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Intelligent Automation Incorporated

A Statistical Validation on the Individuality of Tool Marks Due to the Effect of Wear, Environment Exposure and Partial Evidence

Final Report

Period of Contract: August 01, 2006 – January 31, 2009

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Prepared by

Benjamin Bachrach, Ph.D.

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1. Abstract

The ability to validate that an evidence tool mark was created by a suspect tool can be of significant importance during the presentation of a case in court. Currently, the admissibility of tool mark evidence rarely meets significant challenges. However, our current understanding about the effect of wear or environmental conditions on a tool or a tool mark is limited. Supreme Court decisions such as Daubert and Kumho are making it increasingly necessary to further formalize scientific evidence presented in court. Even if tool mark identification error rates are proven to be adequately low when evidence is found in pristine condition, questions arise regarding the feasibility of identification when partial evidence data is available, or when either the tool mark or the tool is exposed to wear or environmental conditions. The lack of quantifiable results regarding the effect of these variables on tool mark identification poses a threat to the future admissibility of tool mark evidence in court. The main goal of the present study is to evaluate in an objective and quantifiable manner the effect of wear, environmental conditions, and partial tool mark information. At the core of the proposed project are questions such as: Is it possible to reliably identify a tool as having created a tool mark after the tool has been exposed to water for a week? What if the tool mark has been exposed to the environment for a month? Can a tool be identified if only a portion of the tool's working surface created the tool mark? The variety of questions such as these is endless. For the purpose of this study we focused our attention in the case of diagonal cutter tool marks on copper wire and salt water (of various concentrations) as the environment to which the tools or tool marks were exposed.

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2. Executive Summary

2.1 Introduction

An integral aspect of forensic examination is the characterization and identification of tool marks found in a crime scene. Tool mark identification is routinely used as a means to associate a suspect tool with a crime. Such association is possible because the microscopic imperfections found on the working surface of a tool are transferred to the tool mark. The forensic examination of tool marks is the domain of the Tool Marks Examiner, who is responsible for determining whether a suspect tool created an evidence tool mark. In practice, the Tool Marks Examiner operates by creating test tool marks using the suspect tool, and comparing the features found on the test tool marks with those found on the evidence tool mark. Therefore, the ability to perform tool mark-to-tool mark comparisons based on microscopic surface features is at the core of tool mark identification. Currently such comparisons can only be made manually by a Tool marks Examiner inspecting a pair of tool marks under a comparison microscope. This is a very time consuming process, and it requires highly trained and skilled personnel. In reaching a conclusion, the Tool marks Examiner relies on his/her training and judgment, and even if certain of the conclusion, the Tool marks Examiner is generally unable to quantify his/her level of certainty, or the probability of making an erroneous determination. Although there is significant research associated with the topic of tool mark identification in general and identification criteria in particular, there is virtually no published research on the effect of wear and environmental exposure on the tools and tool marks of interest. Similarly, there is limited published research regarding the effect of partial tool mark evidence on the probability of identification error. A summary of some of the most relevant publications in the area of tool mark identification can be found in 3.1.1.

2.2 Scope of the Study

Due to the magnitude of the proposed effort, this project has been broken into three independent phases. Each of the following phases is meant to address a specific issue:

Phase I) to study the effect of environmental exposure on a tool mark:

> This phase of the study will be aimed at providing answers to the following question: **If an evidence tool mark has been exposed to the environment for a prolonged amount of time, to what extent is it possible to match it to the tool which created it?**

Phase II) to study the effect of wear/environmental exposure on the tool:

> This phase of the study will be aimed at providing answers to the following question: **If a suspect tool has been used/exposed to the environment for a prolonged amount of time after having created an evidence tool mark, to what extent is it possible to match the evidence tool mark to the suspect tool?**

Phase III) to study the effect of partial data on tool mark identification:

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This phase of the study will be aimed at providing answers to the following question: **Given a partial evidence tool mark, to what extent is it possible to match it to the tool which created it?**

Prior to undertaking these phases we made a selection of the tool type and media of interest. The selection of both tools and media was made in coordination with FBI tool mark examiner Paul Eugene Tangren. In making this selection our intention was to choose tools and media frequently associated with crime scenes. On the basis of our discussions with tool mark examiner Paul Tangren, we decided to use diagonal cutters as a tool of interest during the course of this study. This decision results from the fact that diagonal cutters are often used in crimes, and tool marks formed from using these diagonal cutters are obtained from the crime scenes, in many cases, after prolonged periods of environmental exposure.

