Method for High Accuracy Cutting Blade Inspection

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Introduction

Inspection of the cutting blades is an important step in the bevel gear manufacture. The proper blade geometry ensures that the desired gear tooth form can be achieved. The accuracy of the process can be compromised when the blade profile consists of several small sections such as protuberance, main profile, top relief and edge radius. Another common obstacle — are outliers which can be caused by dust particles, surface roughness and also floor vibrations during the data acquisition. This paper proposes the methods to improve the robustness of the inspection process in such cases.

The authors propose a procedure for using larger (combined) portions of the blades to evaluate the properties of the small features. This method was inspired by the standard AGMA/ANSI ISO 1328-1-B14 for the evaluation of tooth profiles on cylindrical gears. An example of the application could be the assessment of the pressure angle and blade distance in case when the blades have large toprem and flankrem sections (short cutting/ clearance edge portion).

In cases where the measured data contains outliers, the filtering is proposed using the random sample consensus (RANSAC) procedure. The authors show the effectiveness of the procedure using the actual measurement data.

Finally, the proposed methods were

Figure 1 Face cutter head (Face Milling) with stick blades (Ref. 2).

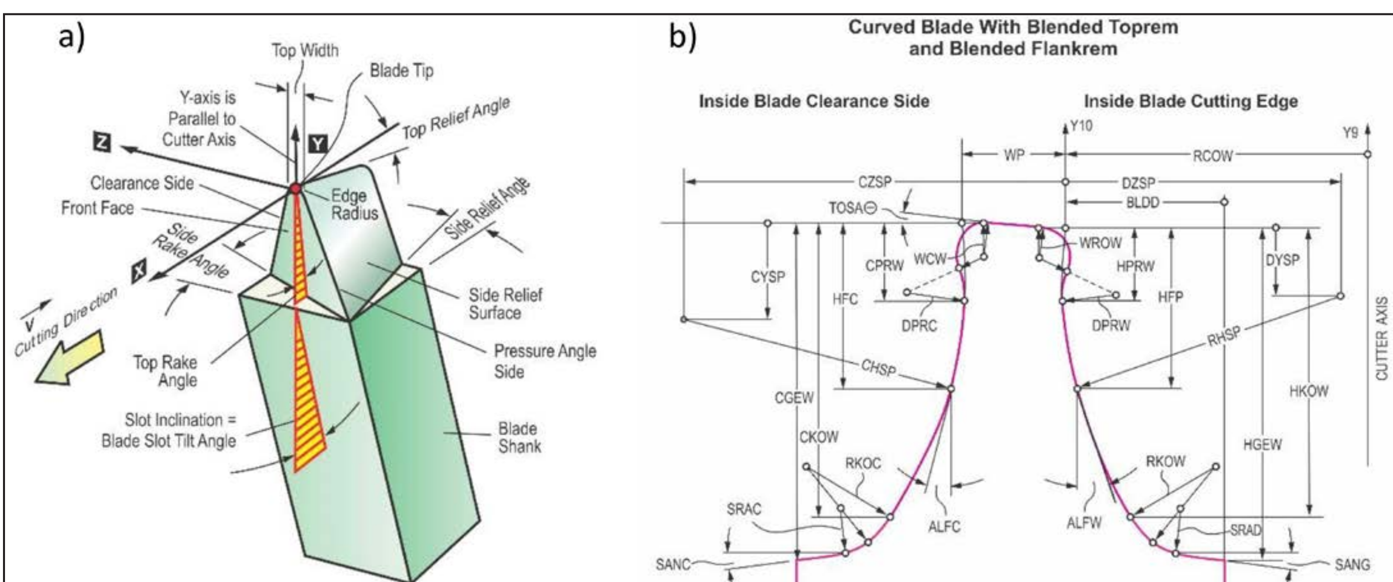

Figure 2 Stick blade geometry (Ref. 3); (a) three-face stick blade, (b) blade geometry definition.

implemented on a blade inspection machine, and the improved accuracy and robustness demonstrated using several examples.

Accuracy of the bevel gear tooth form depends on the accuracy of the cutting blades. The cutting blades are sticks which are positioned in a face cutter head as shown (Fig. 1) (Ref. 2). The accuracy of the blades is usually verified by analyzing and comparing the measurements from the specialized coordinate measurement machines to the nominal (theoretical) coordinates created by the blade definition program. Detailed inspection of a typical stick blade is a demanding task due to the rather complex geometry shown (Fig. 2) (Ref. 3). Accurate analysis of the measured (actual) data can be a challenging task when the data contains short sections, or when it is compromised by the conditions in the inspection environment.

The authors in this work propose the procedure which can be helpful in evaluation of the measurements containing outliers and for the treatment of the short blades with the small number of measured points.

