Human Machine Interface (HMI) in Gear Manufacturing

"Documentation is not a Substitute for an Intuitive Interface"

Yefim Kotlyar

Introduction and Cursory Historical Overview

(*Giving credit where credit is due, the quote contained in this paper's title is attributed to Kenneth Corless.*)

Human machine interfaces (HMI) in the gear industry are continuously influenced by the advances of user interfaces elsewhere in computing. The ever-friendlier and more intuitive interfaces being perpetually enhanced by *Google, Microsoft, Apple, Facebook*, and all other technology leaders are influencing and changing the expectations of the machine users. The machine tools makers are becoming more cognizant of this trend and are making strides to improve their HMIs to meet the changing expectations.

These days gear manufacturing is mostly computerized. While there are still some mechanical gear cutting machines in the field, they are increasingly being phased out, as very few (if any) mechanical machines are being produced today anywhere in the world. As compared to turning and milling, it did take a bit longer for the gear manufacturing industry to fully embrace computerization, but once it did, it never looked back.

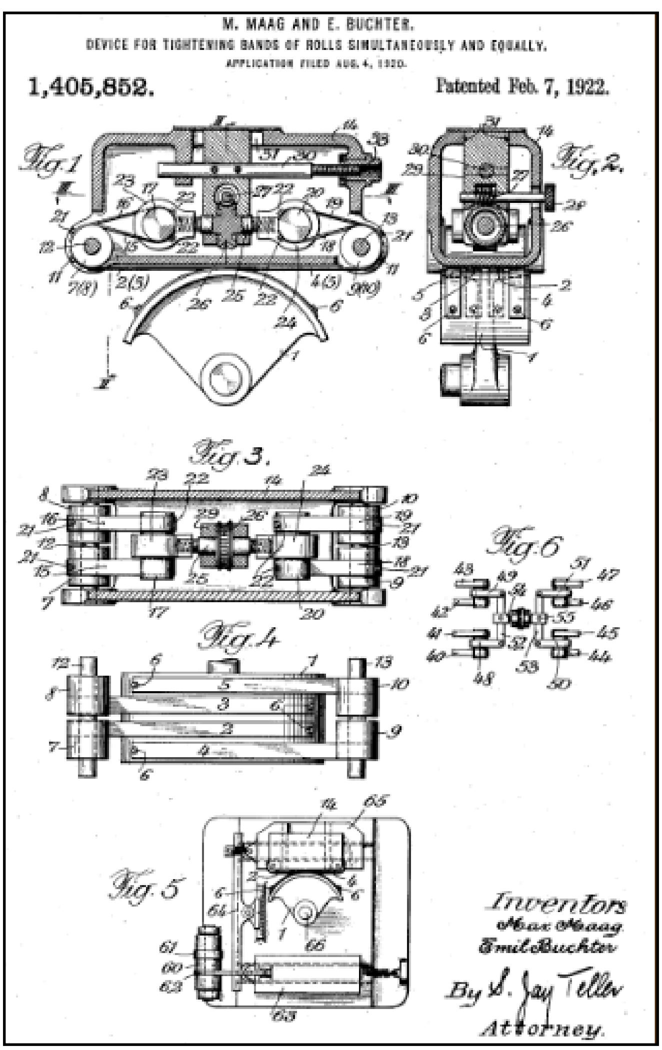

Figure 1 M. Maag & E. Buchter patent for tightening bands of rolls simultaneously and equally, 1920.

During most of the 20th century, improvements of gear manufacturing machinery were centered on perfecting the art of the machine's mechanical foundation, i.e. — increased rigidity; improved accuracy of the axes alignments; introduction of mechanisms for reduction — and even elimination of backlash; introduction of the differential mechanism for cutting helical gears; and introduction of the rolling bands for precision gear grinding (Fig. 1) are just some examples. Also, the use of hydraulics and pneumatics was expanded to support various machine functionalities.

Machine computerization at the end of 20th century brought a new wave of profound and non-stop innovations into the world of gear manufacturing. At the beginning of this computerization process in 1980s and 90s, most of the innovations were driven by computer hardware, i.e. — more powerful, faster controls. But eventually, as Microsoft co-founder Paul Allen said — "Software trumps hardware" — software development has been playing an increasingly greater role in generating new advancements.

The 21st century innovations, whether the expansion of machine functionalities or the elevation of friendliness making the machines easier and therefore faster to set up/operate, are only limited by the imagination of machine users and makers. Thankfully, many users are not shy about verbalizing their imagination and are dispensing new challenges to the machine makers that add fuel to their creative process.

Today, almost anything one can imagine can be mathematically and logically modeled. If an idea can be modeled, it can be turned into a computer code to run the machine.

One side of this unrelenting expansion of machine features, options, and new capabilities is the inevitable expansion of HMI. However, despite the proliferation of features and options, the machine should not be more difficult to operate. Users' high expectations for an intuitive and friendly HMI are cultivated by the likes of, as mentioned, *Google, Microsoft, Apple, Facebook* and many others, i.e. — the expanded possibilities of an app should not necessitate a greater difficulty of use.

A Modern Gear Form Grinding Machine Has Many Functions and Features

Let's look at the example of a contemporary gear form grinding machine that has a lot going on (Fig. 2). While gear grinding

