Generating Precision Spur Gears By Wire EDM

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Master gear accuracy is possible with this technique

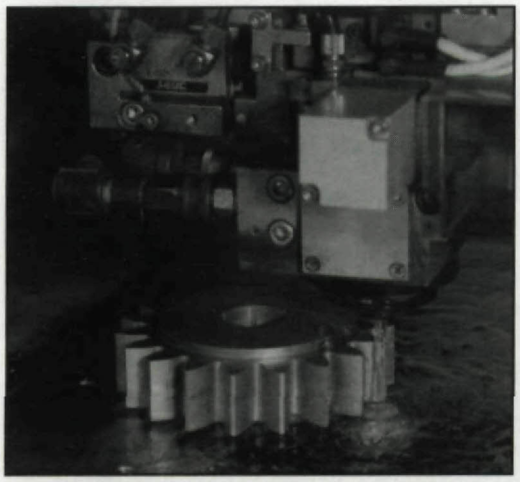

Fig. 1 — Wire EDM gear cutting setup.

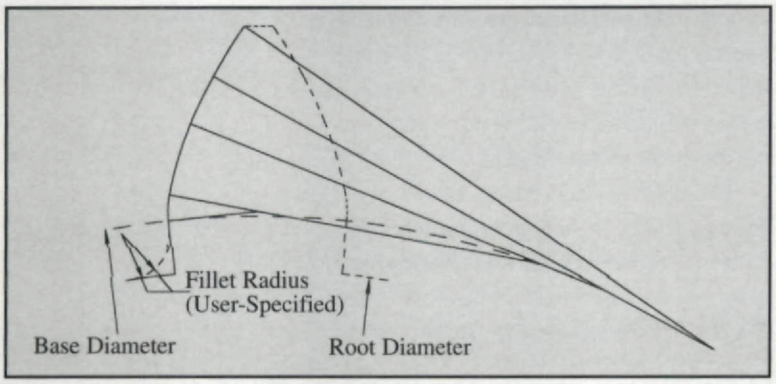

Fig. 2 — Typical EDM gear involute.

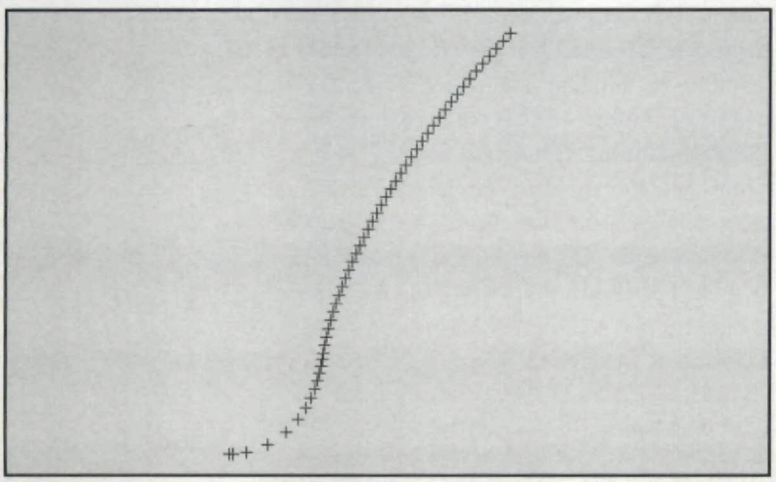

Fig. 3 — Gear surface coordinates.

Introduction

Over the past decade, the wire electrical discharge machine (EDM) has become an increasingly important tool for machining non-standard shapes. It has even been used to cut gears and gear cavities for plastic molds. While generally accepted as a quick and versatile method for cutting spur gears, the EDM gear has lacked the precision of a mechanically machined or ground gear. We suspected that many of the errors associated with these gears were caused by inexact setup procedures, poor tool path control and improper cutting parameters. We decided to test the potential for the wire EDM to make the most accurate gear possible.

