AC 2008-2138: DESIGN OF A METHODOLOGY FOR THE INSPECTION OF BROACHING TOOL

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Design of a Methodology for the Inspection of Broaching Tool

This research paper highlights the results of undergraduate student research work that has been sponsored by aerospace industry. It demonstrates a methodology of designing, building, testing and implementing a inspection instrument for the evaluation of broaching tool. The inspection of the broaching tool is done for the monitoring of the tool geometry and profile so that the dimensions of machining edges are maintained to standards. The results from this new instrument prove that the methodology developed is a viable solution for increasing accuracy, speed, and repeatability of critical broach attributes.

Broaching is a manufacturing process which is very rapid, accurate and leaves a finish of good quality. This process is employed primarily in the automotive industry where parts are produced in large quantities and frequently to given dimensions within small tolerances. Aerospace industry utilizes the broaching manufacturing process to machine blade attachment slots in nickel alloy turbine and compressor disks. It is understood that the current methods for inspection of broach tools was slow and inaccurate. The results from this research prove that the measuring instrument developed is a viable solution for increasing accuracy, speed, and repeatability of measuring critical broach attributes. The critical attributes measured on the broach tool are: cutting edge measurement along the tooth profile, back off angle, lobe dimensions, and the pitch. While the method to inspect all broach tools is addressed, this research method focused on the complex geometry finisher cutters. These cutters usually consist of the last four broach sticks used in the machining process. The paper focuses on the methodology and results that include an instrumentation to accurately measure attributes of broach tools quickly, accurately, and with highly repeatable results. The instrument measures the dimensions with a tolerance of at ten microns, and angles to within half of a degree. The inspection of the broaching tool is done for the monitoring of the tool geometry and profile so that the dimensions of machining edges are maintained to standards. The results from this new instrument prove that the methodology developed is a viable solution for increasing accuracy, speed, and repeatability of critical broach attributes.

Broaching:

Broaching is a manufacturing process which is very rapid, accurate and leaves a finish of good quality. This process is employed primarily in the automotive industry where parts are produced in large quantities and frequently to given dimensions within small tolerances. A broach is a series of progressively taller chisel points mounted on a single piece of steel, typically used to cut splines or a square keyway in gears, drive shafts, or pulleys. Broach tool is used to machine intricate patterns in turbine and compressor disks. This root attachment area is where the turbine blades are attached to the compressor and turbine disks in a turbine engine. The manufacturing problems created by using broach tools that are out of tolerance, and the current measurement system used to measure the broach tools, are explored.

Aerospace industry utilizes the broaching manufacturing process to machine blade attachment slots in nickel alloy turbine and compressor disks. The current inspection process of the broach tools is inadequate. A new method to efficiently, quickly, and accurately inspect the teeth of the broach cutting tools is needed.

The critical attributes measured on the broach tool are: cutting edge measurement along the tooth profile, back off angle, lobe dimensions, and the pitch *(figure 1)*. These parameters need to be verified and compared with drawings of the broach tools and coordinate measurement machine (CMM) inspection data. While the method to inspect all broach tools needs to be improved, this project focused on the complex geometry finisher cutters. These cutters usually consist of the last four broach sticks used in the machining process.

Research Focus

This paper demonstrates the results of industry sponsored undergraduate research work that has been promoted by aerospace industry. It demonstrates a methodology of student learning where the students go through the stages of designing, building, testing and implementing a inspection instrument for the evaluation of broaching tool.

The main focus of this research is to utilize an optical measurement system in conjunction with a LASER to inspect specific points and attributes on the broach tool. By using a LASER, there is increased accuracy compared to methods currently utilized. The time it takes to setup the inspection instrument and inspect the tool compared to previous methods is required to be significantly less. This system will utilize a LASER in conjunction with vision software and data-acquisition system and controlled using LabVIEW software. The goals of the project included developing instrumentation to accurately measure attributes of broach tools quickly, accurately, and with highly repeatable results. The instrument is required to measure a tolerance of at least 5 thousands of and inch, and angles to within at least 30 minutes or half of a degree.

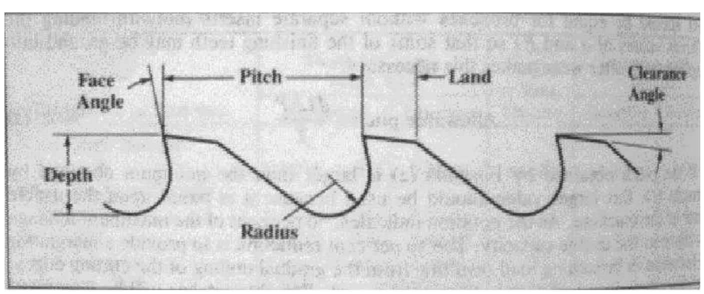

Figure 1: Critical broach tool attributes.