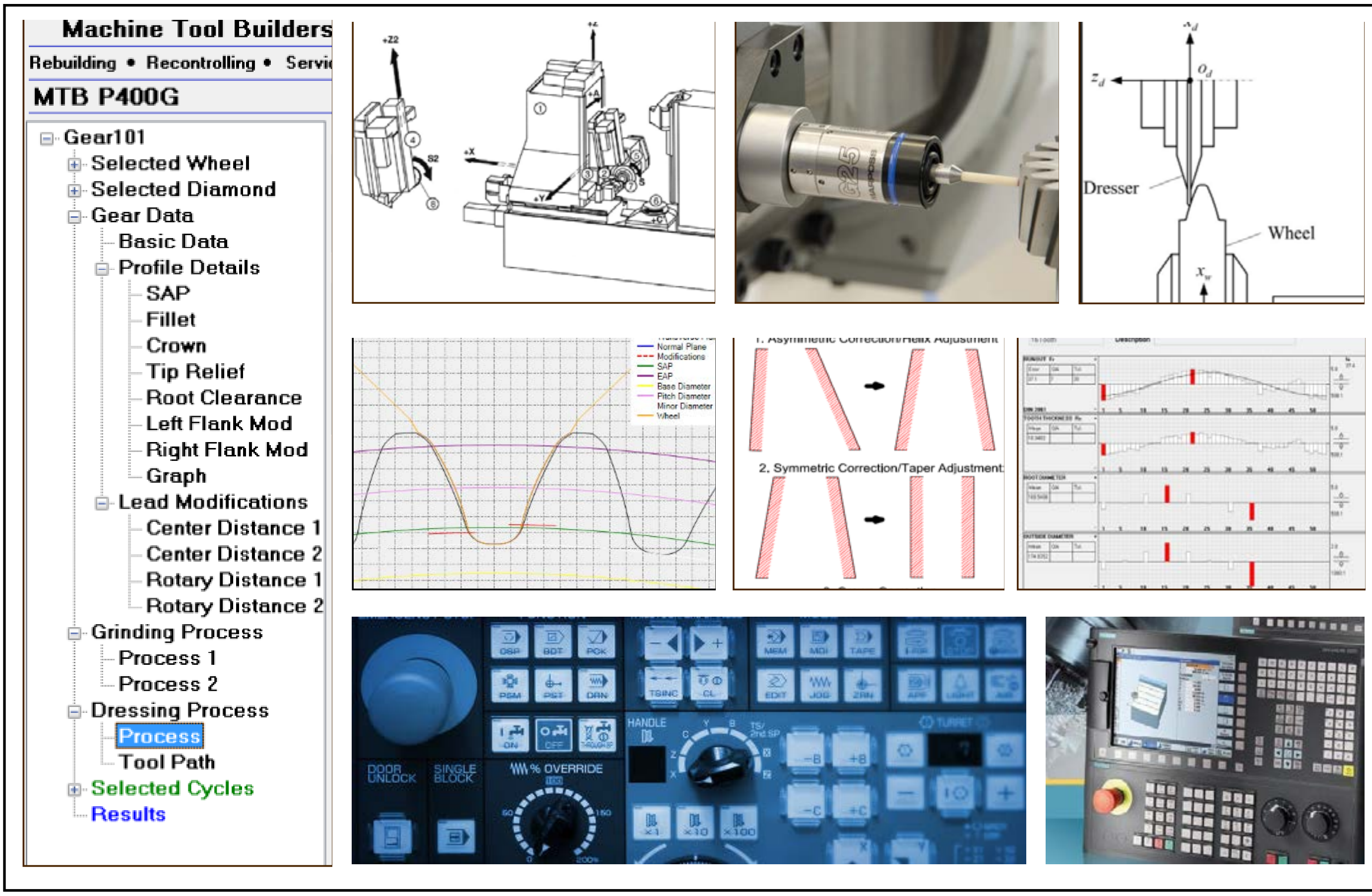

Figure 2 Example of contemporary gear form grinding machine with a lot going on.

is the prime function of the machine, it is only one of its many functions; other supporting functions include:

- On-board dressing of the grinding wheel
- On-board gear inspection and evaluation of inspection results
- Intelligence to make automatic or manual process/setup adjustments based upon on-board inspection results.

All these prime and supporting functions have many data entry fields for the operator to control and to fine tune to ensure proper functionality.

Grinding gears is the main machine function. This function relies on numerous data points defining the basic gear geometry (Fig. 3); profile and lead modifications; the gear axial and angular orientations in relation to the grinding wheel; grinding method; feed and speed rates; number of passes; and many more data points for the "control knobs" to properly complete the task.

Typical features and flexibilities of the form grinding function are:

- Grinding spur and helical gears
- Usage of dressable or non-dressable wheels
- Possibility of grinding two or a single flank at a time
- Profile and lead modifications

On-board dressing is one of the supporting functions. In addition to the basic gear geometry, this function relies on the information about the profile modifications, dressing tool geometry, dressing conditions, and the fine tuning fields to develop optimized dresser passes that minimize dressing time.

Examples of data entry for typical profile modifications and root geometry (Fig. 4):

- Straight or parabolic tip relief
- Profile crowning
- Point-by-point profile corrections
- SAP or TIF (start of active profile or true involute form)
- Root/fillet radius

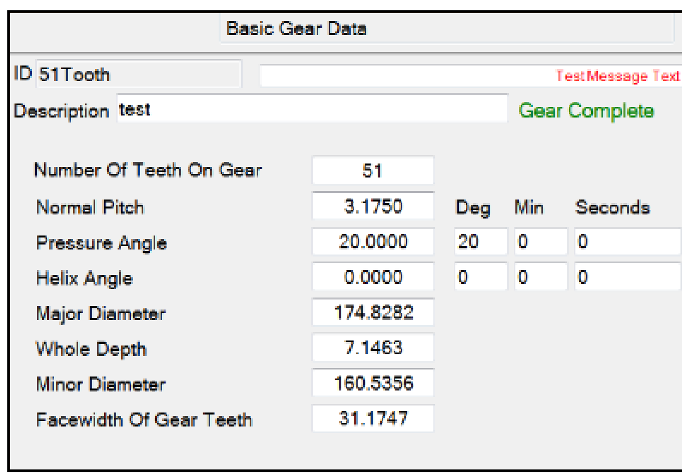

Figure 3 Grinding utilizes numerous data points in defining basic gear geometry.

Figure 5 depicts an example of the dresser geometry, as this is another critical set of information required for generating precision dressing passes.

Figure 6 depicts a typical geometry definition of a purchased grinding wheel; it is a third set of the information needed for the wheel dressing process. Dressing conditions (Fig. 7) are the fourth set of the information needed for the wheel dressing process.

Based on these four sets of data, the dressing passes are generated. Also, some advanced on-board dressing system may include a capability for optimizing the dressing pass travel for maximum efficiency. Figure 8 represents a visual verification of an optimized, initial dressing pass. The operator has a chance to visually review the optimized dresser passes in order to reduce a chance of a crash and to minimize (or eliminate) the number of wasted passes.