Overview of the Stick Blade Measurement Procedure and Its Challenges

A bevel gear geometry is defined through the basic settings and the "tooth forming contour" (Refs. 4–5) of the stick blade. The contour is defined by projection of the actual blade, placed in its cutting position, onto the cutting plane, as shown (Fig. 3) (Ref. 6). The same figure also shows the minimum number of points (five) needed for the blade evaluation. The blade consists of three major parts (as shown Fig. 2a): pressure angle side, clearance side and blade tip. The pressure angle side consists of (Fig. 2b):

a) ***edge radius***: portion of the blade which together with the blade tip, cuts the root and fillet portions of the gear (part of circle with WROW radius)
b) ***toprem***: part which creates the relief (transition) between the fillet and flank (part from edge radius to HPRW)
c) ***main cutting edge***: the largest part of the blade which creates the main portion of the gear flank (from HPRW to HKOW)
d) ***flankrem:*** part which creates relief between flank and the gear tip (from HKOW to shoulder radius start)
e) ***shoulder radius:*** transition portion between main cutting edge/flankrem and shoulder (part of circle with SRAD radius)
f) ***shoulder:*** transition from the stick geometry to the ground blade portion (part from shoulder radius to HGEW)

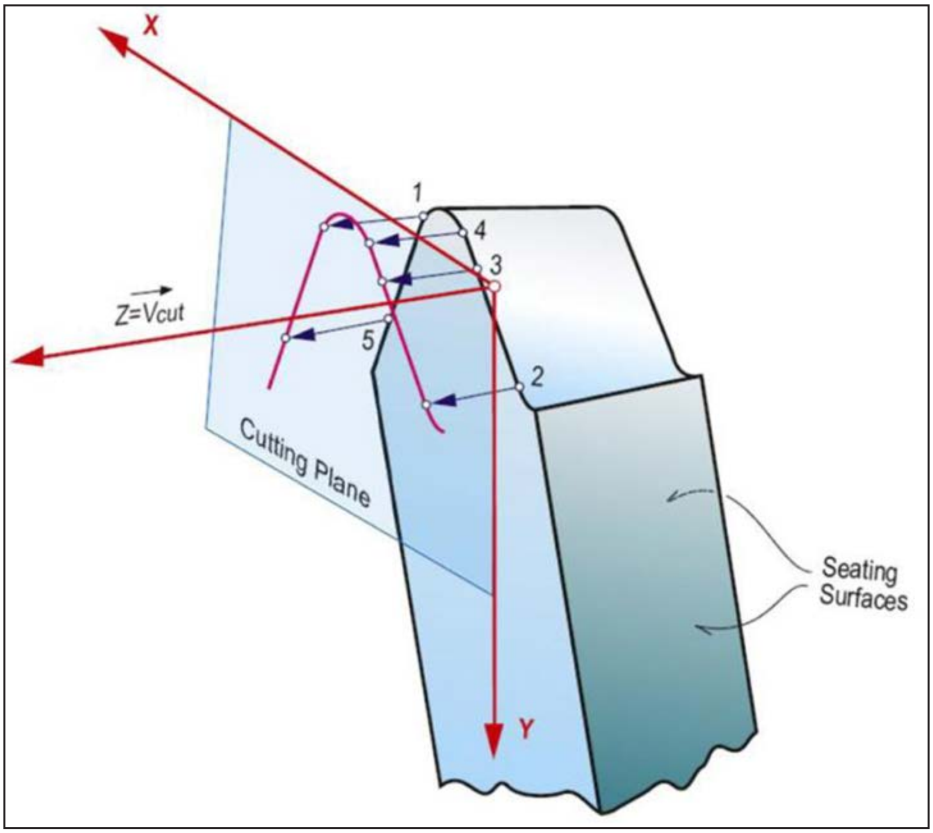

Figure 3 Projection of blade profile onto the cutting plane (Ref. 6).

The sections, as defined in the cutting plane, can have either circular or straight line geometry. Exceptions are the edge radius and the shoulder radius, which are always circular.

Traditionally, blade inspection was performed using manually operated machines and comparison checkers. Today, it is usually performed using a three-dimensional coordinate measurement machine. Lately, the laser curtain principle (Ref. 6) was utilized, together with the automatic clamping and loading to minimize the effects of the probe size and reduce the influence of the operator on the measurement results.

Blade inspection process can be summarized in several steps:

1. Nominal (theoretical) coordinates and normals of the blade profile points are created and provided to the machine prior to the inspection.
2. Cutting blade is positioned in the machine which performs measurement and returns the actual coordinates.
3. The results (actual coordinates) are compared to the nominal coordinates and the necessary corrections are reported to the user.

The corrections include necessary adjustments to the form (radii of curvature and inclination angles) and position (blade distance and the starting positions of the features). Recently, a closed loop system was developed where the corrections are shared automatically with the specialized blade grinding machine and implemented in the regrinding of the blades to their proper geometry.

The described inspection procedure seems to be straightforward. However, there are several sources of the errors embedded in the procedure itself. They need to be addressed in order to ensure that the inspection results accurately represent the geometry of the inspected blade. The inspection errors can be divided in three main groups, based on the source:

– ***errors due to the operator***, which mainly include the variation in the blade handling (placement);
– ***errors due to the environment***, caused by the placement of the machine in the production environment where the