Our experiment was, moreover, based on need. The plastic gears we designed for a gear-driven lawn sprinkler required unique master gears. Lead times for form-ground gears were unacceptable. With our customer's support, we developed a method of cutting these master gears that achieved the desired shapes on time and within cost constraints for fine-pitch master gears. We then employed the same techniques to cut a 19-tooth, 5 DP master gear in order to determine possible errors of scale. Profile inspection revealed that similar accuracy of tolerance was possible for large, coarse-pitch gears. In this article, we will present the methods we employed to achieve this level of accuracy, the inspection data from our work, comparisons with precision hob-cut gears and possible applications of this method to other forms of gear generation.

The EDM Process

Electrical discharge machining is based on the principal of erosion of an electrically conductive material by continuous spark discharge to its surface (Ref 1). With wire EDM, a metallic wire is continuously fed through arms suspended above and below the workpiece (Fig. 1). This charged wire is then guided through the specified tool path while cutting its way through the material.

The process is relatively slow, depending on wire diameter, workpiece thickness and machine settings. The servo-controlled tool path is quite accurate, typical for CNC machinery. The benign environment of the EDM machinery, with slow feed rates, extremely low forces, very little friction or vibration and controlled temperature, make an even finer accuracy possible.

The tool path can be drawn either point-to-point or in simple arcs. Advanced mathematical curves are not directly programmable by software; these must be approximated with arcs and/or line movements. Both the involute and trochoidal sections of a gear fall into this general category. Specified dimensional accuracy and repeatability of the more advance wire EDMs are on the order of .0001". Surface finishes are 16 microinches and can be attained through careful selection of machining parameters, along with multiple finishing skim cuts on low power settings.

Gear Cutting with Wire

Wire EDM machining is primarily a two-dimensional process, although the two wire guides can follow independent paths, allowing slight 3-D modifications. EDM software exists that claims to create a wire path for the spur involute. The software requires standard gear geometry to be input along with tooth thickness, root and outside diameters. Approximate arc segments are then fitted to the involute curve down to the root or to the base circle diameter, whichever comes first. If the base circle is located above the root circle, a straight radial line is connected from the base circle to the root diameter, and the user has the option of specifying a fillet radius for the intersection of those two features (Fig. 2).

Difficulties with this method of generation are immediately apparent: The trochoidal (or root) area is left arbitrary and undefined, and no provision is made for undercut even if it is required. One of the advantages of a hob-cut gear is that any gear will fit within the envelope created by the generating hob because the hob removes any possible interfering material in the root area that may physically interfere with another gear. A majority of non-undercut, standard gears are not sensitive to this possible trochoidal interference, since the standard whole depth provides sufficient clearance, and mating teeth never reach below the base circle. However, as designers modify gear geometry to maximize function or to allow for undercut, this area becomes critical because of possible interference or weakening by excessive relief. The mathematical generation of gear teeth must provide not only conjugate action, but also designed clearance with any mating gear.

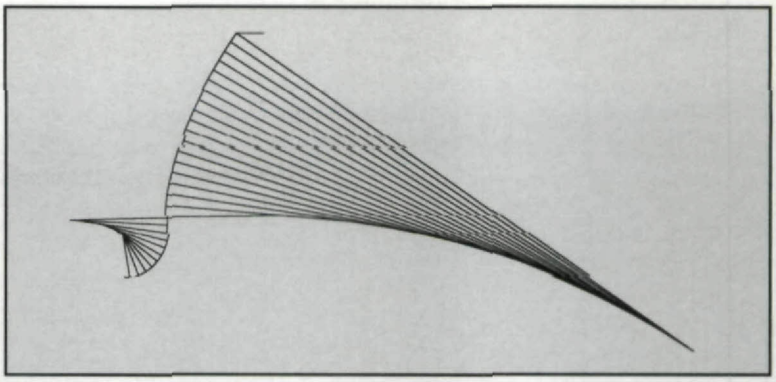

Fig. 4 — Optimal curve fit.

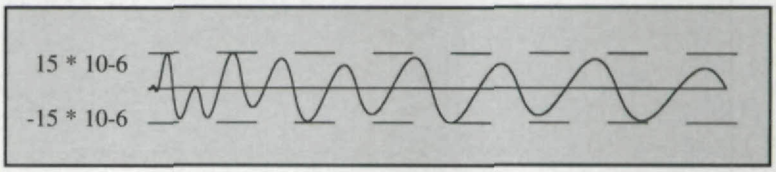

Fig. 5 — Deviation between splined arcs and involute.