On-board inspection. Today's not only large, but also medium-size gear grinding machines are increasingly being manufactured with an on-board inspection capability. Here are some of the on-board inspection features and capabilities:

- Inspection and evaluation of profile, lead, index, tooth thickness, OD and root diameter
- Automatic tooth finder and stock division
- AGMA/ISO/DIN standard determination and tolerance calculation
- Probe calibration without interrupting part setup

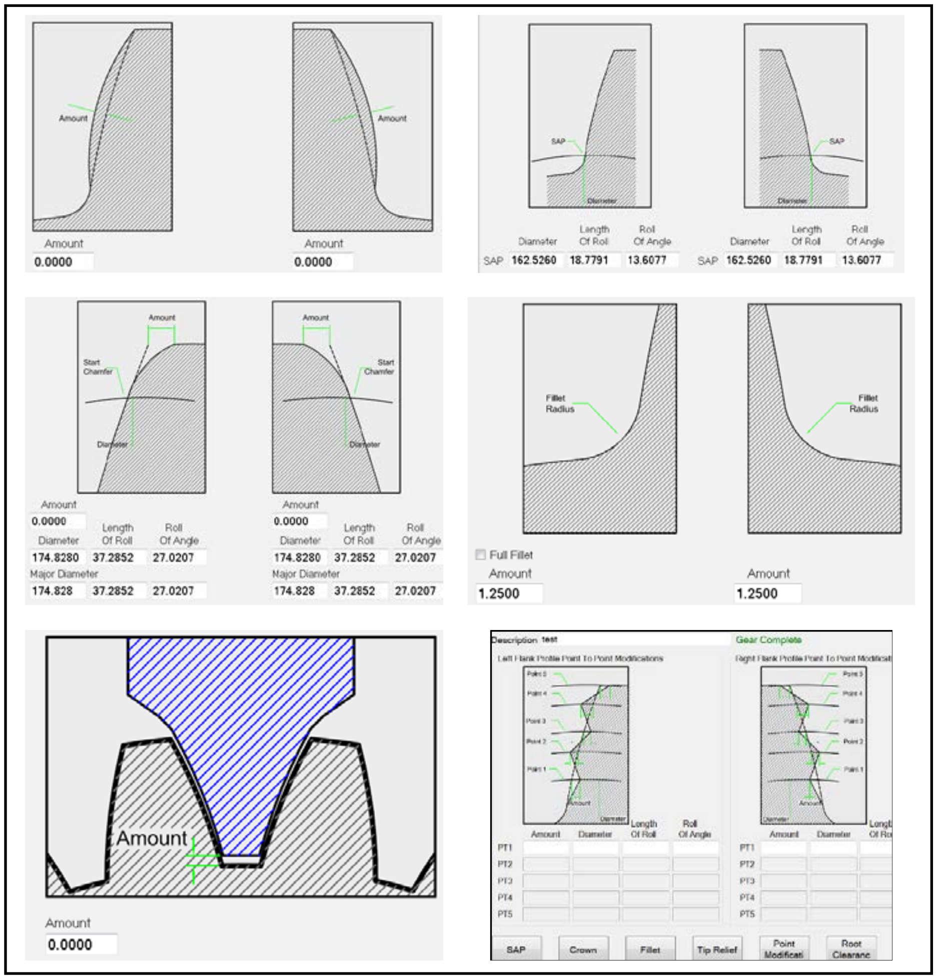

Figure 4 **Various profile modifications and other details.**

Integrating inspection with setup adjustments. While more grinding machines have features to help operators determine the necessary adjustments based on external inspection, the on-board inspection provides a more fertile soil for automating the setup adjustments for profile, lead and tooth size.

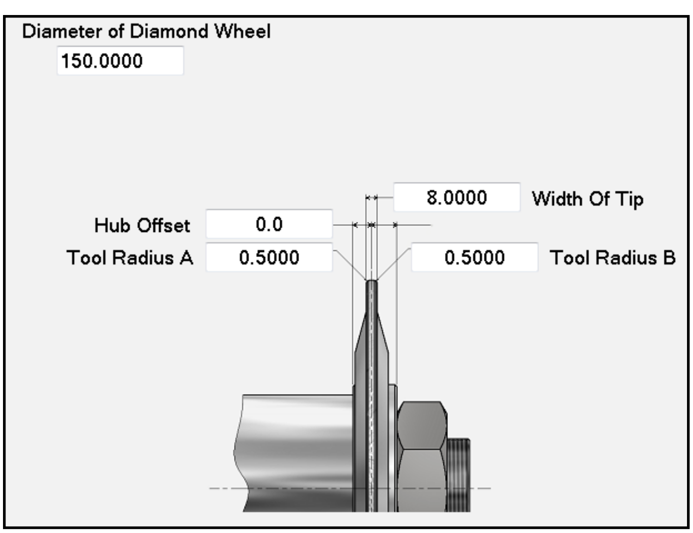

Figure 5 **Example of dresser geometry — another critical set of information required for generating precision dressing passes.**

The Prominence of Human Machine Interface (HMI)

With so many different capabilities, functions, features, and fine tuning "knobs," how does the operator "connect the dots"? How does the operator achieve a situational awareness (SA), i.e. — what do I do next? How do operators maintain their sanity? What makes the machines easy to use?

The trends in gear manufacturing (for making the machine easier to use) are no different than what is happening in computing elsewhere. Computer functionality is becoming more and more accessible to people without an advanced computer education. Our smart phones (that are basically pocket computers with many software features) today are so much more complex and more capable than earlier computers. Yet, thanks to more intuitive and friendlier user interfaces (UIs), billions of people easily navigate smart phones today. In contrast, only a few elite professionals were able to navigate earlier computers that were significantly less capable and less powerful.

HMI or UI are just different names for the same concept, i.e. — means for a human/user to interact and control a machine or a computerized process. HMI bears the prime responsibility for the operator experience and for making the functionality of the machine explicable.

Typical Wheel (Norton)

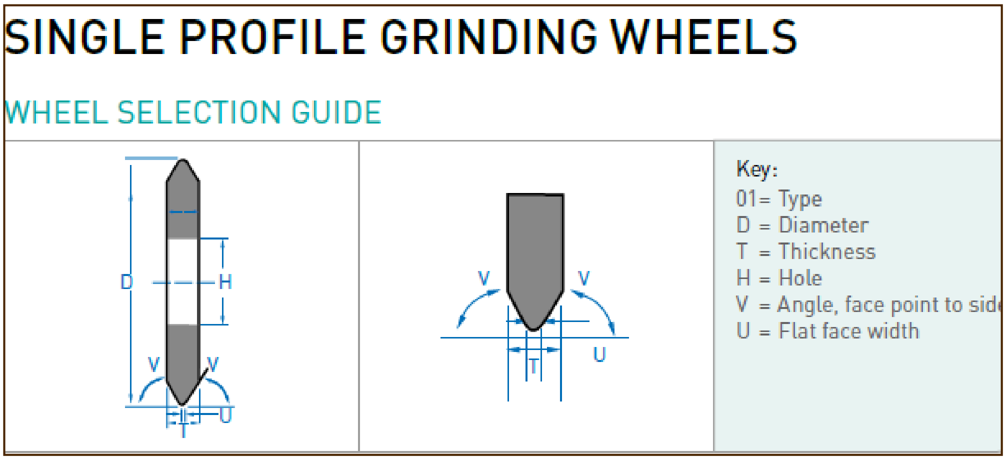

Figure 6 Typical geometry definition of purchased grinding wheel — the third set of information needed for wheel dressing process.