Additional efforts are done to implement the inspection process not only off-line, but eventually on-line, or while the broach manufacturing process is taking place. Being able to take accurate measurements on-line drastically reduces the amount of time need for the inspection process.

The turbine and compressor disks in jet engines are made out of a nickel based high strength alloy. This alloy is difficult to machine so the manufacturing process of broaching is employed to cut the intricate root attachment points where the turbine blades are attached to the turbine and compressor disks. The process of broaching utilizes several broach tools in the operation. In the case of this project the broaching operations utilized a total of 18 broach sticks. The first 14 broach sticks are referred to as “roughers”. These broach sticks are not intricate in profile and therefore are not difficult to inspect. The last four broach tools are referred to as “finishers”. These broach sticks are intricate in profile and therefore difficult to measure tolerances and inspect. A problem, which occurs in the broaching process, is the development of what is called a white etched layer. The white etched layer is brittle in nature and is formed from the extreme pressure and heat exerted on the nickel alloy turbine and compressor disks by the broach tools during the broaching process. The formation of the white etched layer reduces reliability and can lead to catastrophic failure. The formation of the white etched layer can be controlled as long as the broach tools are in tolerance. tolerance.

Background

A set of broach sticks cost around $50,000 and have a usable life of about 5 to 6 uses. The life of a broach tool can be extended by machining particular attributes back to tolerance after being inspected. As design alternatives, several procedures were explored.

(i) The first method was utilizing an optical comparator method. This method, which is currently used by Pratt and Whitney, is slow and inaccurate.

(ii) The second method consisted of Front-Back illumination in conjunction with National Instruments IMAQ Vision software. In this process, the broach tool was placed in front of a fresnel lens and illuminated from the back. Utilizing this method, profile measurements were easily made.

(iii) The third method was by using a Steinbichler 3D-Digitizing System. This system scanned an object using white light fringe pattern detection. The resulting image was then available to be compared to existing CAD drawings.

(iv) The fourth method utilized a LASER Line Profile Measurement System integrated with IMAQ vision system. This method was used as the basis for this project.

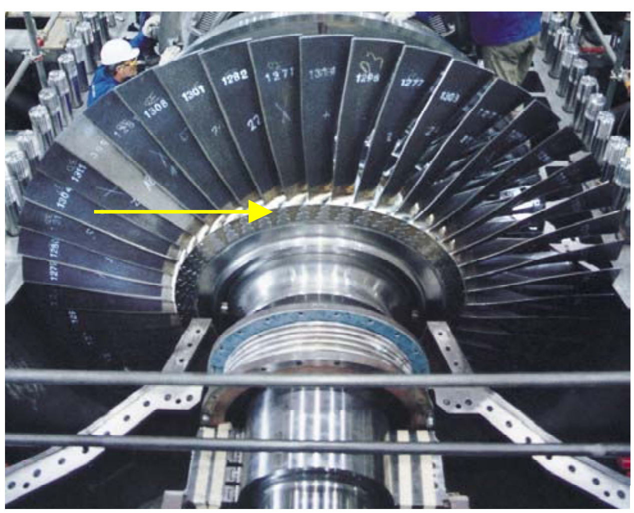

Figure 2: The arrow indicates the root hub, where the compressor and turbine blades fit on the to the hub of the turbine shaft.

Study of Illumination and Vision Software

A software system that was investigated was IMAQ vision system. This software is capable of analyzing measurements and certain characteristics of a captured image. The vast capabilities of the IMAQ software were the major contributors to the development of a functional methodology for measuring the broach tool attributes. A critical parameter in executing an accurate IMAQ analysis is the lighting in which the image is captured. Various lighting scenarios and camera positions were explored to verify which system alignment produced the most accurate results. To gain understanding of the IMAQ software and its strengths, experiments were first conducted with ambient lighting. Ambient lighting provided a relatively clear image of the broach tool. Figure 3 below shows a picture of the image produced using this lighting.