Another not-so-apparent difficulty with the generation of approximate arcs to the involute concerns the nature of the involute itself. With its ever-increasing radius of curvature from the base circle, the involute is anything but a trivial curve-fitting exercise. The desirability of making intersecting arcs tangent at their endpoints compounds the problem of fitting these arcs to the involute. Without careful fitting, it is possible to have considerable error in the approximation, especially in the critical region of the base circle. The trochoidal surface can also be intricate and requires equivalent attention to detail in any generating curve-fitting scheme.

Mathematical Generation

Many texts describe the mathematical generation of the involute. Buckingham (Ref.2) described both polar and Cartesian equations for the involute profile. Point-to-point development of the generated trochoidal region is less well-documented. However, Khiralle (Ref. 3) and Colbourne (Ref. 4) have both published methods to find points on the trochoidal curve for any involute rack. They also describe the necessary iterative schemes to determine the exact involute form diameter for undercut gears. Solving these equations yields an array of discrete coordinate points that exactly describe the entire surface of the gear tooth (Fig. 3).

Curve Fitting

The wire EDM tool path is constrained to follow either straight lines or simple single-arc segments. The involute and trochoid, however, are curves with continuously changing radii of curvature. The designer might create a tool path with infinitesimally small linear moves to maximize the EDM's resolution, but the resulting NC program would be excessively cumbersome. A more

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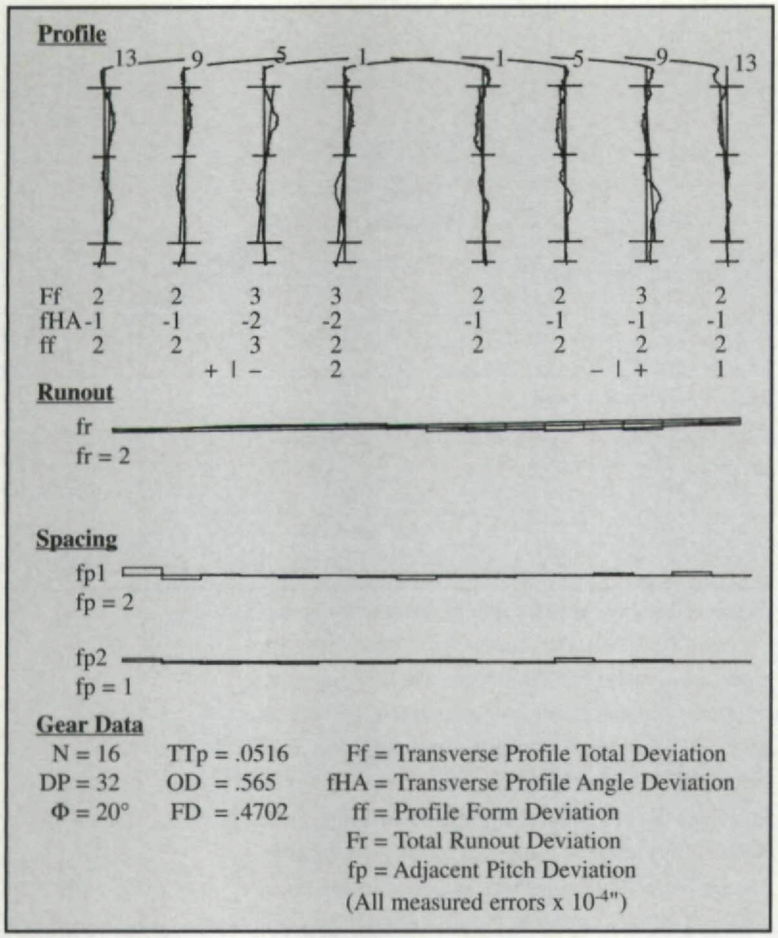

Fig. 6 — 32 DP hob-cut gear data.