How to Design an Intuitive HMI/UI

Everett McKay, the author of *"UI is Communication: How to Design Intuitive, User-Centered Interfaces by Focusing on Effective Communication,"* says that an intuitive interface should include an appropriate combination of the following:

- ***Affordance.*** The UI provides visual clues that indicate what it is going to do. Users don't have to experiment or deduce the interaction. Affordances are based on real-world experiences or standard UI conventions.
- ***Expectation***. The UI delivers expected and predictable results with no surprises. User expectations are based on labels, real-world experiences, or standard UI conventions.
- ***Efficiency***. The UI enables users to perform actions with minimal effort. If the intention is clear, the UI delivers the expected results the first time so that users don't have to repeat the action (perhaps with variations) to get what they want.
- ***Responsiveness***. The UI gives clear, immediate feedback to indicate an action is taking place, and whether it was either successful or unsuccessful.
- ***Forgiveness.*** If users make a mistake, they need the ability to fix or undo the action with ease.
- ***Explorability***. Users can navigate throughout the UI without fear of penalty or unintended consequences, without getting lost.

Data Entry

Data entry is one of the first things the operator needs to do when starting a new grinding project. A gear grinding machine with on-board dressing, on-board inspection, and built-in intelligence for setup corrections requires a cornucopia of data, e.g. — basic gear data; modification data; dressing data; inspection data; grinding data; and so on. Below are some of the data entry principles that would make it easier and more intuitive for the operator.

- ***Minimum data entry.*** While every grinding project requires

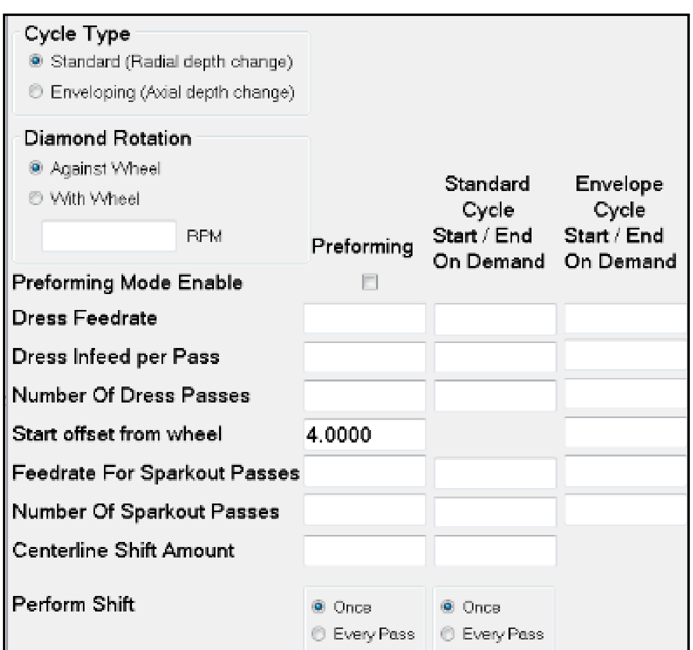

Figure 7 Dressing conditions are the fourth set of information needed for wheel dressing process.

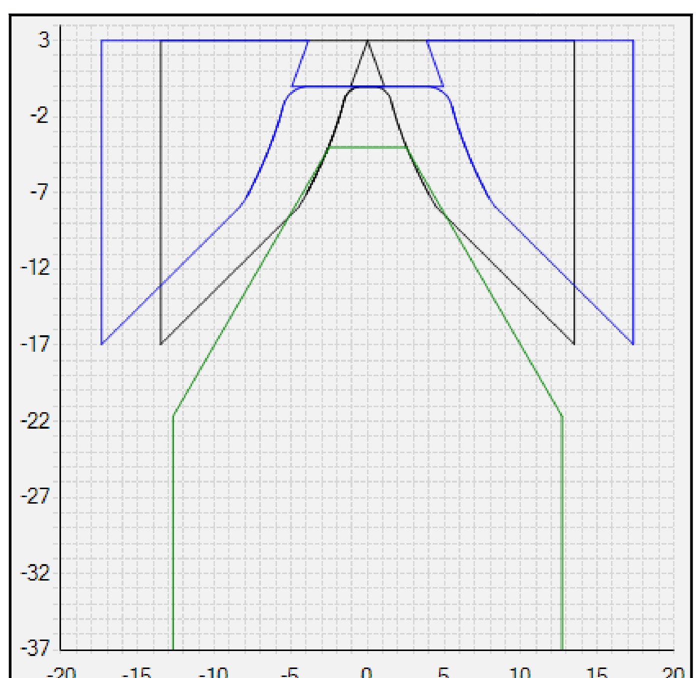

Figure 8 Visual verification of an optimized, initial dressing pass.

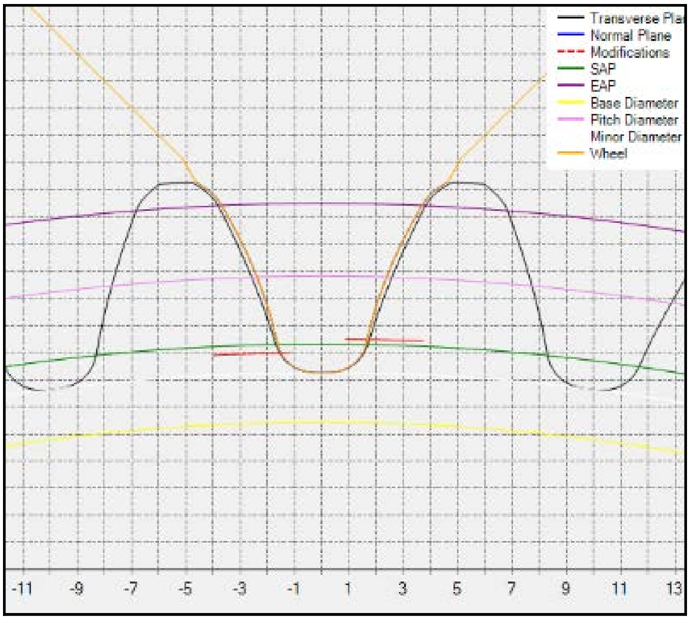

Figure 9 Gear teeth with profile modifications.