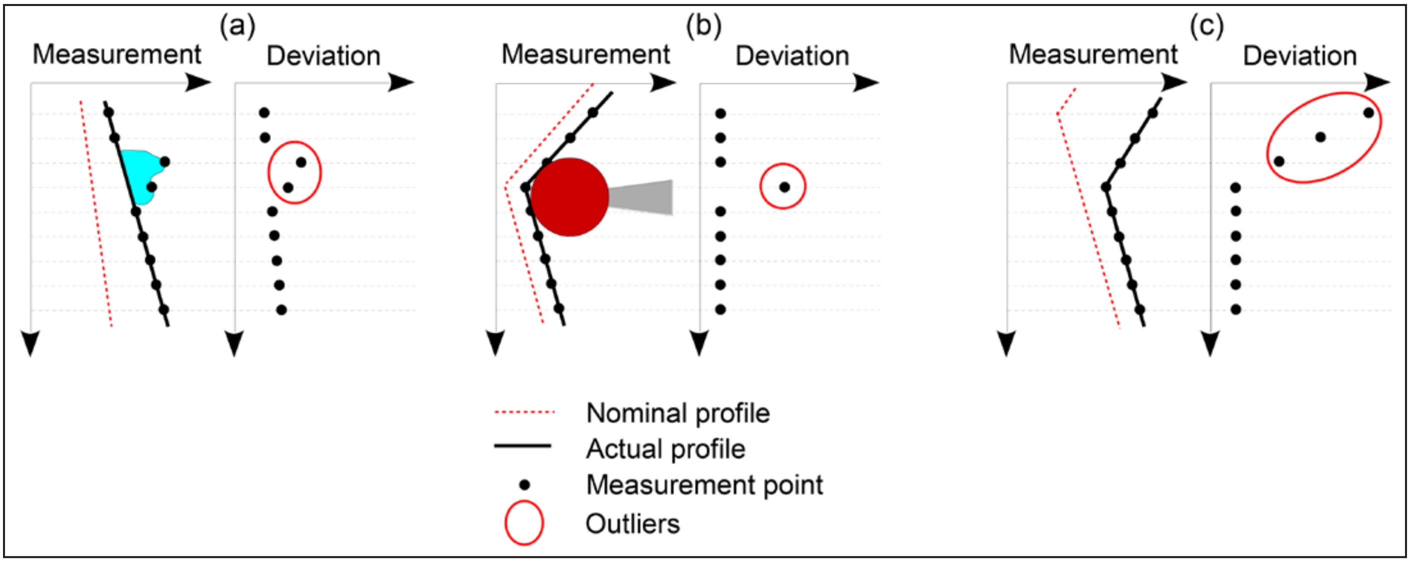

Figure 4 **Common sources of the large date deviation (outliers); (a) dust particles, (b) inadequate probe size and (c) position error of neighboring sections.**

machine vibration can distort the measurements, or where dust and oil can contaminate the blade surfaces;
- ***errors due to the inspection machine capability***, caused by the probe size and resolution limits of the inspection equipment.

The first source of the errors can easily be detected and rectified as it leads to the obvious deviation from the blade geometry. The latter two errors lead to the erroneous data (outliers) which can usually be detected only by carefully reviewing the measurement results. They often lead to the misinterpretation of the blade geometry and faulty geometry corrections, at the end resulting in the wrong blade geometry which will have to be reground. The detection and removal of the outliers is one of the main tasks of this work.

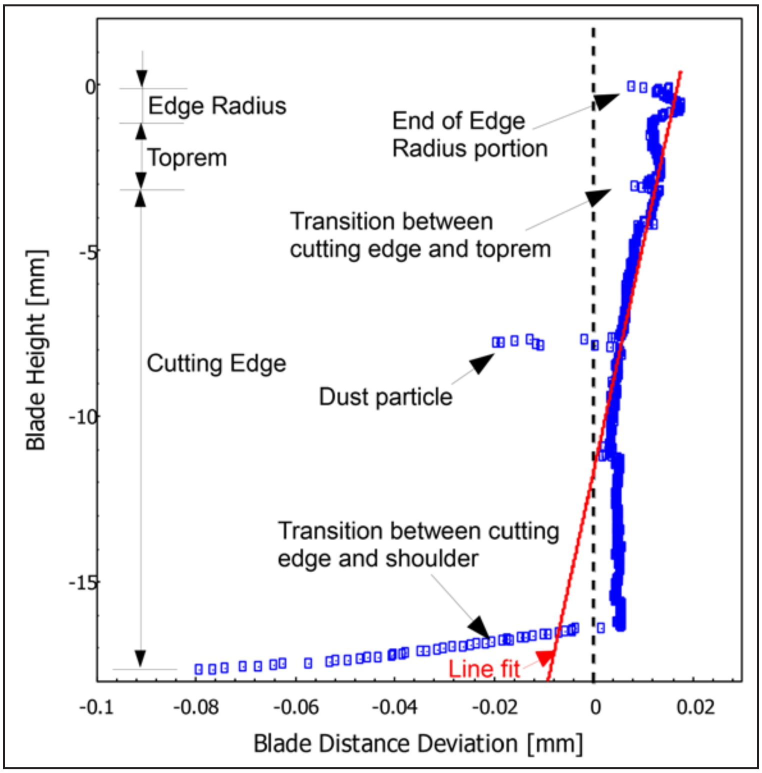

Figure 5 **Example of the deviation of the actual from the nominal data for the blade the common outliers.**

Treatment of the Outliers

Inconsistent data can be detected as the deviation from the expected (nominal) form. Unlike the actual blade geometry error which varies gradually, the outlier deviation tends to vary rapidly and be localized. Figure 4 illustrates some common sources of the outliers. The difference between nominal and actual (measured) profile is usually not larger than 10–20 micrometers and small dust particles, chips left after cutting, or lint from the cloth used for blade cleaning can create large discrepancy in the measurement data, Figure 4a. Another common example would be the inability of the probe to access the actual points due to its size, providing the erroneous measurements, as shown (Fig. 4b.) Such a problem is often encountered between two adjacent sections of a blade. Finally, neighboring sections could have position error in the vertical (axial) direction which can be recorded as a large deviation (Fig. 4c). While this measurement accurately captures the blade geometry, it can still lead to the inaccurate interpretation of the evaluated blade portion geometry. Namely, the inclination angle and the horizontal position of a section are usually calculated using regression analysis, which considers all points measured over the nominal range for that particular section. Using the results from Figure 4c could lead to the conclusion that the sections have inclination and position error — which is *not* correct. Common practice in the past was to reject certain portions of the end points to avoid the situations described in Figures 4b and 4c.

