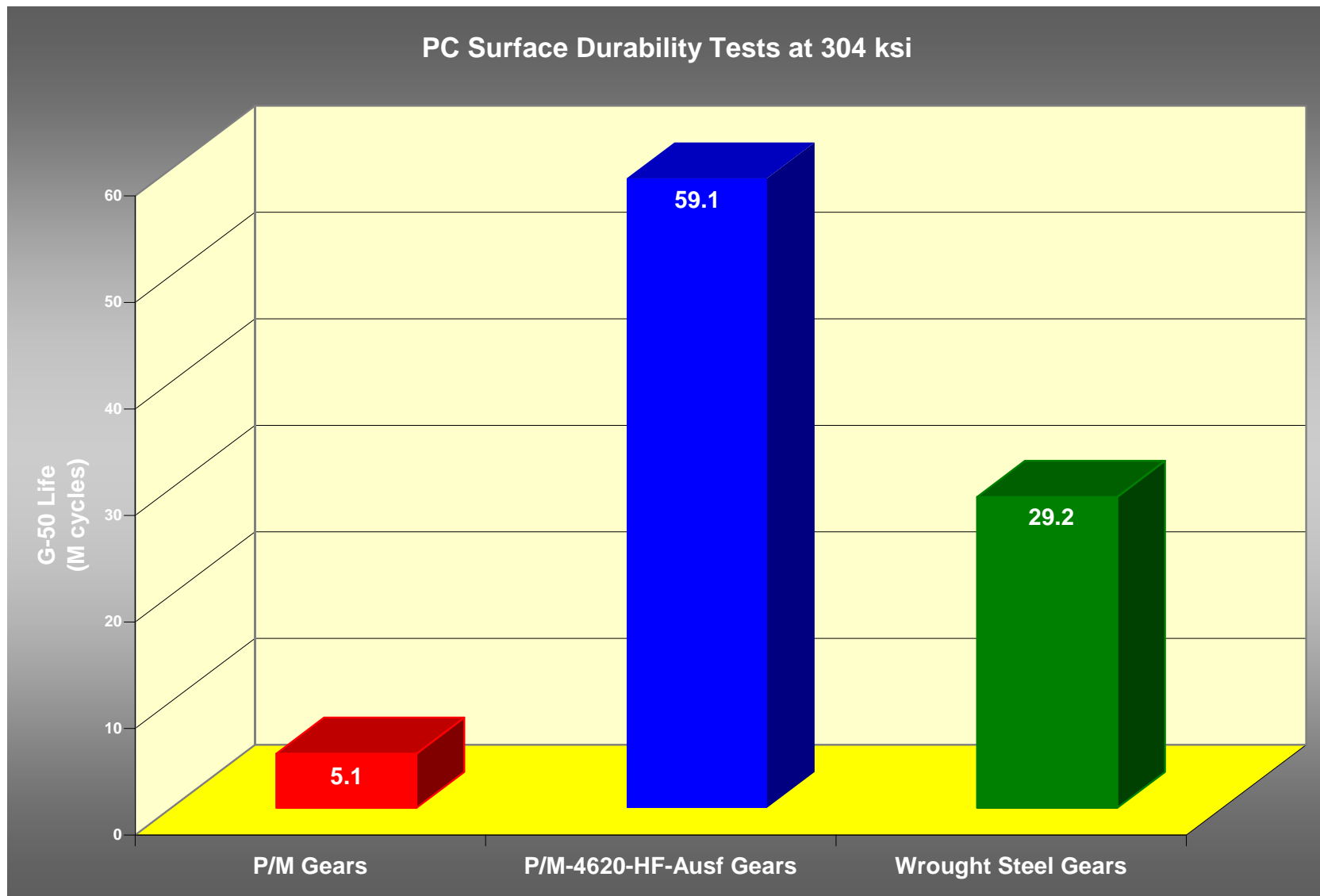


Figure 64 Scoring resistance test conditions

- **Scoring resistance (SR) measured as oil inlet temperature at which scoring occurs**
- **Oil flow throttled to get 50°F rise in oil temperature from inlet to outlet**
- **Test torques same as for RSF tests**
- **Initial oil inlet temperature of 140°F for each test**
- **Increase oil inlet temperature at 1°F/min**
- **Onset of scoring results in sudden rise in oil outlet temperature and/or vibration level**
- **Stop test if no scoring occurs even at oil inlet temperature of 300°F**
- **Change oil after each test**

Figure 65 Typical scored tooth surface of a baseline wrought steel test gear: scored at 260°F oil temperature and 2000 lb-in torque