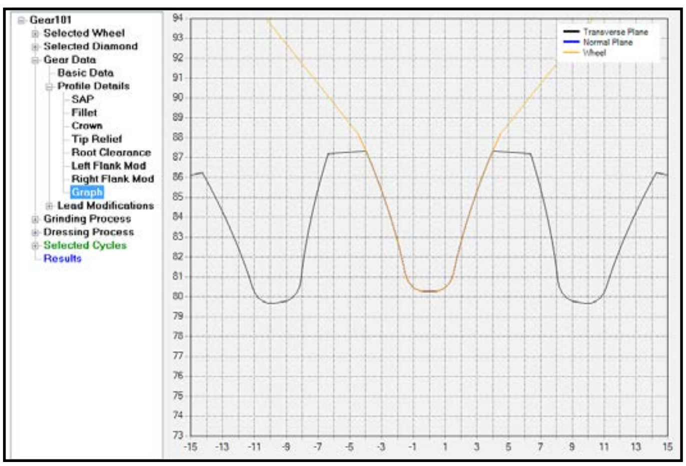

Figure 10 Gear teeth without profile modifications.

hundreds of gear geometry and process data entry fields, there are probably a dozen that "must" be provided by the operator. For example, only the basic gear geometry data is required to be entered in order to start a "plain vanilla" gear tooth grinding.

- ***Defaults***. Availability of friendly defaults for all additional gear geometry fields can dramatically speed up the data entry and the entire setup process. However, the user is always in charge and should be able to update any defaults that are calculated and displayed.
- ***User-centered.*** The data entry interface should satisfy different traditions for the geometry specs, standards, and other company-specific preferences for gear specs; for example, angle vs. length of roll, or diameter, tooth thickness vs. span or DOP, and metric/inch switchable at any time.
- ***Forgiveness.*** Automatic reconciling of any interdependent fields (e.g. decimal degrees vs. min.; and sec., tooth thickness vs. DOP and span; length of roll vs. angle and diameter, etc.) The user should be able to see all calculated references, such as base circle and lead, that were not entered but were critical characteristics for proper functionality.

Figure 3 shows an example of the minimum basic gear data entry; there are only seven data entry fields. All other gear geometry characteristics—with the exception of modifications and root radius—can be derived from the basic gear data. An operator should not have to update additional data entry fields, unless the profile (Fig. 4) or lead modifications (Figs. 11–12) are required.

Visual Gear Data Verification

Visual data verification transforms the numerical data entered into a scaled pictorial gear representation, thus delivering an extra level of confidence and allowing the operator to quickly detect mistakes and typos. Figures 9 and 10 depict examples of gear teeth with and without profile modifications respectively. Normal (and transverse in case of helical gears) representations of the grinding wheel geometry can be superimposed and viewed on both figures.

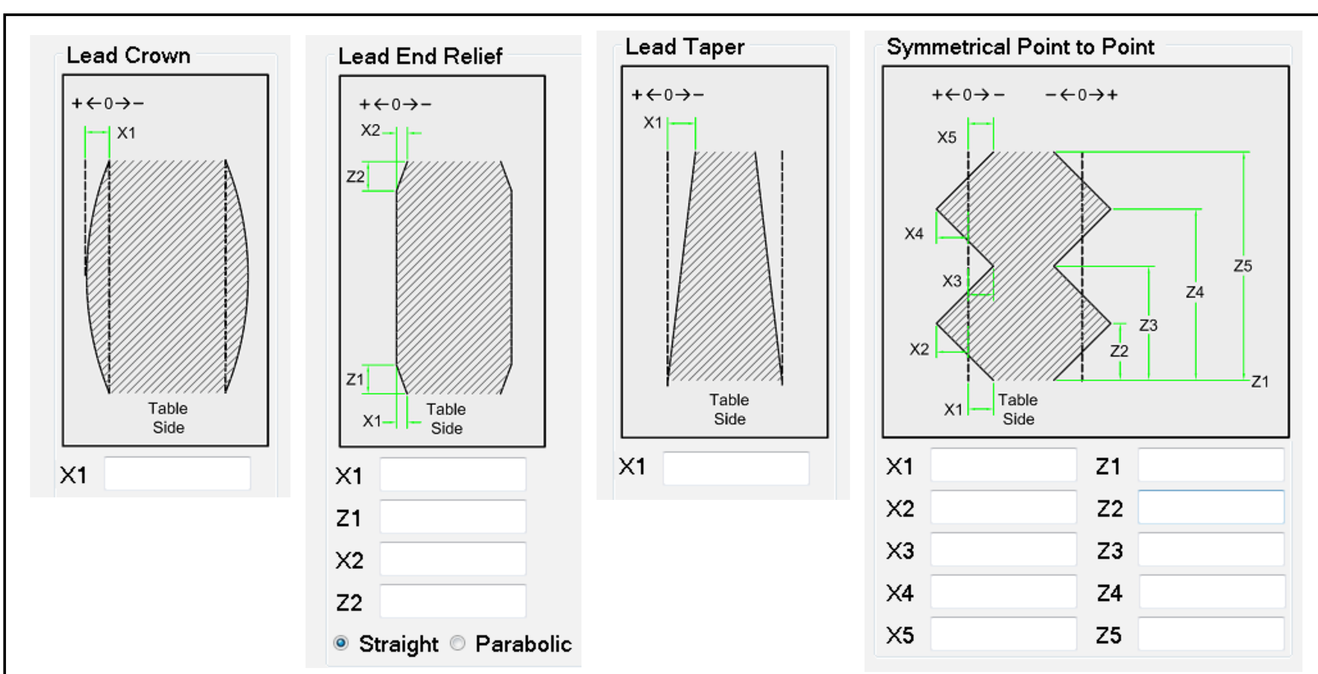

Figure 11 Symmetric lead modification.