A typical blade used in the automotive industry is considered as the first example (Example #1). The blade has axial (total) grind depth of 19 mm and its tooth forming contour consists of edge radius, toprem and cutting edge. Figure 5 shows the deviation of the measurement from the nominal data. The expected deviation would be a smooth line (either straight line or a curve). The position of the outliers can be clearly seen, particularly at the transition between the cutting edge and the shoulder section. The figure also shows the line fit (red line) to the deviation data, when all points (including outliers) are used in the fitting procedure. It should be apparent that the line fit does not accurately describe the inclination of the actual sections. In this particular case, using all data in the calculation of the necessary corrections would lead to the incorrect results. The outliers need to be removed in order to obtain more accurate results.

A simplified application of the Random Sample Consensus (RANSAC) (Ref. 7) algorithm is used by the authors to detect and remove the outliers from the measurement data. It is an iterative algorithm which finds and removes the outliers based on their departure from the behavior of the majority of the points. The expected behavior, or shape (e.g. straight line or circle) must be known in advance, and it would be represented by a parametric model. In the case of the blade geometry, the models are the (parametrized) equations of line, or circle, depending on the shape of the blade section. The algorithm starts by creating random set of two (for line) or three (for circle) inspection points and finding the parameters for the equation. It calculates the distance of all other inspection points to the line or circle and compares it to the predefined allowed margin. The points which are outside the given margin from such a line or circle are designated as potential outliers, i.e. — the outliers for that particular case. The procedure is repeated for a number of iterations (point sets), with the aim of finding the equation of the line, or circle which describes the behavior of the largest number of inspection points (the smallest number of outliers). Once the equation is determined, the outliers from such a case are removed from the data set. While the total number of the possible inspection point combinations can be prohibitively large, good results can be obtained using a relatively small number of non-repeating combinations (e.g. up to the total number of points).

RANSAC analysis is applied separately to each section of the blade profile, using the shape (line or circle) of the section and the margin (distance) of the allowed deviation from the fit. In the particular example shown in Figure 5, three sections were analyzed:

- cutting edge, with the circular profile
- toprem, with the straight profile
- edge radius, with the circular profile

The allowed margin of deviation from the fit was set to 0.001 mm for all sections. The result of the analysis is shown in Figure 6. Comparison to the original deviations (Figure 5) clearly shows that the outliers were removed. The numbers of the removed outliers for each section are:

- cutting edge: 99 outliers removed from 488 starting points
- toprem: 6 outliers removed from 67 starting points
- edge radius: 8 outliers removed from 33 starting points

As mentioned above, the analysis also provides parameters of the fitted model (equation of line or circle), which describe the position and shape of the measured sections. It should be noted that the RANSAC algorithm uses sets of the data points, forcing the fitted equation to pass through these chosen sets of points. Because of that constraint, the RANSAC analysis does not provide the best-fit line which generally does not have to pass through any of the points. Accurate fit, appropriate for the calculation of the corrections, can be obtained by using the filtered (outlier free) data in a specialized procedures. In case of the example shown in Figures 5 and 6, the radius of curvature of the cutting edge was determined by RANSAC and Taubin fit (Ref. 8) as 869.554 mm and 870.113 mm, respectively. The radius of curvature of the Edge Radius was calculated as 1.824 mm (RANSAC) and 1.838 mm (Taubin fit).

Usual spacing of the blade inspection points varies between 30 and 100 μm in a typical automotive application. However, the spacing step can be increased for the large blades. The number of outliers under normal circumstances should not exceed 25% of the total number of