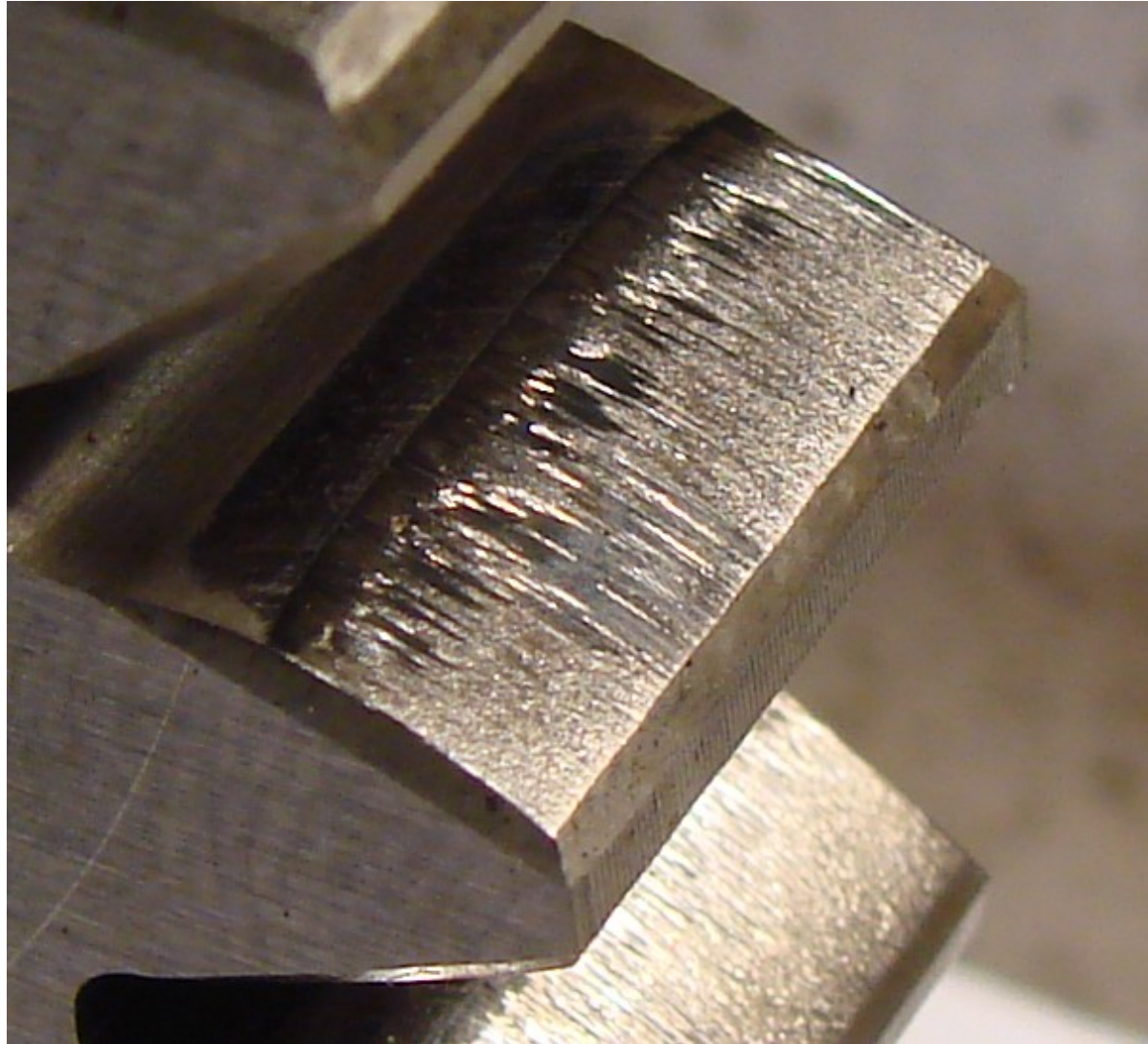


Figure 66 **Tooth surface of P/M-4620-HF-Ausf gear: scored at 300°F oil temperature and 2200 lb-in torque**