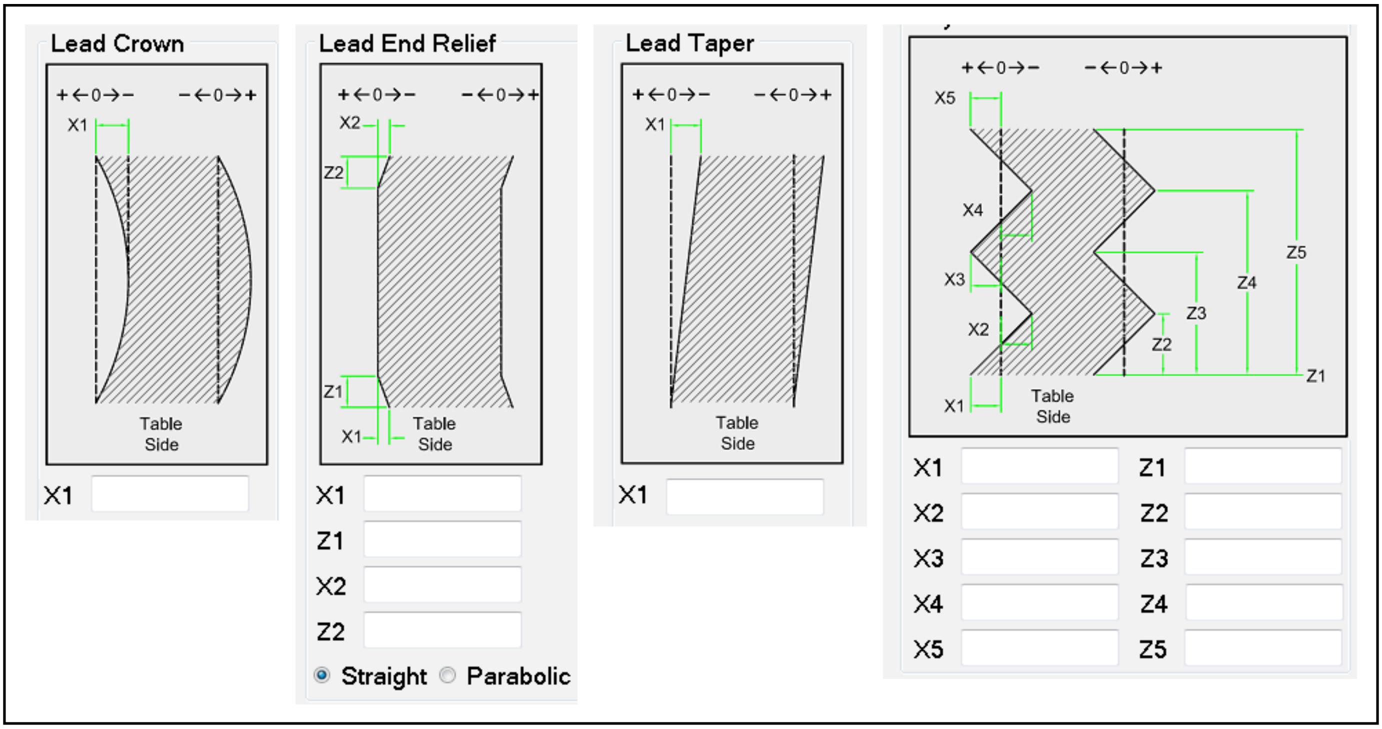

Figure 12 **Asymmetric lead modification.**

Some Principles of a Good Graphic Design

Graphics are very powerful tools for brief and clear communication. It is not uncommon for a gear grinding (or other gear manufacturing) machine to have an HMI that utilizes graphical communication for the data entry fields. Paul Gruhn's *Good Graphic Design Concepts/Visual Clues* lists some principles of a good graphic design.

- Grouping: related items are kept together (e.g., all symmetric lead modifications)
- Contrast: things that are different should look different
- Alignment: every element has some visual connection
- Proximity: things that belong together are placed together
- Repetition: repeat visual elements

Figures 11 and 12 are examples of applications of these principles for designing data entry pages for symmetric and asymmetric lead modifications. Graphics provide visual explanation for achieving symmetric lead modifications by adding delta X-axis (center distance) travel in relation to Z axis (axial travel). Asymmetric lead modifications are achieved by adding delta C-axis travel (table rotation) in relation to Z (axial travel).

On-Board Gear Inspection

A contemporary gear grinding machine can have an on-board inspection with a plethora of inspection and evaluation capabilities. Figure 13 depicts a scanning probe installed on a form gear grinding machine. Every inspected feature requires numerous data entry fields that define the inspection and evaluation parameters. However, a friendly and an intuitive HMI can have the intelligence to default most, if not all, of the data inspection requirements based on the basic gear data. Of course the operator should be able to review all defaults and update them, if desired. Below is an incomplete list of a typical on-board inspection and evaluation capabilities on a gear grinding (or cutting) machine.

Figure 13 **Scanning probe installed on a form gear grinding machine.**

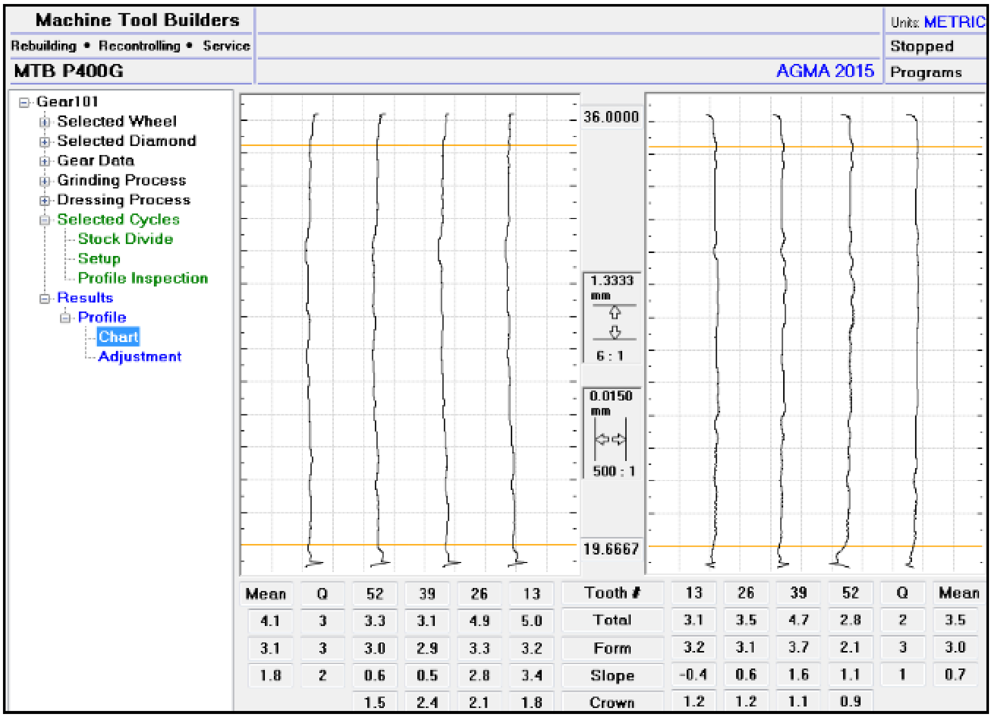

Figure 14 Example of profile inspection and evaluation.