2.3 Summary of Conclusions

The results of the present study strengthen the scientific foundations of tool mark identification in a variety of areas. However, it is important to consider the extent to which these results apply to other tools of the same type (tools of similar action). Strictly speaking, the conclusions of this study apply to the specific tool considered in this study. However, it is worth noting that the tools used in this study were selected - among other reasons - because there is nothing unique or unusual about them. In fact, to the best of our knowledge, they are fairly generic and representative of any tool of their type (in terms of quality or manufacture). Therefore, while only extensive research of all brands and models of tools can guarantee the accuracy of all encompassing conclusions, the author is confident that while the **detailed** results presented in this study may not repeat for all tools of the same type, the **general trends** observed for this tool will be repeated for all similar tools. With this in mind, the conclusions of the present study can be summarized as follows:

- The results of our preliminary experiment indicate that the tool marks deteriorate very slowly in air and tap water, but dramatically in salt water. These results validate the choice of salt water as an environmental exposure media of interest.
- The study of tool wear effect unveils the fact that the most significant wear of a cutting tool takes place within the first individual cuts (one or two). After that, the effect of tool wear slows down rapidly as the working surface of the tool settles. Based on our experiments, we could verify that the tool marks created by diagonal cutters are easily identifiable after 300 cuts. While we did not go beyond 300 cuts, the rate of change of the similarity measure between tool marks seems to indicate that identification should be possible well beyond this number of cuts. On the other hand, while the rate of change of the tool's working surface is slow, there is evidence that tool marks created in close proximity to each other (after a small number of cuts) will be more similar than tool marks created many cuts apart.
- The study of tool mark exposure confirms our expectations that identification of a tool mark exposed to the environment becomes more challenging in a manner proportional to the time of exposure and the corrosiveness of the exposure media. In as short time as 4 weeks of exposure to 3.5% salt water, the matching and non-matching distribution of tool

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mark similarity measures overlap significantly, indicating that these tool marks would become challenging to identify. In the case of 1.75% salt water identification becomes challenging somewhat later (perhaps between 4 and 6 weeks), while in the case of 0.88% salt water concentration identification appears to be possible even after 6 weeks.

- The study of tool exposure, the time frame at which the identification of tool marks becomes challenging is even shorter than in the case of tool mark exposure. In as little as 2 weeks of exposure to salt water the distribution of the matching similarity measure overlaps significantly with the non-matching distribution for all concentrations, indicating that these tool marks would be challenging to identify. Not surprisingly, the tool marks created while the tool is at a given level of exposure are easily identifiable among themselves.
- The study of partial tool marks validates the premise that a partial tool mark can provide satisfactory ground for identification; just as reliable as a complete tool mark. In addition, it validates the fact that the identification of diagonal cutter tool marks on wire can be achieved by comparing against a tool mark made on a copper sheet. Nevertheless, it is also apparent that the best way to make a comparison is to duplicate the conditions under which the original tool mark was created. This is a well known practice among firearms and tool marks examiners

It is important to understand the results of this study in the appropriate context. While the above statements are significant, it is important to remember that ultimately each tool and tool mark is unique and it may behave in unique ways. For a more detailed discussion of our conclusions see Section 4.

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3. Technical Report

3.1.1 Tool mark Identification Criteria

A substantial volume of work has been carried out in the arena of tool mark identification as a result of concern for possible Daubert challenges. A valuable introduction and important source of information to the subject of tool marks identification can be found in [6] and [7]. Tool mark identification criteria are discussed in a variety of articles, such as [8], [9], [10], [11], [12], [13]. Further discussion of statistical aspects of tool mark identifications are discussed in [14][15][16]. A number of attempts have also been made to view the similarity estimation as a statistics problem [17][18]. A variety of articles have been published regarding the identification of specific tool marks such as bolt cutters [19] [20], screwdrivers [21], staples [22], cuts on wire [23] [24], knifes [25], tongue-and-groove pliers [26] , cut nails [27] and the effects of angle of tilt and angle of progression on the creation of tool marks. A study on tool wear was conducted in which it was demonstrated that a new tool working surface changes rapidly initially, until the initial break-in has occurred. After that point, the wear becomes slower and more uniform through normal use. This was demonstrated in the shearing process of producing cut nails [28].