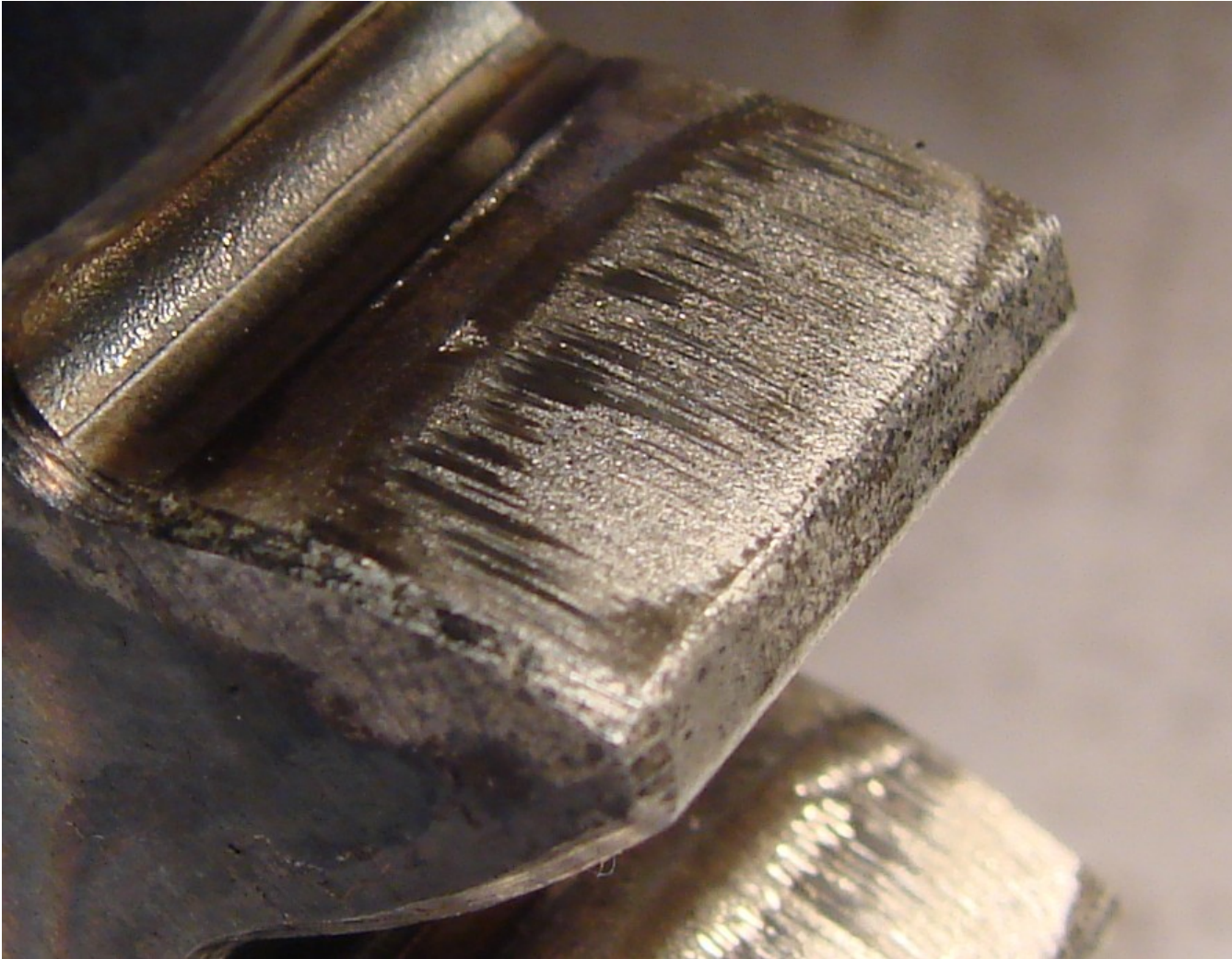


Figure 67 Summary of scoring resistance test results

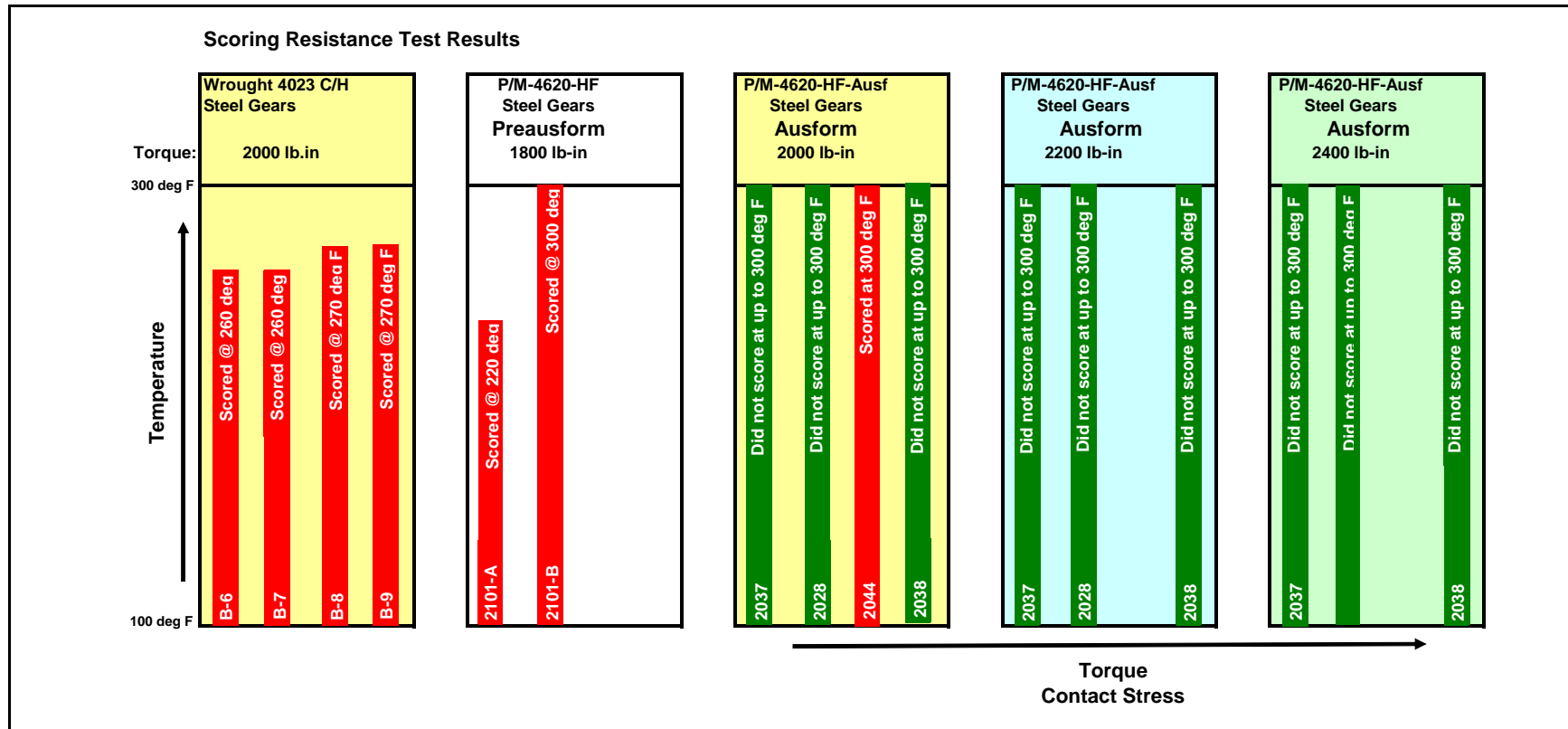


Figure 68 Drop-weight gear tooth impact testing machine