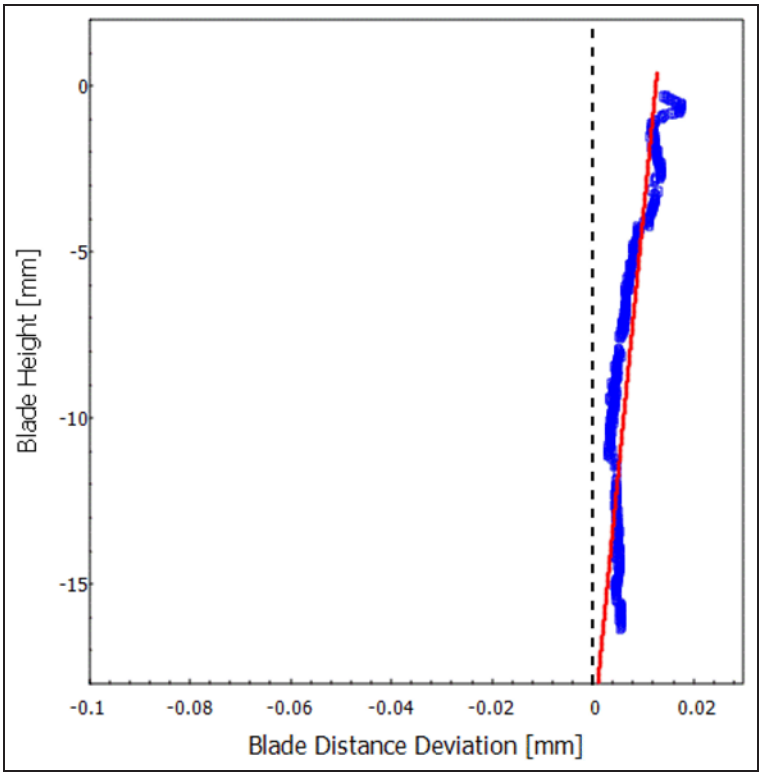

Figure 6 Data deviation after removal of the outliers.

points in each section. Large number of outliers could also point to the problems with the blade definition. As an example, the inspection of a blade with the curved main cutting edge, with the inspection settings for the straight cutting edge would result in a large number of outliers. The value for the filtering margin used in the analyses could be determined from the angular tolerance and the length of the analyzed section. In the above example, shown in Figure 5, the length of the cutting edge section is equal to approximately 15 mm. The pressure angle tolerance for the application (typical automotive industry blade) is equal to ±2 minutes—yielding the appropriate filtering margin of 0.009 mm. A considerably smaller margin (0.001 mm) was used in the example to show the effectiveness of the method in removing the outliers.

Measurement of the Blade Parameters

Figure 2b shows the parameters used in definition of a blade geometry in the cutting plane. Number of the variables in the complex cases can as high as thirty. This work concentrates on two main parameters—Pressure Angle and Blade Distance—designated as ALFW and BLDD, respectively, in Figure 2b. Pressure angle is defined as the angle between the tangent to the cutting edge and vertical line. Blade distance is the distance between the side of the blade and the point where the tangent to the cutting edge intersects y=0 line (Fig. 2b).

It is more convenient to determine the deviation of the parameters from their nominal values, instead of determining their absolute value. These deviations are called Blade Distance Error and Pressure Angle Error. The values are the corrections which are applied in regrinding of the blades to their satisfactory geometry.

Measured points generally have both, x and y coordinates different from their nominal values. The process of calculating the deviations starts with recalculating the nominal coordinates at the y coordinates of the actual points. Then, the deviations of the actual from the nominal points in x (horizontal) direction are calculated for each I=1…N points, where N is the total number of points.

$$E_i = x_{a,i} - x_{n,i} \quad i = 1 \ldots N \qquad (1)$$
$$y_{a,i} = y_{n,i} = y_i$$

Pressure Angle Error, E_{ALFW}, can be calculated as the average angle between the neighboring points, Figure 7a:

$$E_{ALFW} = \tan^{-1}\left(\sum_{i=1}^{N-1} \frac{E_i - E_{i+1}}{y_{i+1} - y_i}\right) \qquad (2)$$

Alternatively, the value for EALFW can be calculated by using regression analysis.

Blade Distance Error, E_{BLDD}, can be determined by first calculating the centroid of the data points, $C\ (x_C, y_C)$, Equation 3. Then, the intercept with the y=0 axis can be easily found by using Equation 4. Alternatively, Blade Distance Error can be found as the intercept of y=0 line and of the line obtained from the linear regression analysis of the deviation points.

$$x_c = \frac{1}{N}\sum_{i=1}^{N} x_i \ , \qquad (3)$$
$$y_c = \frac{1}{N}\sum_{i=1}^{N} y_i$$

$$E_{BLDD} = x_c - y_c \cdot \tan(E_{ALFW}) \qquad (4)$$

Using Multiple Sections for Pressure Angle and Blade Distance Measurement

The parameters determined in the previous section rely on the data points collected in cutting edge section (Fig. 3). A particular problem is encountered when the short blades are inspected, or when toprem and flankrem sections occupy sizable portion of the total blade height, making the cutting edge portion very short. Determination of the blade distance and pressure angle can be a challenging task in such cases, due to:

a) reduced number of the inspection points
b) sensitivity of the short sections to the small measurement variations

An effective approach in such cases could be to combine the neighboring parts of the blades into the larger sections. The approach is inspired by the inspection of parallel axes gear flanks in the standard AGMA/ANSI ISO 1328-1-B14 (Ref. 1).

The procedure used up to this point will need to be modified in order to be able to use the complete tooth forming portion of the blade in the evaluation of the Blade Distance and Pressure Angle. In certain cases the toprem, flankrem and edge radius sections have rather high deviations, not caused by the outliers. Blade Distance and Pressure Angle Errors would not be determined correctly in such cases, if the data for these sections was used in the calculations. Instead, the authors propose using the second filtering to automatically remove potential large deviations from the linear regression line fitted to combined sections. The tolerance on the pressure angle could be used as the margin of allowed deviation for the second filtering.