3.1.2 Tool mark Identification Systems

The concept of using a 3D characterization of a surface for identification purposes goes as far back as 1958, when J. H. Davis [29] proposed the idea of the “Striagraph” for ballistic identification. However, the technology necessary to make depth measurement with the required accuracy was not available at the time. The application of 3D methodologies for ballistics identification applications has been reported in [30] and [31]. The significance of 3D methodologies and their potential is explicitly recognized by the National Institute of Justice (NIJ) and the Office of Law Enforcement Standards (OLES) of The National Institute of Standards and Technology (NIST) [32]. More recently, Banno et al [33] developed a neural network that was able to estimate bullet striation similarity from ten unidentified bullets and ten database bullets. Additional research on the use of 3D data for tool mark comparison can be found in [3].

3.2 Project Design, Data and Methods

The approach followed in this study relied on three main elements: a) the use of topographical data (or 3D data) for the characterization of the surface of the tool marks under analysis, b) the use of a consistent and objective processing of the data to develop a set of “signatures” for each of the tool marks under analysis, and c) the use of well established statistical techniques to quantify the degree to which individual tool marks can be associated as being created by the same tool. In this section we discuss the main elements of the 3D-based tool mark comparison system.

3.2.1 Automated 3D-based Tool Mark Comparison System

The implementation of an automated comparison system requires two main components: a) data acquisition hardware and b) data analysis software. The data acquisition hardware is responsible for capturing the physical characteristics of the specimen being analyzed. The data analysis

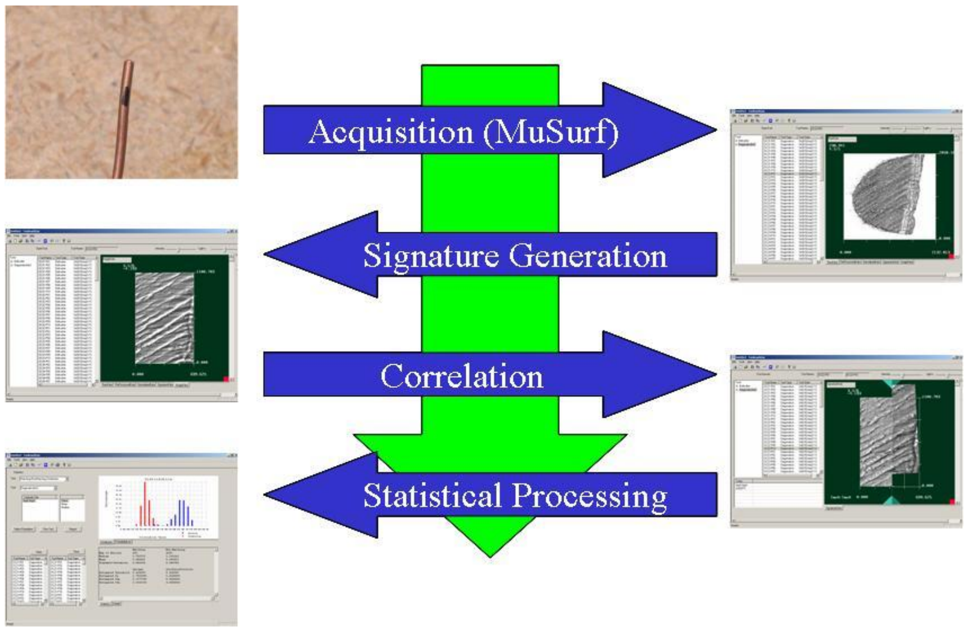

Figure 1: Basic components of 3D-based tool mark comparison system

software is responsible for the storage, management, processing and comparison of the data acquired by the data acquisition hardware. Figure 1 shows the conceptual work flow of the automated tool mark comparison. In the following sub-sections, we describe all components of the automated comparison system.

3.2.1.1 Data Acquisition Hardware

The acquisition of tool mark data was achieved using a white light confocal microscope manufactured by NanoFocus AG (MuSurf Confocal Microscope). A photograph of the confocal microscope together with its basic performance characteristics are shown in Figure 2. The surface topographical data of tool marks created on copper wires with diagonal cutters were first acquired by the Nanofocus sensor. These data was then displayed as topographical images on a computer screen, and its quality was assessed by the operator before saved to the storage.