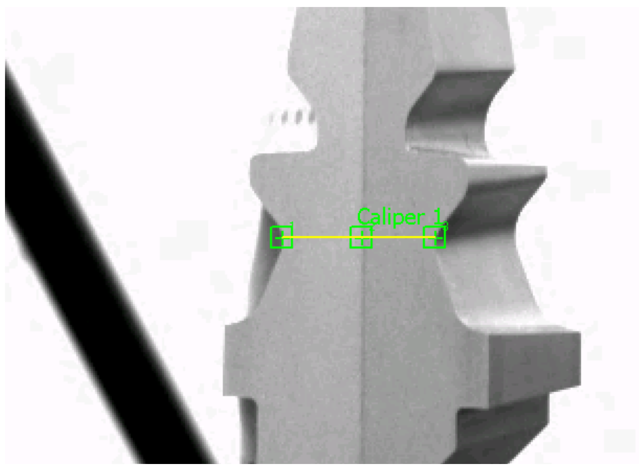

Figure 3: Image produced using ambient light

Ambient lighting can provide sufficient illumination of the broach tool to conduct the necessary measurements. Although this is possible, the ambient lighting condition is subjective to error due to the reflectivity of the tool. The depth of the tool is less defined then the closest face. This is primarily due to the focus of the camera and the uniformity of ambient light. The camera is only capable of focusing to one distance, making it impossible to gain a clear and accurate image of the entire broach tool. Ambient lighting conditions would inhibit the ability to accurately measure the back off angle, condition of the profile, and the angle of the desired profile lines. From this initial exploration of the IMAQ software and the camera components, it was determined that the tool must be illuminated at a constant distance and images must be taken in individual “slices”. With this is mind it was determined that the tool would have to be translated in one direction while the light source remained steady.

Rear Illumination:

The next method considered was rear illumination of the tool using a portable light source. A diagram of the lay out is shown below.

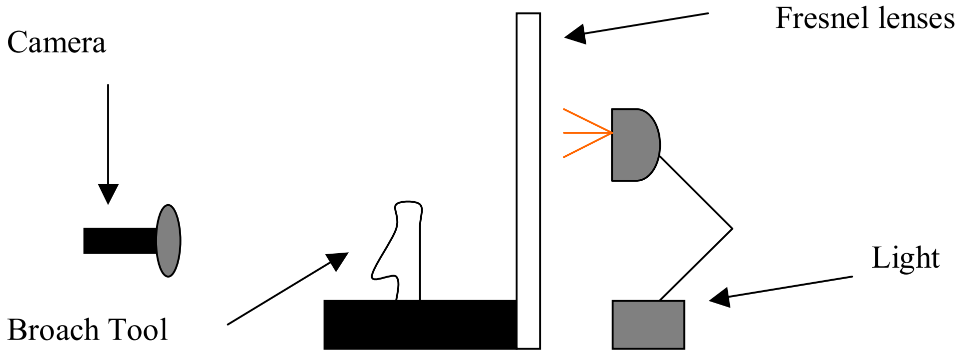

Figure 4 Front/Back Illumination

The test setup consists of a CCD camera, a Fresnel lens, and a light source. The Fresnel lens was used as a dispersive medium of the light. Fresnel lenses are used in applications where image focus is not critical. They are used in the illumination surface of overhead projectors to disperse even illumination of a document. The lack of focus would allow for the image acquired by the camera to have an even rear illumination, thus eliminating the varying intensity at different depths, which inhibited the usefulness of ambient lighting. A sample image of the rear illumination technique is shown below.

Figure 5 : Front/Back image captured with IMAQ Vision system.

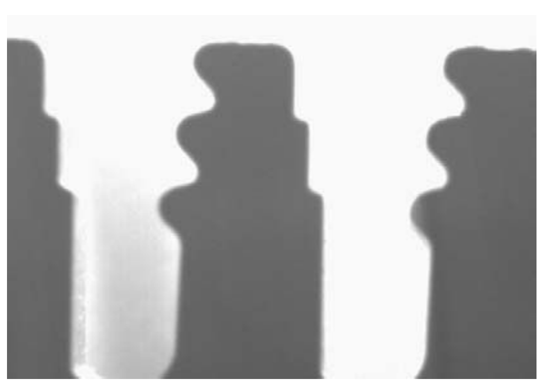

Figure 6: Front/Back image acquired with IMAQ Vision system.