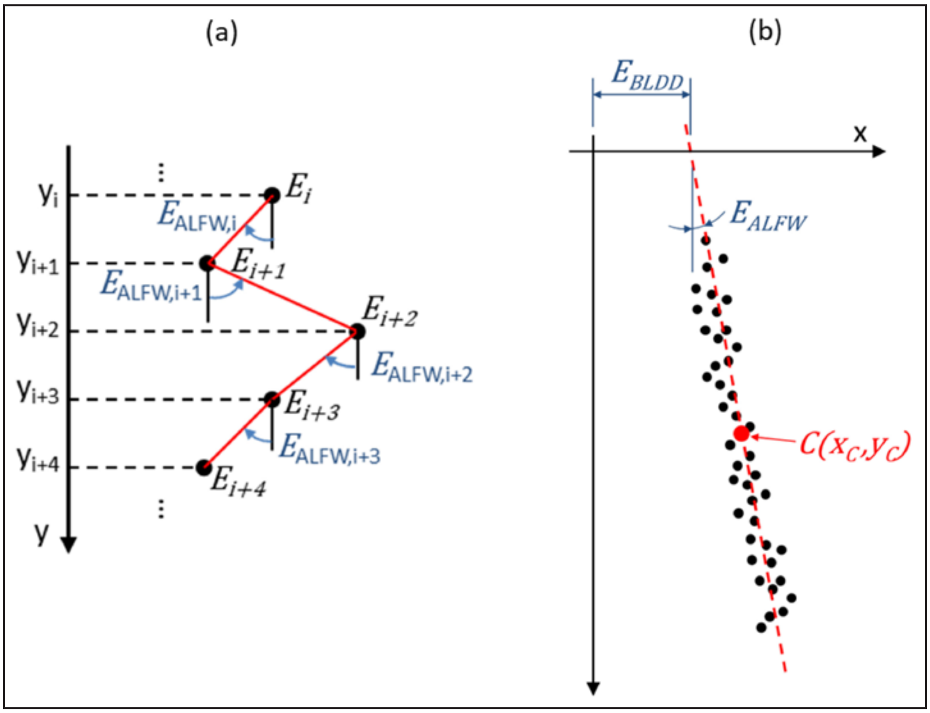

Figure 7 Calculation of (a) Pressure Angle Error, and (b) Blade Distance Error.

The examples shown (Figs. 5–6) will be used again to demonstrate the method. Unlike the first time when it was used on each section separately, RANSAC analysis is now used on all points remaining after removing outliers. With the axial grind depth of 19 mm, and the pressure angle tolerance of ± 2 minutes, the second filtering margin is set to M2 = 0.01 mm. The result of the second filtering is shown in Figure 8. The variation, mostly in the toprem and edge radius sections, was removed. Linear regression line, shown in red, describes the behavior of the large portion of the cutting edge rather well.

The described method could be particularly useful in the inspection of short blades. As the second example (Example #2), Figure 9a shows the deviation of the actual from the nominal points for the blade with the axial grind depth of less than 4 mm, and the inspected portion of the blade equal to 1.2 mm. The blade has three inspected sections — cutting edge, toprem and edge radius — all with the circular profile. The deviation data for all sections overall seems not to have a large scatter, but the number of the inspection points is relatively small (40 starting points for complete blade), Figure 9a. Using the first filtering of outliers with 0.0005 mm allowed margin, only three outlier points were removed, Figure 9b. The second (overall) filtering with the margin of 0.002 mm (2 minute deviation over 4 mm length), removed an additional seven points, as seen in Figure 9c. As expected, the scatter of the points was further reduced. It should be noted that more than 40% of the remaining points come from outside the cutting

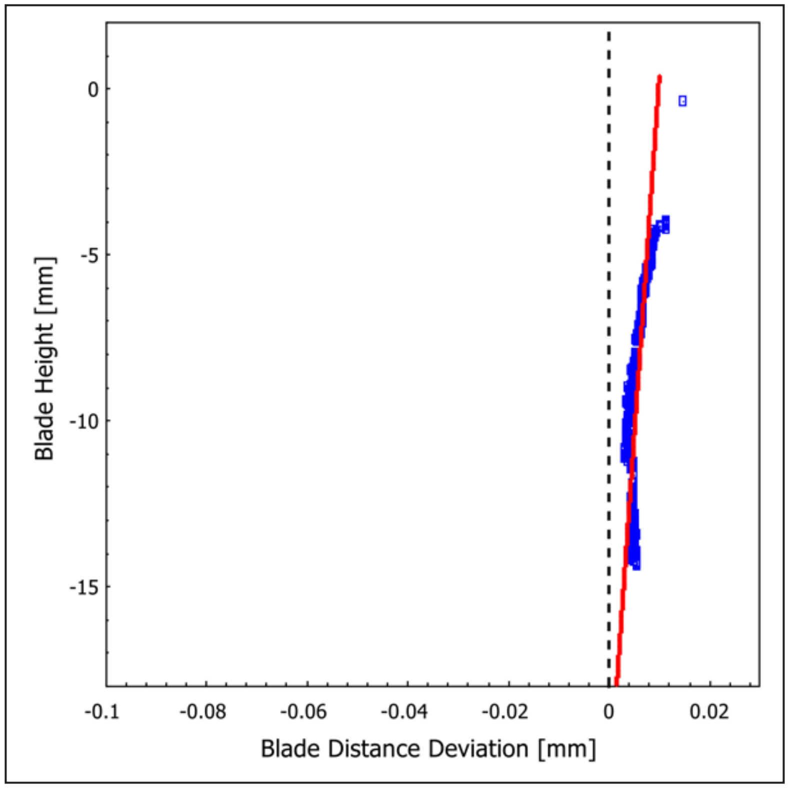

Figure 8 Data deviation (Example #1) and linear regression fit after the second filtering.