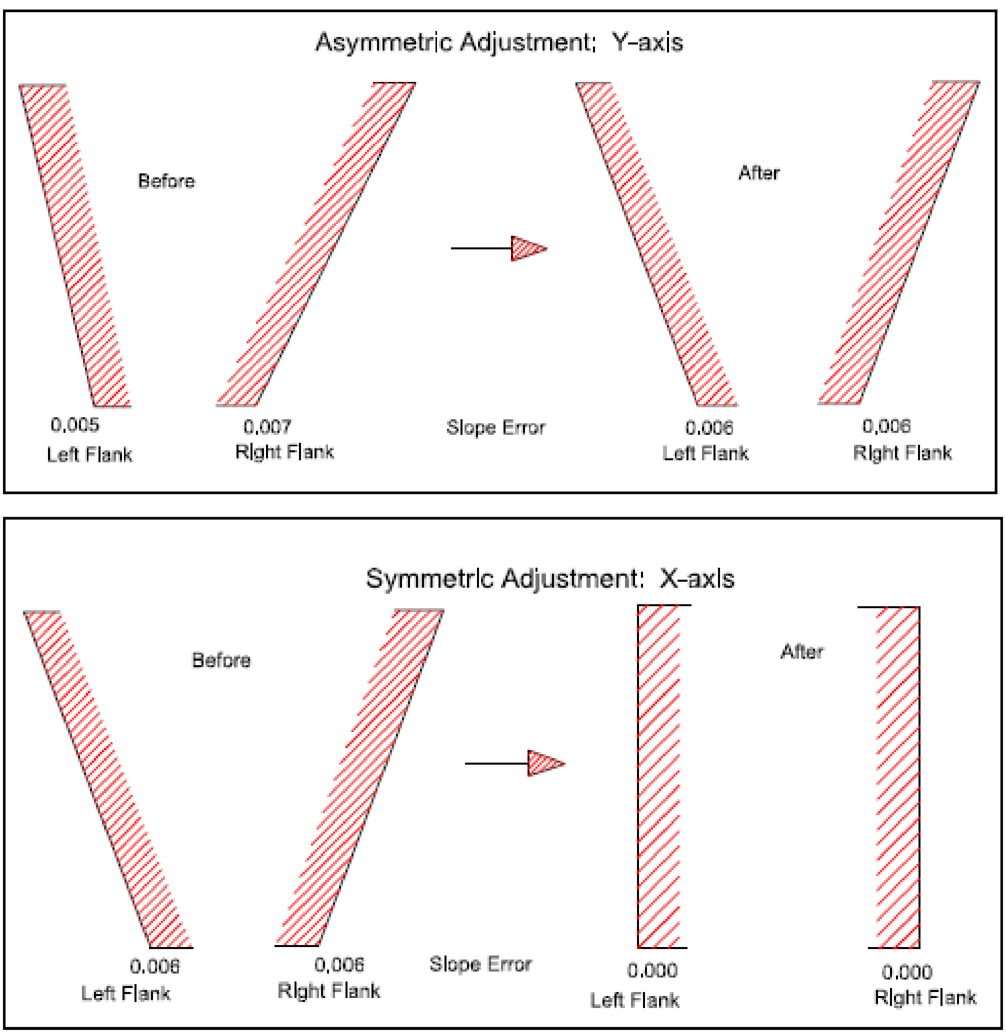

Figure 15 Profile slope setup adjustment in two steps: symmetric and asymmetric.

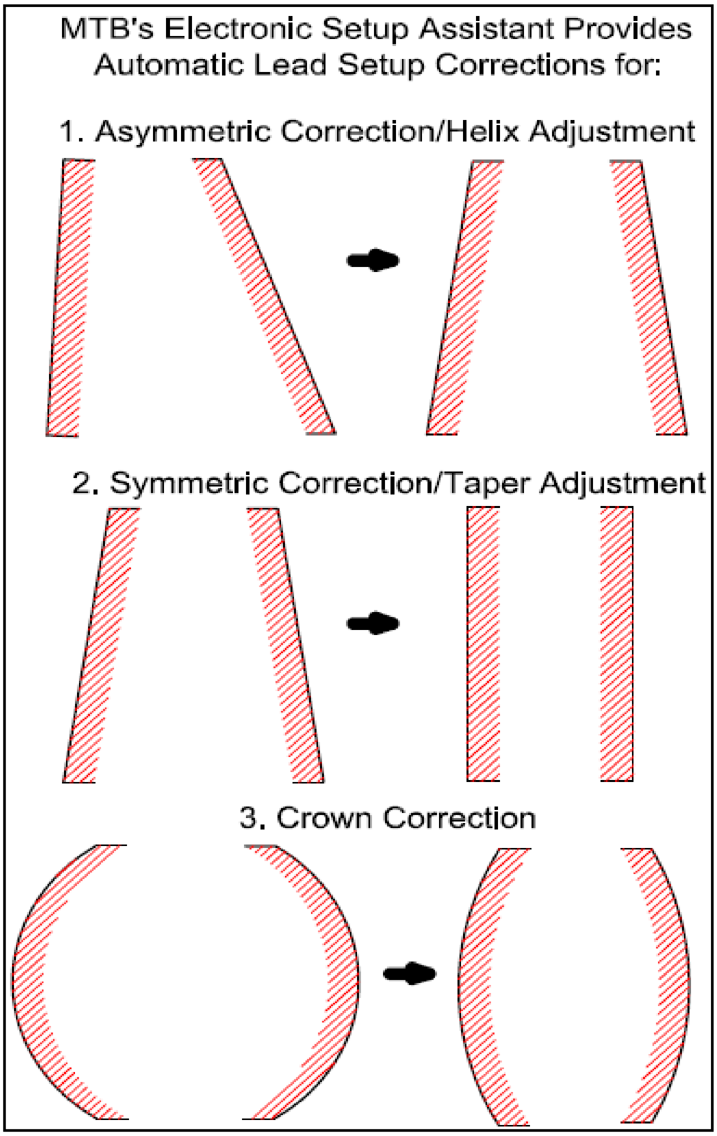

Figure 16 **Lead setup adjustments are conceptually similar to the profile.**

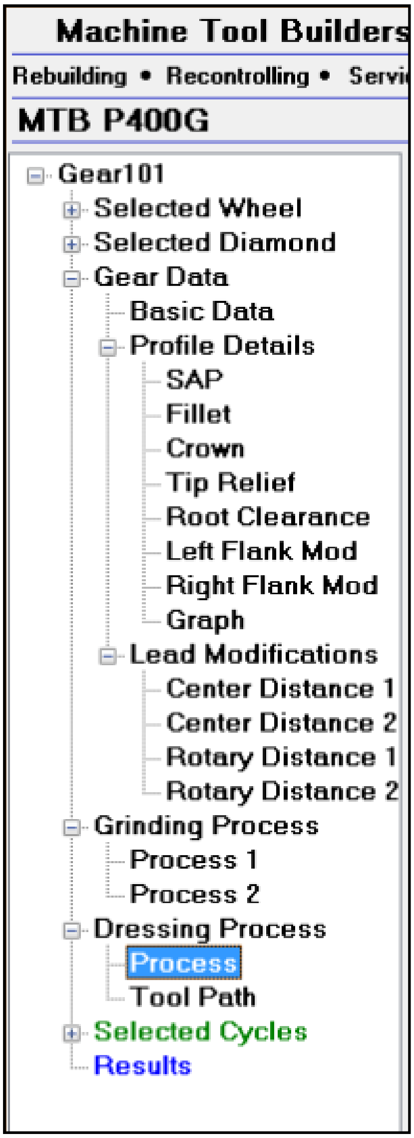

Figure 17 **Tree project structure (without the right pane) with expanded notes.**