The rear illumination technique is very efficient in providing accurate measurement of the profile and pitch. The lack of ability to measure characteristics located on different planes is also a major downfall of this method. This method is similar to the optical comparator method, but the human error introduced in that process is eliminated. Therefore, the only source of error is the camera focus and contrast. Due to the intensity and uniformity of the lighting arrangement, the contrast must be adjusted to provide a proper balance of between the light and dark spots of the image. The intensity of the light source could also be adjusted to eliminate this effect on the acquired image. The rear illumination technique should be used in measuring properties that are located in the same plane. The camera can be positioned orthogonal to that plane and measurements can be obtained without camera positioning induced error. Studying the effects of the illumination of the broach tool was extremely critical in obtaining the required measurements. We studied previous experiments utilizing a LASER as source of illumination. From these studies an experimental setup was derived that incorporated a laser.
(1) The first prototype setup is shown below.

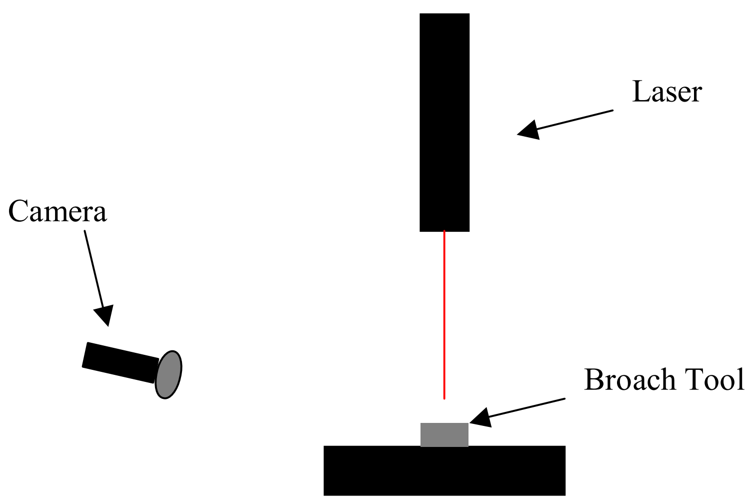

Figure 7: Schematic of first prototype setup.

The test setup consisted of a laser coupled with a line generator and a CCD camera. The broach tool was placed on its side to capture the entire profile of the broach. A sample image captured using this setup is shown below.

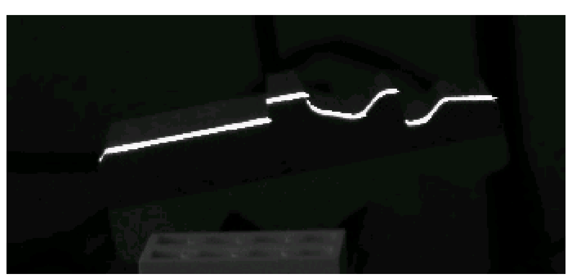

Figure 8: Line laser profile image.

From this experiment, it was discovered that the angle at which the laser was projected onto the broach tool affected the ability to capture the entire profile. This was mainly due to the intricate lobes of the tool, in which the variance between valleys and peaks caused the valleys to be shadowed by the peaks. This was also due to the directivity of the laser. Once the path of the laser is interrupted, any surface behind the location of interruption would not be illuminated. Therefore, the optimal positioning of the broach tool was difficult to achieve.

Also, from this experiment, it was concluded that camera cannot be positioned orthogonal to the desired measuring plane. The intensity and directivity causes less of a glare than previous arrangements. The off axis arrangement of the camera will add error to the obtained data. The camera, laser, and broach positioning are critical aspects in obtaining useful data. The design criteria obtained in this experiment were critical in developing a more robust apparatus. The requirement to measure the entire profile, the attributes located on the side of the tool, and ones viewable only from the top of the tool were considered in the next design phase. The diagram of the second prototype instrument is shown below.

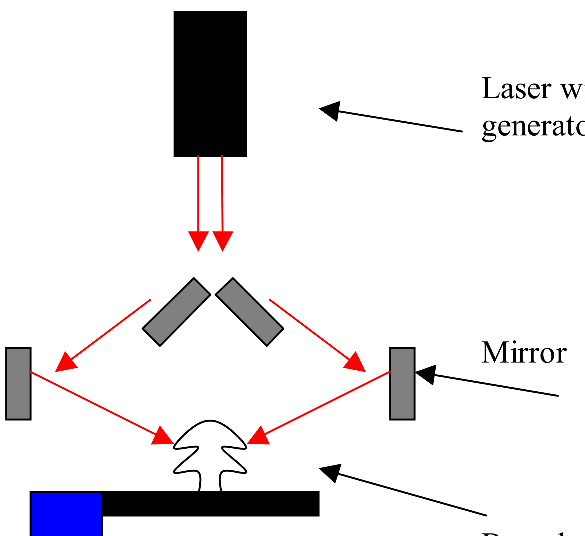

Figure 9 Schematic of first prototype setup with beam splitter.