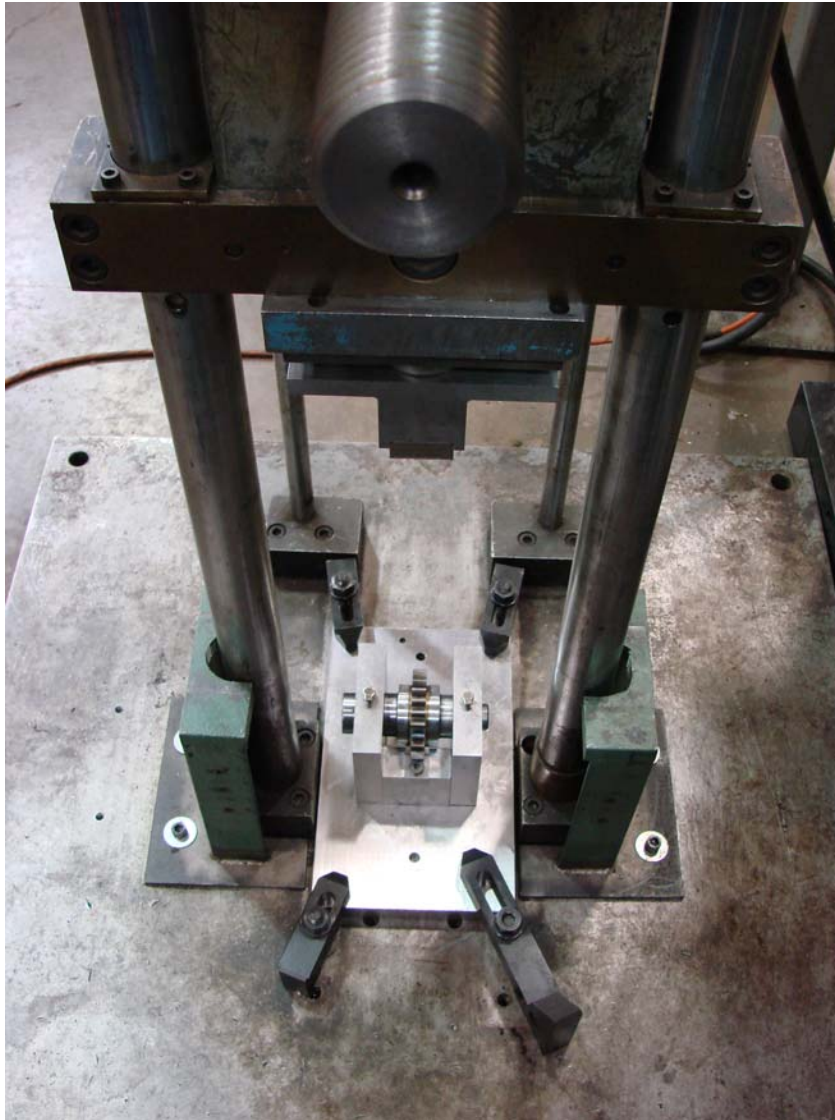


Figure 69 **Gear tooth impact test fixture for P/M standard gear**

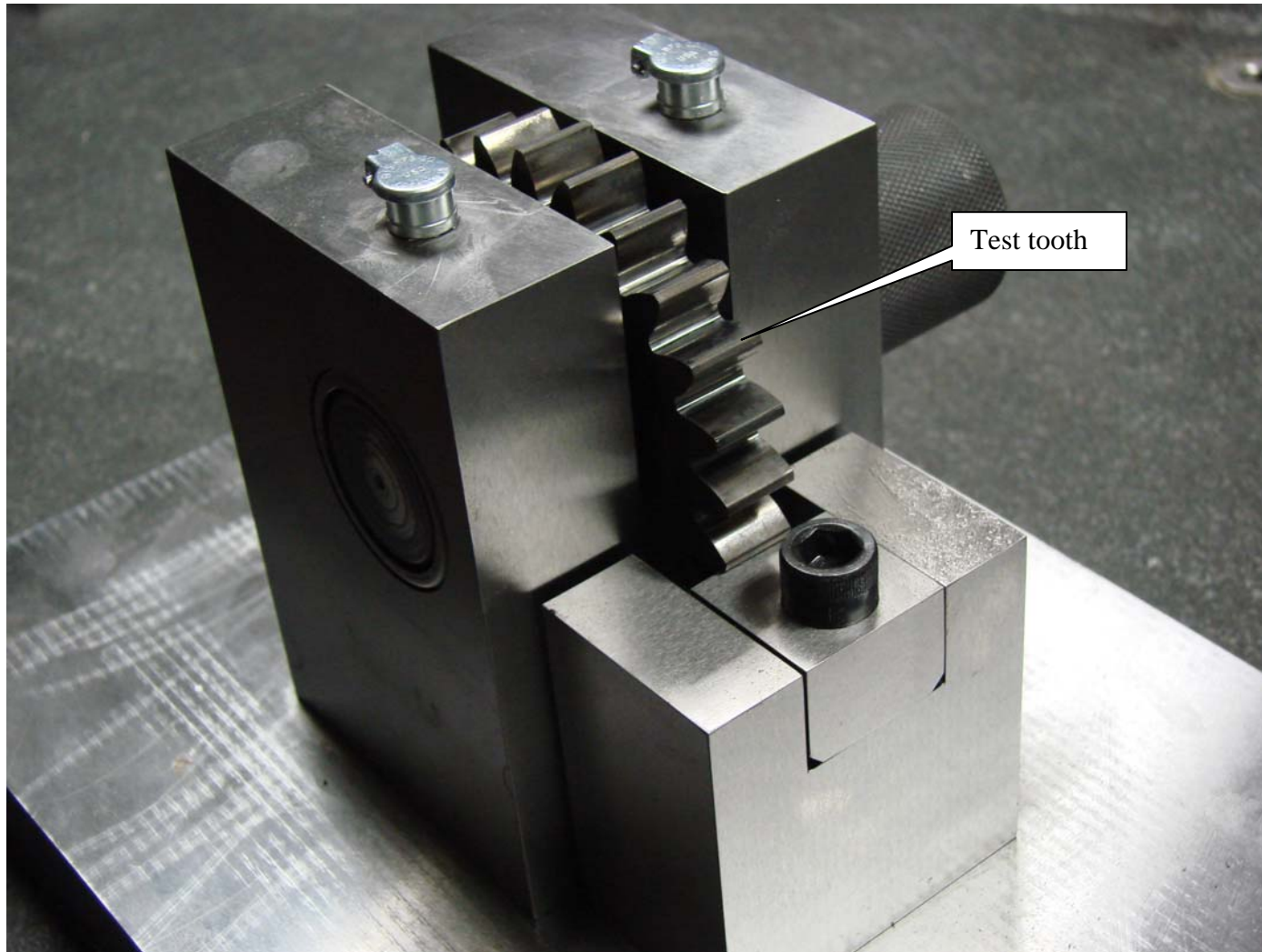


Figure 70 Gear tooth impact test layout