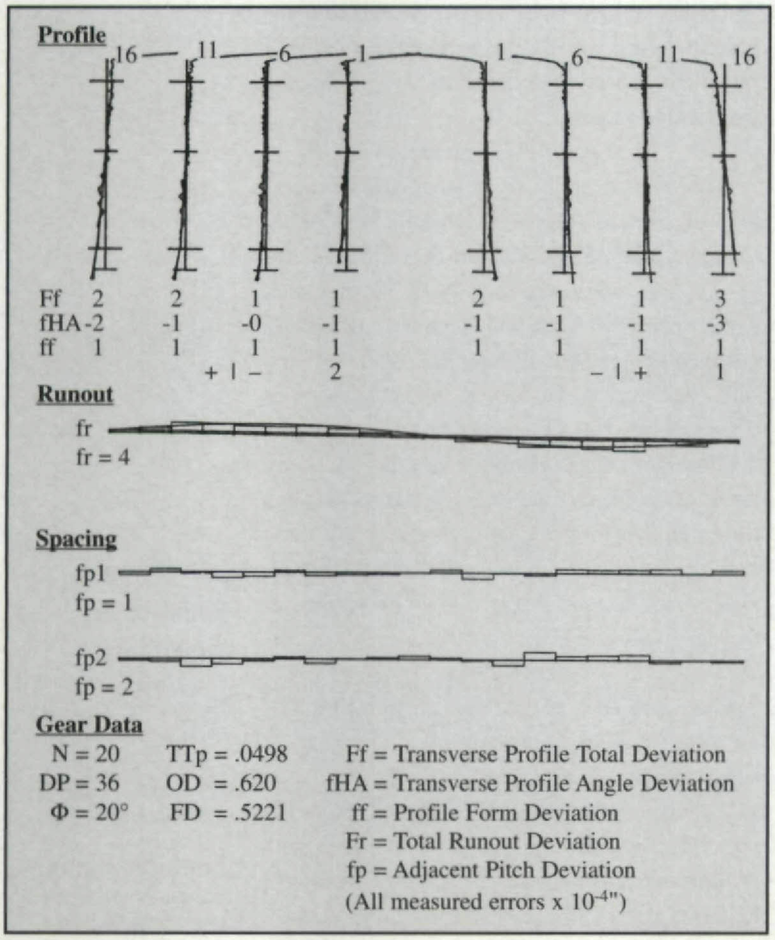

Fig. 7 — 36 DP wire EDM gear data.

efficient approach would be to allow the machine's own software to optimize the cutting path. A mathematically satisfying curve-fitting routine would link approximated arcs with common tangents to the profiles (Fig. 4). The machine tool would then follow the nearest *x-y* path to this profile.

At first glance, it would appear a simple task to approximate the involute and trochoidal curves with splined arcs in the minimum least-squared sense; however, since any arc segment is mathematically nonlinear and multivalued, and because the function that represents a splined series of arc segments includes nonlinear parameters, this is not the case. The curve-fitting task is difficult, but not insurmountable. Numerous general purpose optimization algorithms can be adapted to solve this kind of problem (Ref. 5). The use of these methods to solve curve-fitting problems is not an exact science and has sometimes been called an art. With careful selection and tuning of methods, we have been able to generate splined arc approximations of the involute and trochoid with arbitrarily specified maximum error criteria (Fig. 5).

Initial Setup

Four external gears were made. The diametral pitches were 32, 36, 40 and 41. Inspection equipment included a Mahr Model 896 gear roll tester and a Zeiss ZMC 550 gear coordinate measurement machine for profile, lead and spacing checks. The 36, 40 and 41 DP gears were cut by EDM, and the 32 DP gear was cut with a 1" diameter Grade AA precision hob in order to get a sense of the relative accuracy possible with each method. Two of each gear were made so they could be roll-tested against themselves to examine close-meshed conjugacy. They were then inspected independently on the CMM for absolute accuracy. We felt that roll testing was imperative for wire-cut gears, since the cutting process was purely mathematical in function. Any local aberration in the cutting or fixturing of the gear that might not be detected by the single point of a profilometer would be more easily seen on a double-flank roll tester.

Discussion of Results

Figs. 6, 7, 8 and 9 show the profilometry of the fine-pitch gears as measured on the Zeiss CMM. Total profile deviation (*Ff*) for the EDM gears in Figs. 7, 8 and 9 varied between .0001" and .0003", while the profile form deviation consistently stayed within .0001". The hob-cut gear in Fig. 6 maintained profile deviation between .0002" and .0003", however total form deviation also varied by that amount. The EDM profile traces appear as more nearly straight lines, while the hobbed profile exhibits waviness. The lead error on all gears was .0001" maximum, and the adjacent pitch deviation (*fp*) remained less than .0002" for all gears. In total runout, the hobbed gear held .0002", while the EDM gears varied between .0003" and .0005".