In order to illuminate the entire profile of the broach tool, a series of mirrors were positioned. As shown in the figure, two mirrors were positioned to evenly split the laser line. An apparatus was constructed using Lego blocks, in which the angle of both mirrors could be adjusted in equal and opposite proportion. This allowed for the fine-tuning of the profile illumination. The outer mirror and laser positions remained fixed. Also, a translation device was constructed using Lego pieces. This would allow the profile to be captured along the length of the broach tool. The prototype apparatus and image obtained from it are shown below.

Figure 10 : First prototype.

Figure 11: Image captured from the prototype.

It was found that this was the best orientation to illuminate the profile of the tool. It was also verified that the correct camera settings and location, along with the proper laser positioning provided sufficient clarity to obtain accurate results. The results obtained from this experimental setup reinforced the design criteria. A second prototype was developed to reduce the loss of laser energy due to the angled mirrors and their inaccuracy. This was achieved by changing the mirrors to split the laser beam to a cube prism beam-splitter. A diagram of the final design is shown below.

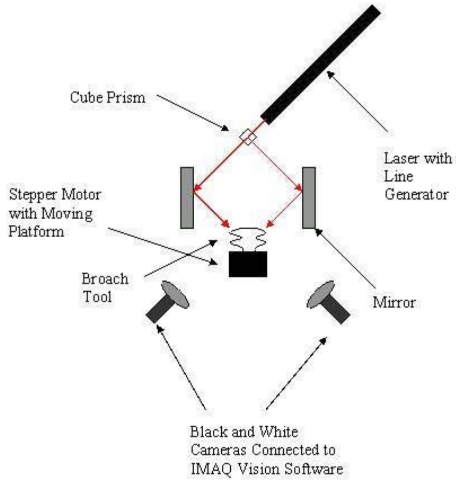

Figure 12 Schematic of final design setup.

The cube prism is very directive. It allows P-polarized light to pass thru and reflects S-polarized light at 90 degrees. The transmissibility of the cube prism is 92% for S-polarized light, in which the difference in intensity of the separate paths is visibly undetectable. A second camera was also incorporated into the design to allow the simultaneous measurement of both sides of the tool. The IMAQ software is capable of simultaneously acquiring images from several cameras. The following images depict the final design layout.

Figure 13: Final design layout.

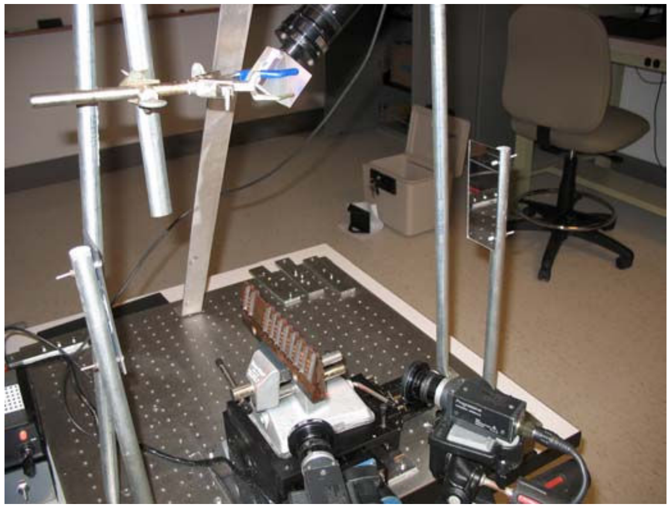

Figure 14: Another angle of the final design.

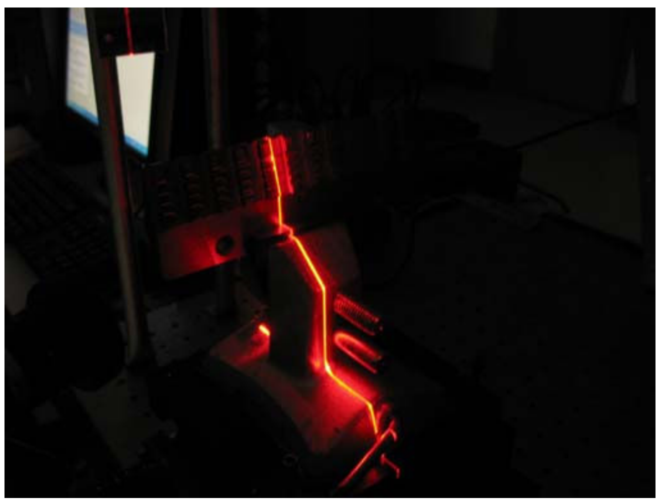

Figure 15: Image of a measurement being taken with the line laser setup.