Table 1 Pressure and Blade Distance Error for the provided examples

	Blade Distance Error (E_{BLDD}) [mm]	Pressure Angle Error (E_{ALFW}) [°]
Example #1	–0.0098	0.026
Example #2	–0.0014	–0.512

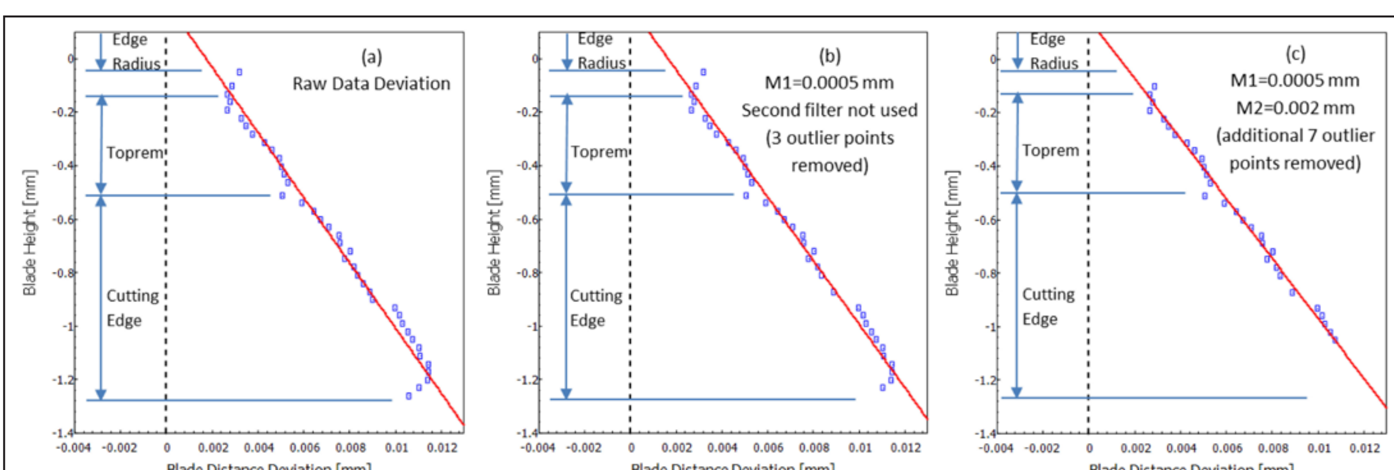

Figure 9 Treatment of the short blade; (a) raw data deviation, (b) deviation after the first filtering (outlier removal) and (c) deviation after the second filtering.

edge section, showing that using multiple of the sections can be useful method when inspecting short blades.

As the final step, the filtered data was used for the Blade Distance Error and Pressure Angle Error calculation by using Equations 2–4. The values are summarized in Table 1, and the deviation of the data before and after correction is shown (Fig. 10).

Summary of the complete process is provided (Fig. 11). In the current form the process is suited for the linear nature of the corrections. However, the process could be modified in the future to handle the non-linear response of the system to the intended corrections.

Conclusion

The authors of this work present a novel method of evaluating blade geometry deviations. The method would be particularly useful in cases with large number of outliers and when the small number of data is created during inspection (typical for short blades). Two major deviation parameters were considered, Pressure Angle and Blade Distance.

The method relies on the RANSAC algorithm to remove the outliers from each section separately, based on the allowed deviation from the predetermined mathematical model. Actual example was used to demonstrate the effectiveness of the proposed procedure.

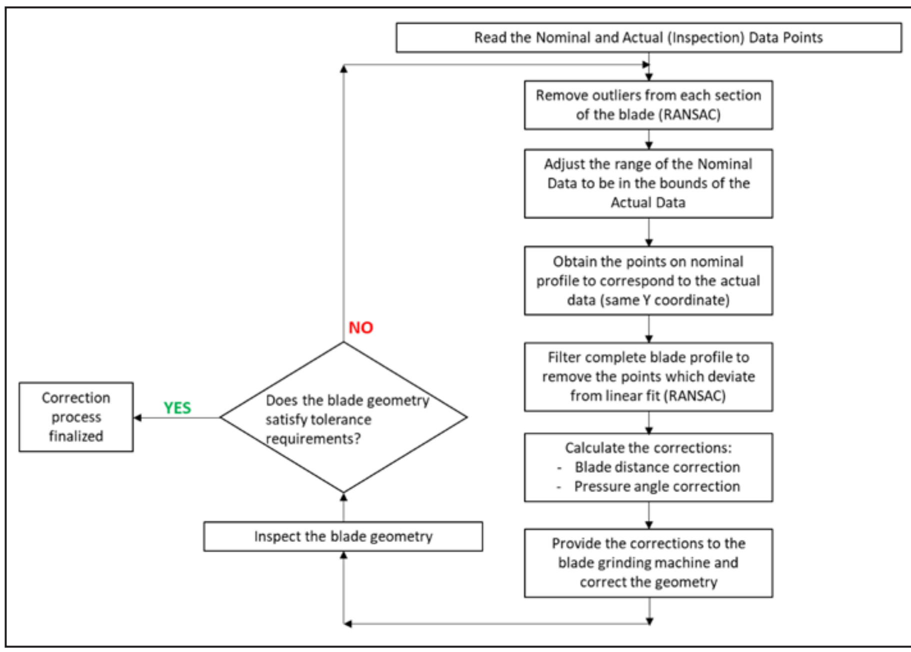

Figure 11 Summary of the proposed procedure for blade correction.