Roll tests of the gears against themselves are presented in Fig. 10. A comparison trace of 32 DP form-ground master gears rolled against each other is included as reference. The scale is identical for all traces at .0003" per large division. These traces were taken when the gears were new without running them in lightly first. Later traces were more uniform. Unfortunately they were not retained. We believe that light running-in of EDM gears is desirable to polish the matte surface and deburr edges.

A Coarse-Pitch Example

The remaining question was whether EDM errors would be magnified by scaling the generation process for coarse-pitch gearing. We decided to wire-cut a 5 DP, 19-tooth gear and concentrate on improving runout and optimizing the curve fit. This gear would be roughly 8 times the size of the previously cut fine-pitch gears. We generated 15 arcs for this involute with a maximum mathematical error of ± 15 microinches. The material was through-hardened 420 stainless steel. A complete profile inspection was done for each flank of this gear. A representative sample of results is given in Fig. 11. Total profile and form deviation stayed within .0001" and .0002", and total runout was held between .0002" and .0003" Spacing and lead were both held to .0002". In effect, we were able to improve the dimensional characteristics of the larger gear by improved cutting methods and closer mathematical approximations. This wire EDM gear was ultimately used to monitor a production run of thread-ground spur gears.

Conclusions

Wire EDM is suitable for producing accurate spur gear shapes. These early fine-pitch gears were adequate for their intended purpose of plastic gear inspection. Both profile and form deviation for these gears were generally improved over their hobbed counterparts. Total runout of these gears was slightly greater than for the cut gears, but further modifications in fixturing and machine setup should improve this feature. At present, this method has not reached the same accuracy as form-ground masters, but gears cut this way cost less and can be cut in a week. For certain applications, that can be the deciding factor. The coarse- pitch gear in this experiment benefitted from the lessons learned on the smaller gears. It suffered no degradation in tolerances despite being 8 times larger.

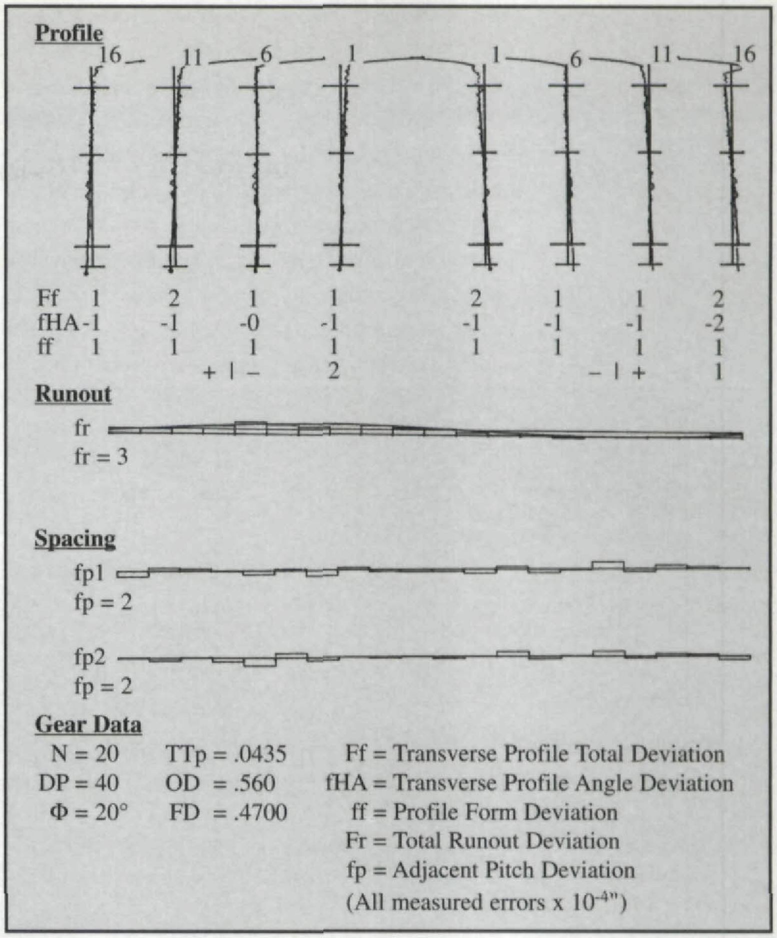

Fig. 8 — 40 DP wire EDM gear data.