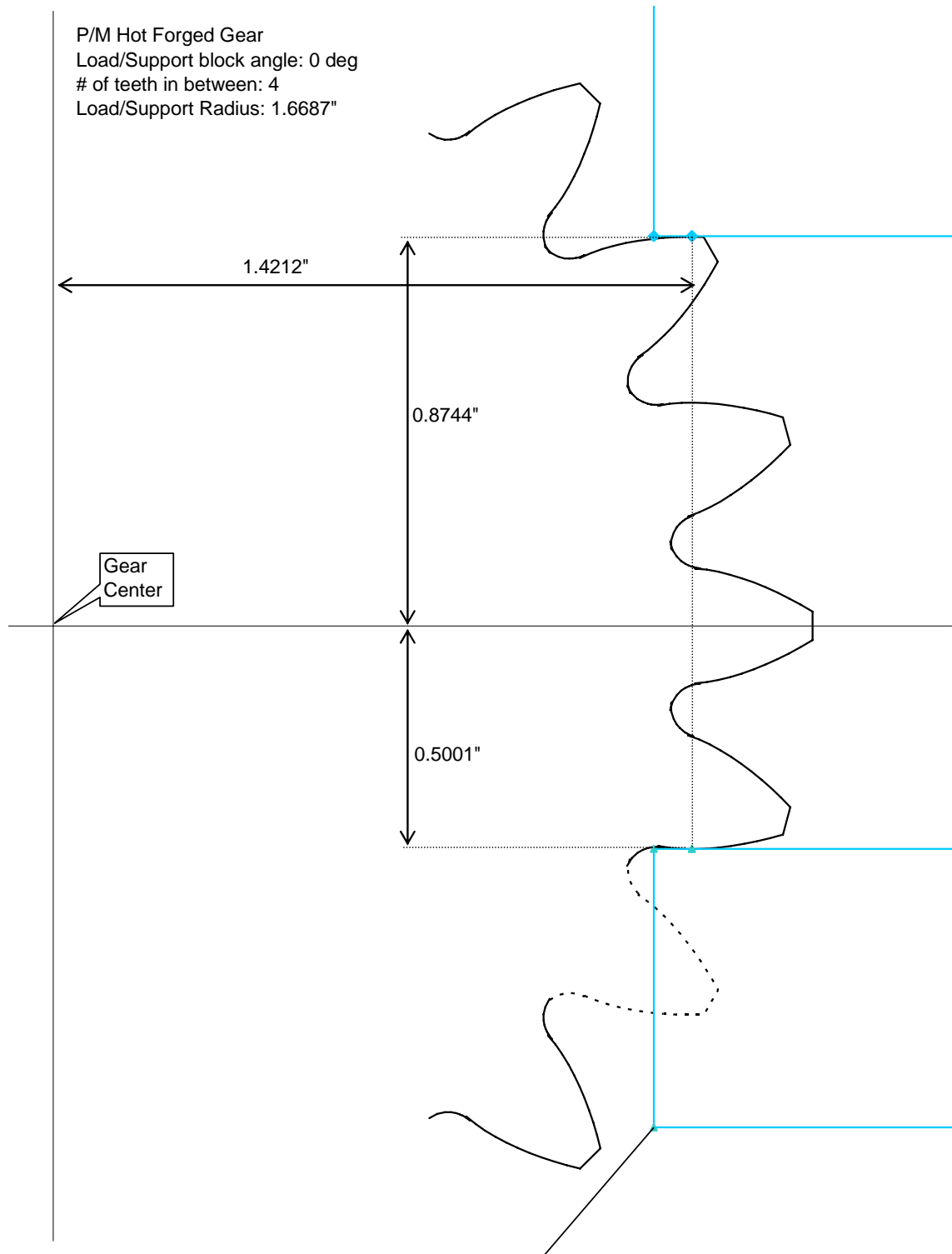


Figure 71 Typical gear tooth impact failure surface of wrought steel gear

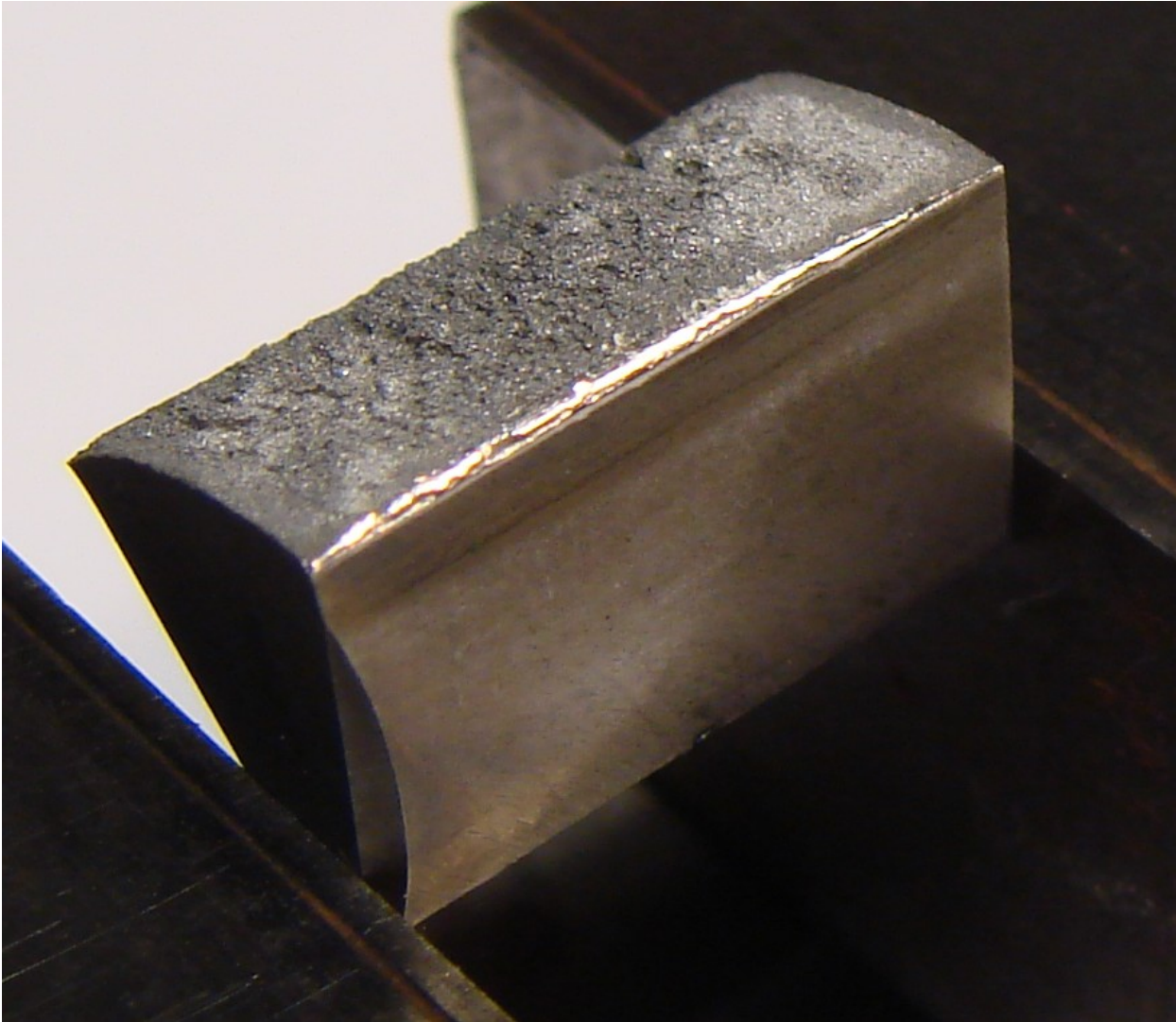


Figure 72 Typical gear tooth impact failure surface of high strength P/M-4620-HF-Ausf steel gear



Figure 73 Typical impact force vs. traverse plots for drop-weight gear tooth impact tests