Using this apparatus, accurate measurements were obtained of the profile and pitch along the length of the tool. After conducting these various experiments with lighting conditions and positioning of the camera, the best methods for measuring the required characteristics were determined. In order to obtain accurate measurements, the IMAQ software must be calibrated based on the location of the camera. Therefore, for each required measurement there are corresponding optimal camera positions. When integrating this system for on-line inspection, there may be a requirement for multiple cameras dedicated to specific measurements. By designating cameras to individual characteristics, the respected calibration can remain unchanged. As discovered in the initial design phase, ambient and rear illumination may provide an equivalent or more accurate image of the tool. Therefore, there could be several "stations" along the broach inspection line in which various illumination methods can be utilized. The optimal measurement viewing location for each characteristic is shown below.

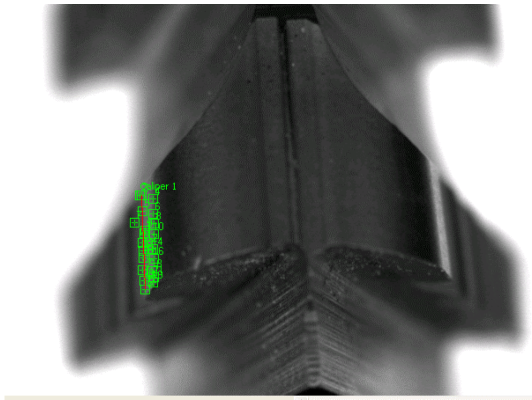

Figure 16 (a) Clearance Angle

The clearance angle can be measured using ambient and laser illumination. In order to achieve the optimal image using ambient light, the camera must be positioned above the tool as it translates. The accuracy of the ambient light can be altered using the focus and contrast threshold setting in the software. The major downfall of this method is the blurriness of the deeper lobes. There could be independent cameras dedicated to measuring the characteristics at each height. This method may not be economically advantageous, but may be feasible in the event a laser cannot be implemented. The following image depicts how the clearance angle can be determined using a laser.

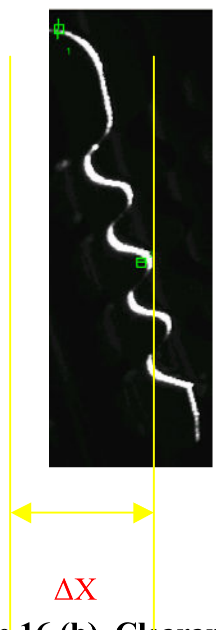

Figure 16 (b) Clearance Angle

By monitoring the change in ΔX as the tool is translated through observation point, the angle can be accurately interpolated. The data can be obtained using the software and exported into Excel for easy calculation of the angle. The reference point (top) can be any location on the tool in which there is no change in horizontal location.

Cutting Angle

The cutting angle can also be measured using ambient and laser lighting. The same procedure and limitations present in the clearance angle measurements are applicable to the face angle. A reference point can be specified along the midline of the tool and the variance in the x displacement can be used to determine the face angle. However, the camera would have to be positioned directly above the tool without interfering with the laser light projection.