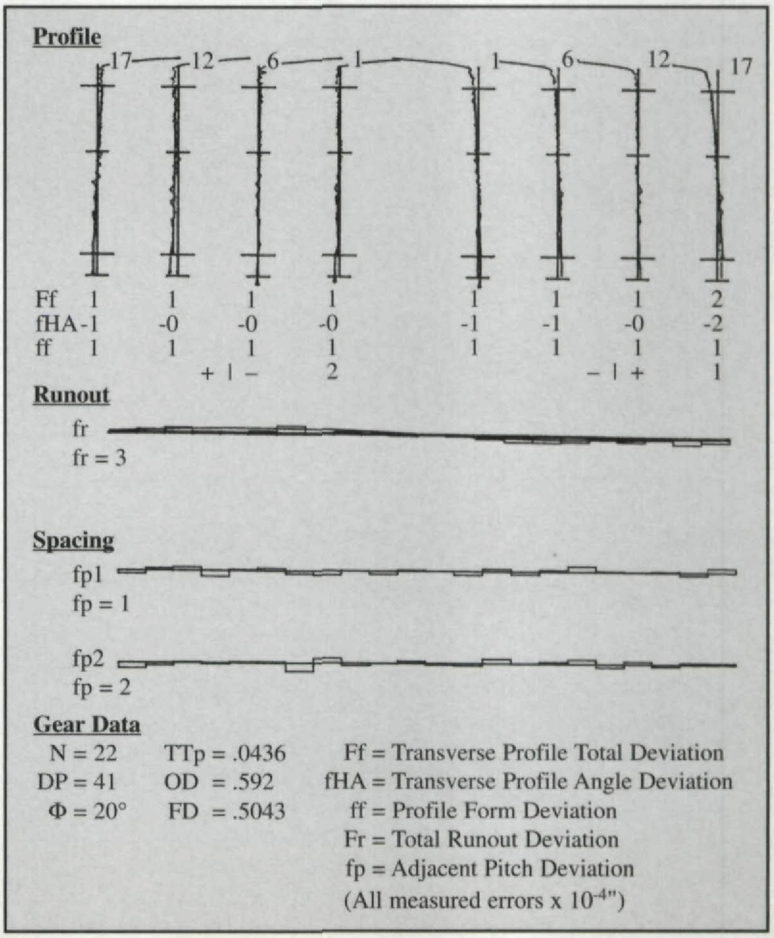

Fig. 9 — 41 DP wire EDM gear data.

This 5 DP gear satisfies the criteria for a Class 2 master gear, with similar cost and production advantages over form-ground gears.

The involute shape is not particularly difficult for the wire EDM. Any mathematical path that can be described in arcs and/or lines can be generated with similar accuracy. Tip relief, root relief and noninvolute tooth forms can be generated with very little added complexity or cost. The ability to cut two separate shapes at the same time with the upper and lower cutting arms opens other possibilities as well. We have already produced bevel gears using Tregold's approximation of the equivalent spur gear form. Low helix angle gears can be accurately cut with only slight overcut on the root area at one end of the gear. Even crowning can be approximated. In many ways, the use of this process is only limited by the user's cleverness.