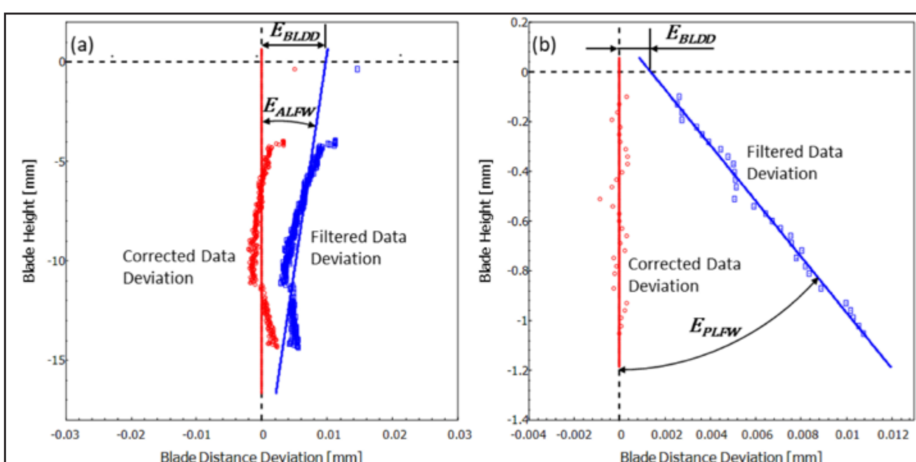

Figure 10 Final data correction; (a) Example #1 (blade with the large number of outliers), and (b) Example #2 (short blade).

The RANSAC algorithm was applied again to the complete blade profile in order to automatically remove the large portion of data, or complete sections, deviating from the linear behavior. Such approach makes it possible to utilize the data from several sections in calculation of the Blade Distance and Pressure Angle. The effectiveness of this method was demonstrated through a short blade example where the starting number of points is relatively low.

As a future task, the authors will apply the proposed methods in the actual blade inspection process, followed up by the geometry correction (grinding) and verification of the corrections (re-inspection). While the proposed method looks simple, the complete process might not be linear, and several iterations, performed automatically, might be necessary in order to obtain proper blade geometry. The study will include the possibility of improvement of the process by using a simple transfer function for scaling of the correction values in case of the non-linear behavior.

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Haris Ligata joined Gleason's R&D Department (Rochester, NY) in 2017 as a Senior Gear Theoretician, working on cutting blade inspection and bevel gear technology. Prior to Gleason, he worked in GE's Global Research Center (Schenectady, NY) on a wide range of projects related to rotating machinery, and in American Axle & Manufacturing (Detroit, MI) on straight bevel and helical gear differential technology. He obtained his Ph.D. degree in Mechanical Engineering from the Gear Lab at The Ohio State University in 2007.

Dr. Hermann J. Stadtfeld is the Vice President of Bevel *Gear Technology* and R&D at the Gleason Corporation and Professor of the Technical University of Ilmenau, Germany. As one of the world's most respected experts in Bevel *Gear Technology*, he has published more than 300 technical papers and 10 books in this field. Likewise, he has filed international patent applications for more than 60 inventions based upon new gearing systems, gear manufacturing methods, as well as cutting tools and gear manufacturing machines. Under his leadership and guidance, the world of bevel gear cutting has converted to, environmentally friendly, dry machining of gears with significantly increased power density due to non-linear machine motions and new processes. Those developments also lower the noise emission level and reduce the degree of energy consumption. Over a span of over 35 years, Dr. Stadtfeld has had a remarkable career within the field of Bevel *Gear Technology*. Having received his Ph.D. with summa cum laude in 1987 at the Technical University in Aachen, Germany, he became the Head of Development & Engineering at Oerlikon-Bührle in Switzerland. Dr. Stadtfeld held a Professor position at the Rochester Institute of Technology in Rochester, New York From 1992 to 1994. In 2000 as Vice President R&D he received in the name of The Gleason Works two Automotive Pace Awards, one for his high- speed dry cutting development and one for the successful development and implementation of the Universal Motion Concept (UMC). The UMC brought the conventional bevel gear geometry and its physical properties to a new level. In 2015, the Rochester Intellectual property Law Association elected Dr. Stadtfeld the "Distinguished Inventor of the Year." Between 2015 and 2016 CNN-Networks featured him as "Tech Hero" in a Website dedicated to technical innovators for his accomplishments regarding environmentally friendly gear manufacturing and technical advancements in gear efficiency. Currently, he continues in his Senior Management position at Gleason Corporation to mentor and advise graduate level Gleason employees, and he supervises Gleason-sponsored Master Thesis programs as Professor of the Technical University of Ilmenau, helping to shape the future of gear technology.

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CORRECTION

In the March-April issue, the technical paper — Experimental Study on the Pitting Detection Capabilities for Spur Gears Using Acoustic Emission and Vibration Analysis Methods — by M. Grzeszkowski, C. Gühmann, P. Scholzen, C. Löpenhaus, S. Nowoisky and G. Kappmeyer — an incorrect biography and photo were used for one of the co-authors — **Sebastian Nowoisky**. For the correct information, please refer to the online version of the paper at *www.geartechnology.com*. *Gear Technology* regrets the confusion.