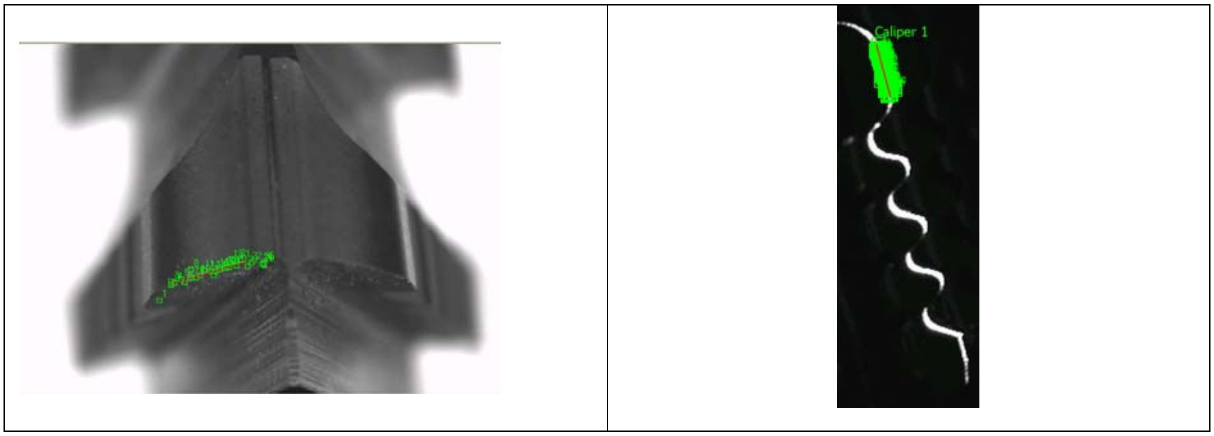

Figure 17 Cutting Angle

The face angle can be accurately measured using laser illumination. The IMAQ software is capable of interpolating multiple points. The angle at which the line lies is instantly displayed. Besides the known camera issues, the only sources of error are that the inspection plane may not be level relative to horizontal, and not enough vertical points were taken along the profile of the tool.

Lobe Dimensions

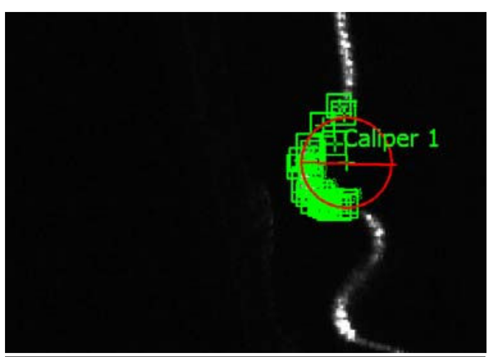

Figure 18 Lobe Dimensions

The lobe dimensions can also be measured using laser illumination. The profile image obtained using the face angle measurement will also allow the measurement of the lobe dimensions. The IMAQ software is capable of obtaining these measurements simultaneously

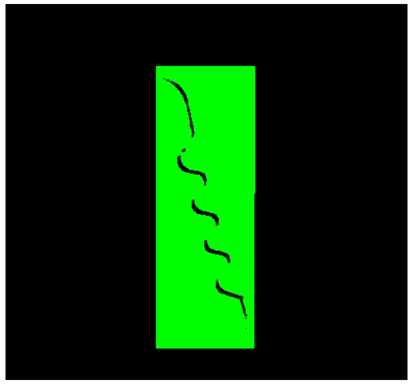

Figure 19 Condition of the Cutting Edge

The condition of the cutting edge can be qualitatively determined using the standard/golden template feature in the IMAQ software. This feature allows the user to instantly view any deviation in the broach tool from the predetermined standards. The black spots within the green areas represent the difference in the actual broach from the golden standard. In the same sense, there can two golden templates applied for the lower and higher tolerance limits. Therefore, an inspector can determine whether the cutting edge is within the acceptable range.

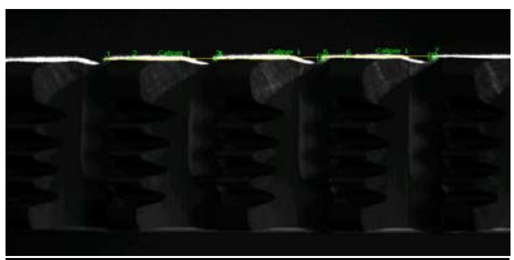

Figure 20 Pitch

The pitch measurement can be obtained easily and accurately using rear and laser illumination. Due to the simplicity of this characteristic, the definition of the cutting edge can be clearly seen from a perpendicular perspective. In the event a laser cannot be incorporated into the design space, rear illumination will supply an equivalent accuracy.

Performance Evaluation

There are several variables that can enhance or negatively affect the outcome of the results. The best methods were decided based solely on qualitative analysis, as the difference between different techniques was clearly distinguishable.. During the design phase of this project, with various lighting techniques were experimented with in order to determine which were optimal for the design criteria. The first experiment conducted was measuring the tool using ambient light. As seen before, ambient light can provide relatively clear images of the tool. The major downfall of ambient lighting conditions is the inability of the IMAQ software to clearly distinguish each characteristic at different depths. This is due to the uniformity of ambient light. However, the use of ambient light may be feasible in acquiring certain characteristic data. Ambient light can be used in measuring attributes in which the entire measurement is located on the same plane and where there is nothing located behind the measuring surface. The negative space between the two desired measuring points assists in clarifying the edges. A good example of this is shown below.