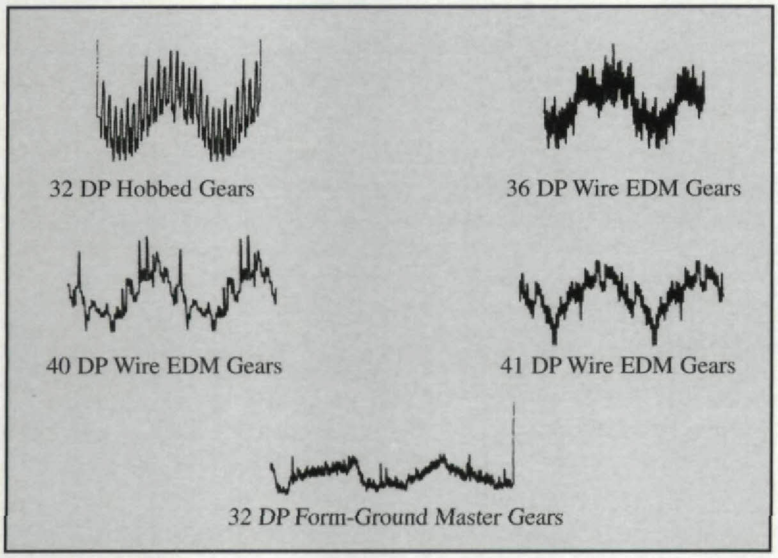

Fig. 10 — Roll tests.

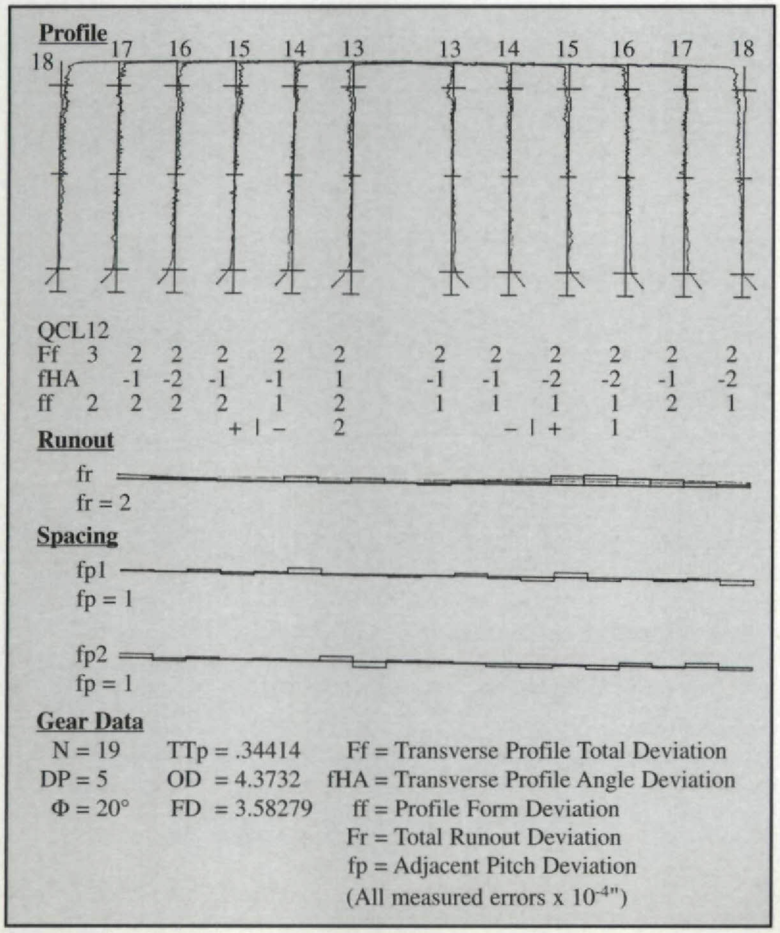

Fig. 11 — 5 DP wire EDM coarse-pitch gear data.

Further investigation needs to be done on the production and effect of the EDM process. Since the generating method is new, current standard inspection criteria may not adequately cover all possible production errors. Simply specifying maximum tooth-to-tooth and total composite error may not be sufficient. It would also be interesting to investigate the effect of EDM metallurgy on life, wear, pitting, etc. For instance, hardening with EDM is achieved with through-hardened steels, but the cutting process under water can produce an additional hard thin surface layer exceeding 70 Rockwell C. Whether this effect can be significant for gears is unknown.

Mathematically describing the total gear shape can be extended to other generation methods as well. The latest CNC equipment can follow the same type of path as the wire EDM. NC dressers can directly form grind spur and helical forms. This type of generation is bound to become more available as the gearing community continues to seek a continually improved and cost-effective product. Computer generation of the necessary forms and numerically controlled inspection of the resultant shapes will ultimately yield an accurate and verifiable product. ⭘

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