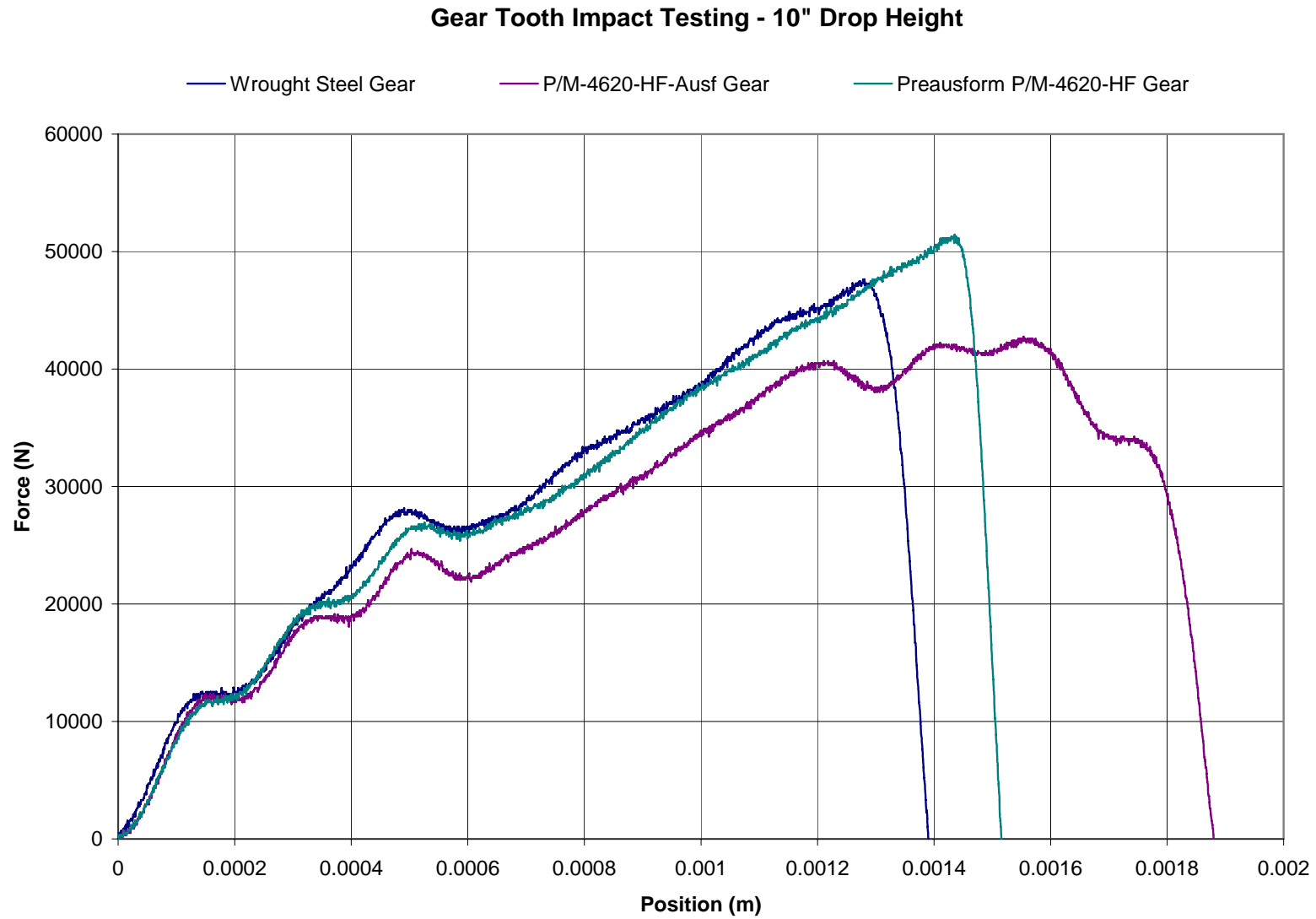


Figure 74 **Summary of gear tooth impact test results**

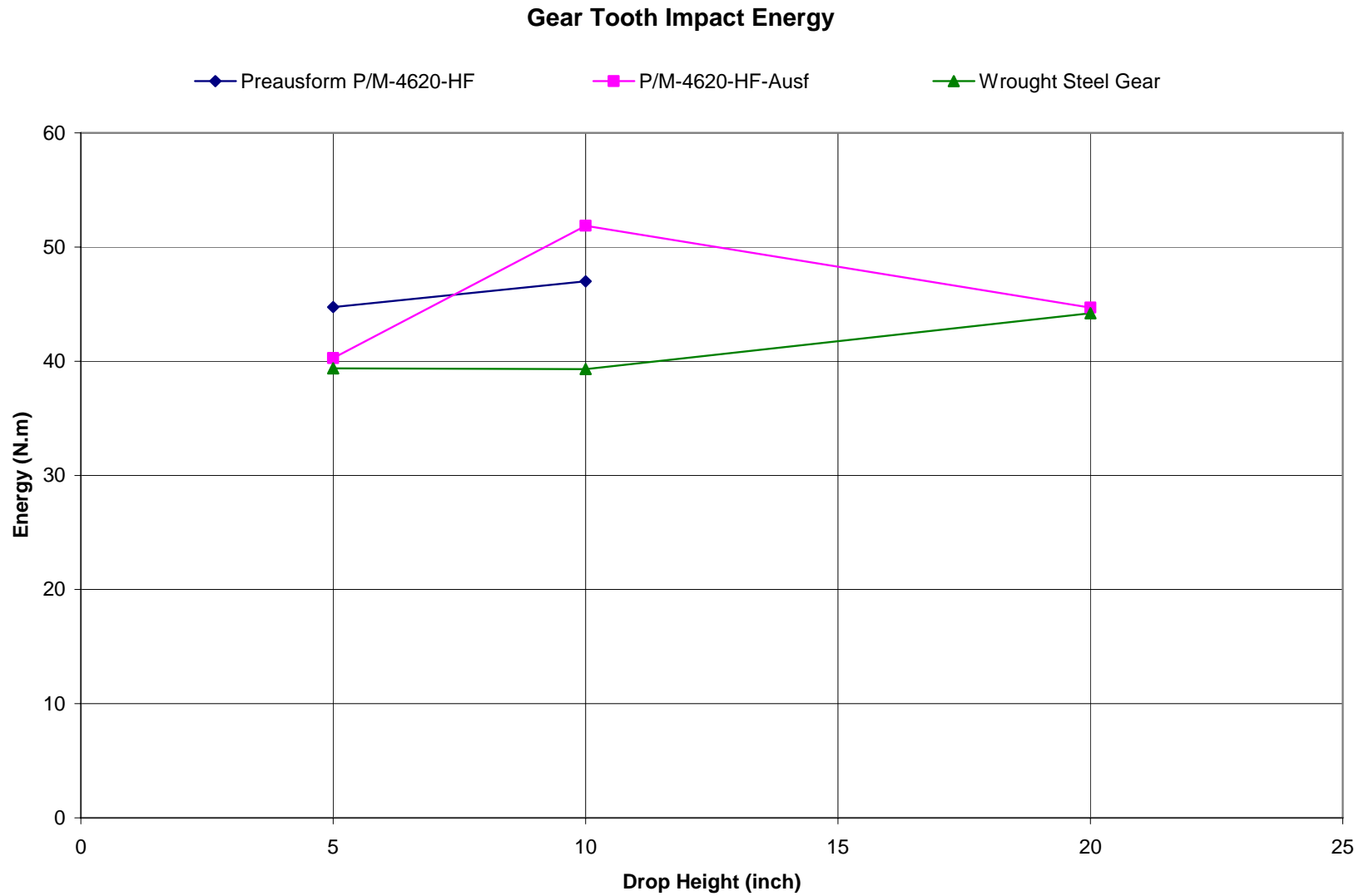
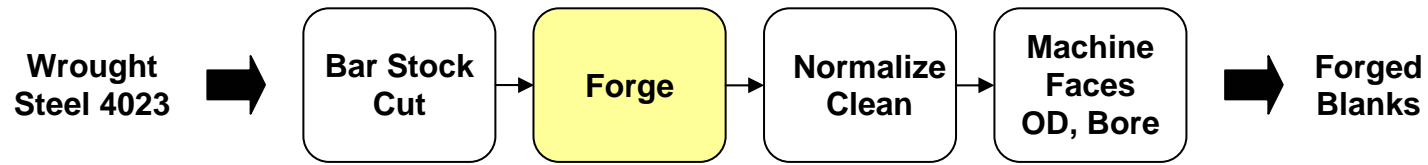