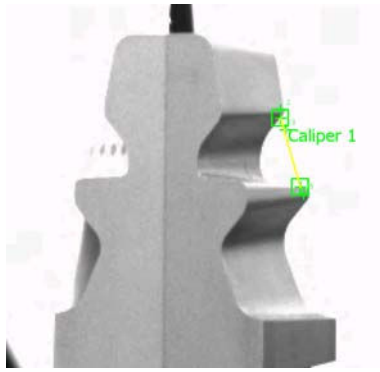

Figure 21 Edge Inspection

Experiments with Rear Lighting:

The next lighting arrangement that we experimented with was the use of rear illumination. Rear illumination removes the reflections caused by using ambient light. Rear illumination provides a sharp measurement of profile attributes. The camera must be located orthogonal to the plane of measurement. We experimented with varying the intensity of the light source. The light source, camera contrast and focus, and alignment of the broach tool are critical in obtaining an accurate measurement.

There are infinite combinations of these arrangements, making it difficult to specify an exact method of measurement, The settings obtained in this method is completely subjective to the attribute that is to measured. However, once the optimal settings are determined and remain unchanged, the test is highly repeatable. There is no significant variance in measuring the same characteristics under the same lighting conditions and positioning. An example of a measurement obtained using the rear Illumination technique is shown below.
The final method experimented with was the laser illumination technique. The laser technique has many variables, but if it is fine tuned properly it can provide extremely accurate measurements. The main variables are laser line projection and the camera settings. It may be difficult to find the optimal angle of projection of the laser line due to the intricate design of the broach tool. However, through the use of mirrors, the optimal projection can be achieved. The laser line thickness and intensity can cause excess illumination of the tool, which can inhibit the IMAQ software from distinguishing the actual edge of the laser line.

A major contributor to error in all measurement procedures is the initial calibration of the IMAQ software. Once the camera is calibrated, the location and visual settings must remain unchanged to obtain useful results. Calibration consists of a grid of dots in which their spacing is a constant value and has very small tolerances. In order to perform proper calibration, the desired tool should be fixed in a location and the camera must be adjusted both visually and by position in order to capture the desired measurement. Once the camera location is determined, the tool must be removed and the calibration grid must be placed in the identical plane and distance as the desired attribute. In the IMAQ software, there is a calibration option which automatically calculates the amount of pixels per desired measurement unit. When a measurement is taken, the software displays the measurement in pixels and in the desired units. It also displays the standard deviation of the measurement. An example screenshot of the calibration process is shown below.

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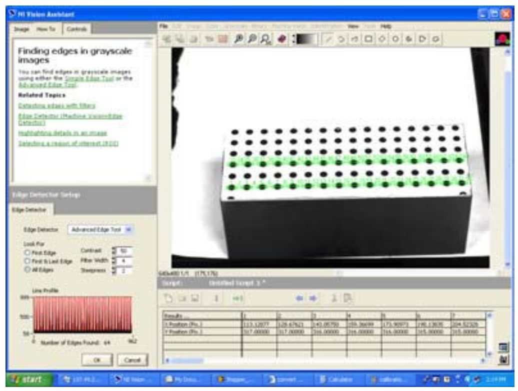

Figure 22 Calibration and Measurement

With the calibration error in mind, the location of the camera is critical. A baseline analysis was conducted to determine how accurate the calibration can be. The camera was positioned as close as possible *(1" away from the laser and 4.5" above)* to the one-toothed broach tool. Once this location was determined, the software was calibrated and thickness measurements were conducted at several locations along the profile of the tool.

Discussion on measurement errors:

Based on the results, the closer the camera is to the desired measurement, the more accurate it will be. When the camera is closer, there are more pixels per inch, which allows for a better approximation of the actual value. It was determined that a camera with a higher pixel density in the same location will have a much more accurate measurement. Therefore, the critical source of error in this methodology is the calibration. All other variables can be optimized and adjusted. With the optimal fixed alignment, the human induced error in the positioning of the calibration dots will determine the accuracy of the analysis. Using precise measuring devices to position the dots can reduce this error. The proper method for ensuring the accuracy of the measurements would involve calibrating the software, measuring the desired characteristics, and finally measuring the calibration dots to ensure that the apparatus' settings remained constant.

Conclusions

This paper shows how an aerospace industry sponsored project can be adopted for undergraduate research work. It demonstrates a methodology of student learning where the students go through the stages of designing, building, testing and implementing a inspection instrument for the evaluation of broaching tool. The outcome of this research is very significant and beneficial to the development of a more robust apparatus. This baseline analysis of this problem and solution validates the initial presumptions of the experimenters. The system is accurate and can be fine tuned to compensate for any error that can inhibit the acquisition of accurate data. Further exploration of integrating this method on-line of the broaching process could be beneficial to the aerospace industry

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