On-board gear inspection and evaluation features:

- Profile: total/slope/form/modifications
- Lead: total/slope/form/modifications
- Index: pitch/spacing/runout
- Tooth thickness/DOP/span
- Tip and root diameters
- AGMA/DIN/ISO
- Tolerance band/K-chart

Additional on-board inspection and evaluation features:

- Auto average stock divisions
- Axes alignment mapping
- Automated setup adjustments — MTB setup assistant

A modern on-board inspection feature includes most, if not all, the inspection and evaluation capabilities of a traditional gear measuring center. An example of the profile inspection and evaluation is depicted in Figure 14.

Setup Adjustments

One particularly exciting HMI feature is built-in intelligence for setup corrections.

One of the most helpful outcomes of the on-board gear inspection and evaluation is that the system can use the inspection results to determine all the necessary setup adjustments. This opens up a possibility for either automated or manual setup adjustments of profile, lead, and tooth thickness features.

- One way to make profile slope setup adjustments is to break it down into two steps: symmetric and asymmetric adjustments (Fig. 15). The asymmetric adjustment is achieved by shifting the tangential axis (Y-axis) and the symmetric by adjusting the center distance (X-axis) between the gear and the dressing wheel. This can be accomplished in an automatic mode or semi-automatic mode when the operator would be selecting (Yes/No) for including the adjustments.
- Lead setup adjustments are conceptually similar to the profile (Fig. 16); it is typically broken down into two steps: symmetric and asymmetric. The asymmetric adjustment (helix) is achieved by refining the synchronization of table rotation (C-axis) and axial travel (Z-axis). The symmetric adjustment (taper) is achieved by refining the synchronization of X and Z axes. The lead crown correction can be combined with symmetric and asymmetric corrections. Based on the crown

inspection results, the X-axis and Z-axis synchronization can be further refined.

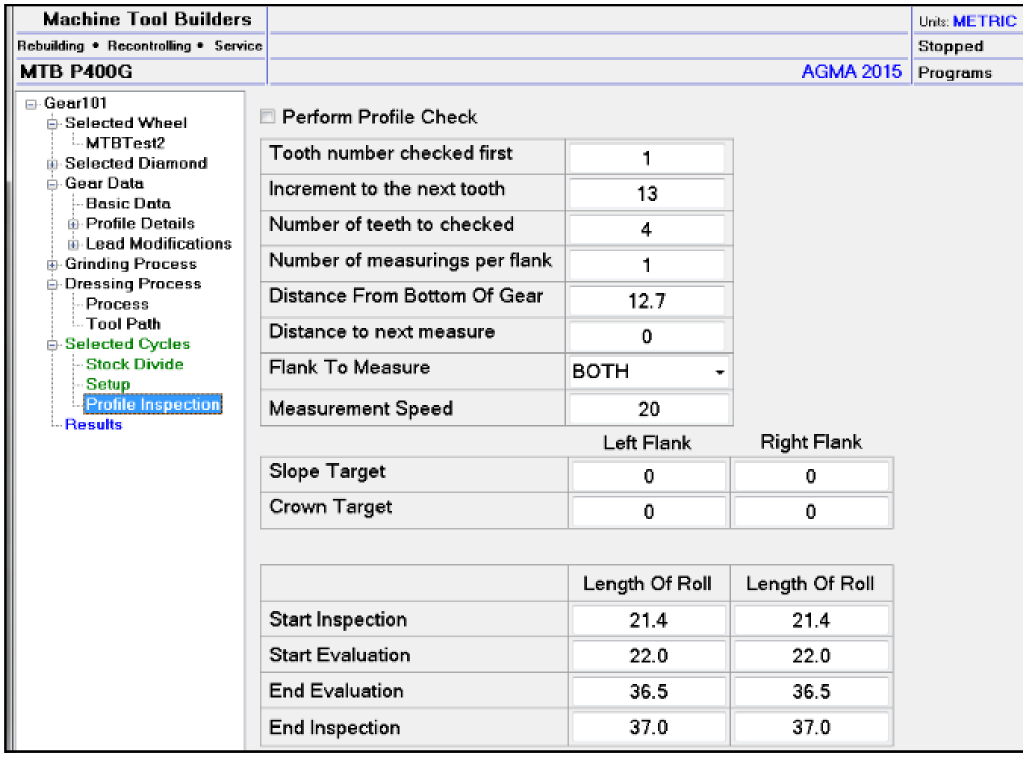

Figure 18 Example of profile inspection details via project tree profile inspection node.

Situational Awareness or Navigating the Gear Grinding Project

An intuitive navigation through the gear grinding project is a very important facet of the HMI. A familiar project tree structure (used in a wide variety of computer applications) enables the user to easily move through many data screens. A project tree structure also provides consistent means for viewing and editing every single detail on the right pane of the project while seeing the "big picture" of the entire project on the left pane. Grinding project comprises:

- Grinding wheel
- Diamond/dressing wheel
- Gear
- Grinding process
- Dressing process
- Selected cycles (orientation — aligning of the grinding wheel with gear tooth, grinding, inspection, adjustments)
- Results of inspection
- Setup adjustments recommendations

Grinding project tree can include familiar navigational features such as:

- Collapsing/expanding nodes in the project tree
- Adding/removing/sequencing grinding process items (orientation, dressing, grinding, inspection)

A tree project structure (without the right pane) with some expanded notes is shown (Fig. 17). The operator may collapse or expand each node at will. Figure 18 depicts an example of the profile inspection details as viewed by clicking on the project tree "profile inspection" node.

Conclusion

Once again, HMI bears the prime responsibility for the operator experience and for making the functionality of the machine explicable and intuitive. With friendlier and more intuitive HMIs that have default features, minimum data entry requirement, visual verification, and easier navigation, users are now empowered with both a more pleasant experience and a setup time reduction.

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Yefim Kotlyar is the application engineering manager at Machine Tool Builders (MTB), responsible for the development of new gear manufacturing and gear metrology technologies. His broad experience in the art of gearing includes the development of various gear cutting technologies, analytical inspection and evaluation technologies for gears and hobs, as well as gear system design and validation. Kotlyar has served on a number of AGMA technical committees, and he has authored numerous articles on gearing.