Figure 75 Modified NPG process to produce wrought steel gears of ground surface finish and quality

Forged Blanks Procured from Vendors



Modified NPG Manufacturing Process

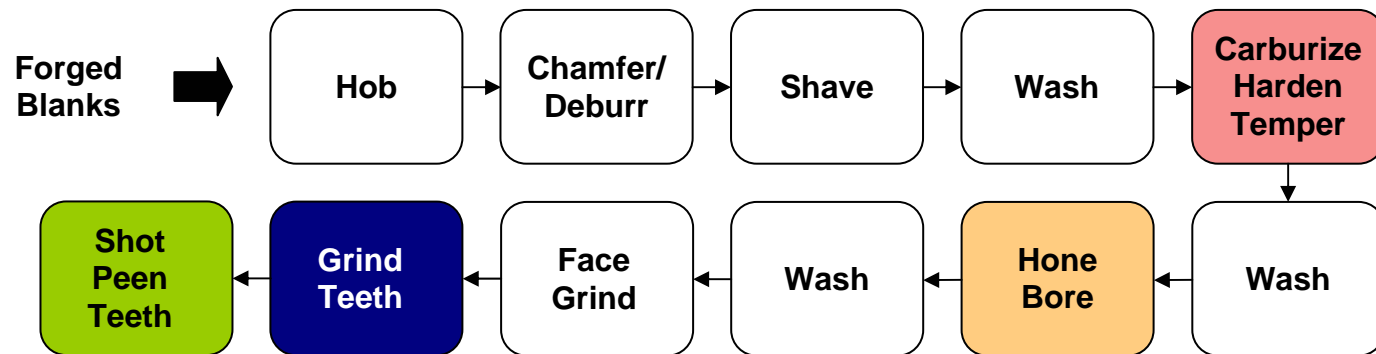


Figure 76 Process sequence for ausform finished P/M 4620 C/H steel gears without hot forging and related operation

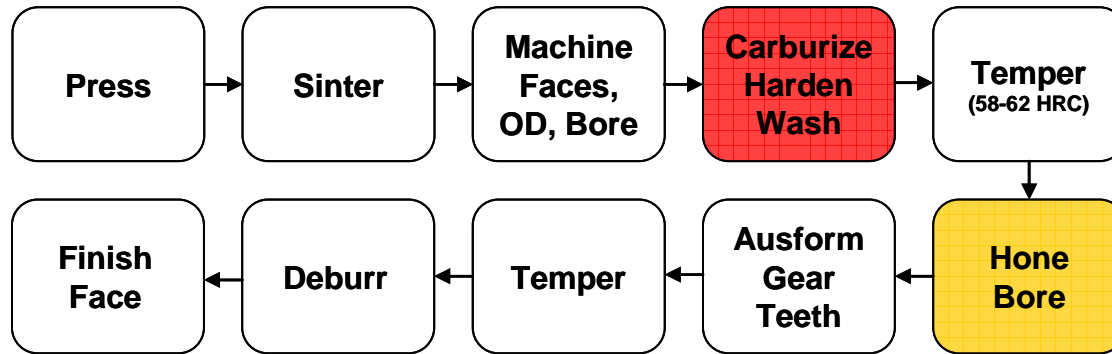


Figure 77 Process sequence for ausform finished P/M 4680 steel gears without hot forging and related operation

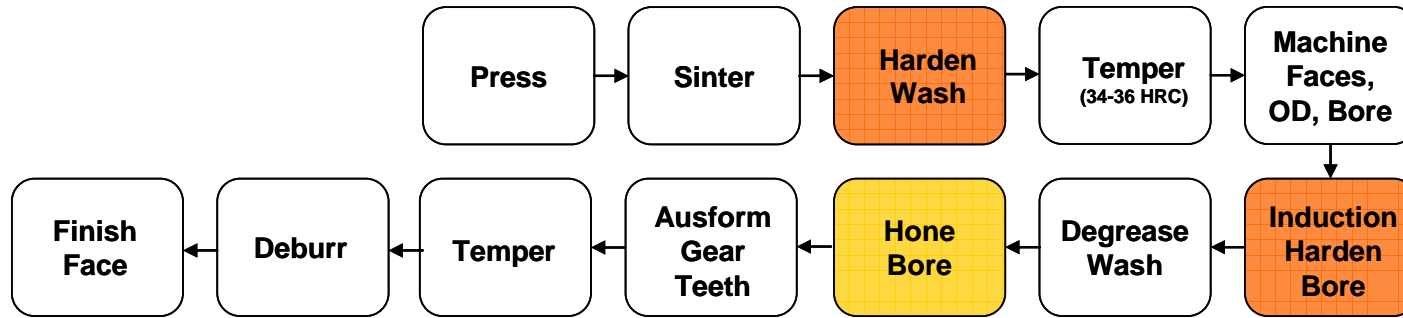


Figure 78 **Comparison of unit cost of HMMWV planetary helical pinion produced by various alternate processes**