3.2.1.2 Data Analysis Software

After acquiring data of all interested tool marks, we applied a set of automated tool mark comparison algorithms developed at IAI to analyze the tool marks. The algorithms typically perform the following three major tasks. First, the algorithms preprocess the collected tool mark data and find the region of interest that has the greatest likelihood to contain useful "individualizing" features. In our current study, such region was taken to be a rectangular area near the line where the tool made the cut on the copper wire (see

- Measurement field: 800/320 micrometers.
- X/Y-Resolution: 1.5/0.6 micrometers.
- Z-Resolution: 20/10 nanometers.
- Numerical Aperture: 0.40/0.50.
- Working Distance: 12/10.6 mm

Figure 2: NanoFocus' White Light Confocal Microscope (MuSurf)

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Figure 33 for an example). Second, they correlate the selected pairs of signatures from different tool marks and compute the similarity measure of comparison. Third, they generate a statistical report of the comparison between multiple tool marks acquired from the same tool (matching) and different tools (non-matching). An extensive discussion of these three main elements of the study was included in the original proposal. Further detail regarding the data processing of the topographical data can be found in [3], [4], and are summarized below.

3.2.1.2.1 Signature Generation

The signature generation consists of the following steps:

Pre-processing: The un-processed data obtained from the acquisition hardware is referred to as "raw data." Raw data often includes inaccurate or questionable data points. We refer to such points as *unreliable* data points. The pre-processing module is responsible for the identification and preliminary handling of unreliable data points. The data pre-processing module consists of a five step process: 1) identification of dropouts, 2) identification of outliers, 3) recording of unreliable points (both dropouts and outliers), 4) interpolation of the unreliable data, and 5) Selection of region of interest. These steps are discussed below.

1. Identification of dropped points: Most 3D imaging systems provide the user with a "level of confidence" value associated with each data point taken (for optical systems, the level of confidence usually corresponds to the percentage of light reflected by the target). If the level of confidence is too low, the point is deemed "unreliable," or in other words a dropout.

2. Identification of outliers: As opposed to dropped points, "outliers" are data points inaccurately measured by the 3D imaging system, which are not reported to the user as inaccurate by the acquisition hardware. For this reason, they are much more challenging to identify. We use two approaches to identify such outliers. The first approach is by estimating the local slope between a point and its neighbors. If the slope is above a certain threshold, the adjacent points will be identified as outliers. The second approach is by considering the statistical distribution of the data. If a particular point is excessively far from the local median in terms of standard deviations, it is identified as an outlier.

3. Recording of unreliable points: Once all dropped and outlier points are identified, a "mask" is created to store this information for use during the comparison stages so that the unreliable points can be excluded from the comparison. In the current software implementation, the mask is an array of the same dimensions as the data, and its entries are "1' for those points deemed to be reliable, and "0" for those points identified as dropouts or outliers. The left side of Figure 3 shows an example of raw diagonal cutter data, where the third dimension (z-axis) is color coded. The right side of Figure 3 shows the corresponding mask, where the points identified as dropouts or outliers have been colored blue, and the points deemed "reliable" have been colored red.

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4. Selection of Region of Interest: having automatically identified the unreliable points (both drop outs and outliers), the system identifies a section of pre-defined dimensions within the acquired data that: a) shows the least number of unreliable points, and b) satisfies some desirable constraint, such as being closest to the vertical center of the data and the right edge of the data. The region thus selected will be isolated and used for the remainder of the process. This step is taken because whenever tool marks are created by the same type of tool and acquired in a consistent manner, the region of interest is always in the same relative location. In other words, this step guarantees that the portion of the tool mark that is used for comparison is the portion of the tool mark where useful data is found, and is not contaminated by data which does not contain tool mark data. The resulting data (left) and mask (right) corresponding to the selected region of interest are shown in Figure 5.

5. Interpolation: For display purposes and in order to accommodate the digital filtering performed at a subsequent stage, the values of dropped points and outliers are replaced by interpolated values based on the neighboring points.

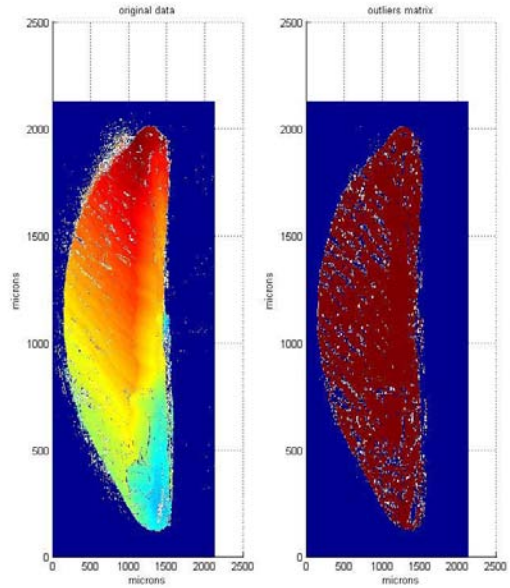

Figure 3: Identification of unreliable points: Raw data (left) and corresponding unreliable points mask (right)

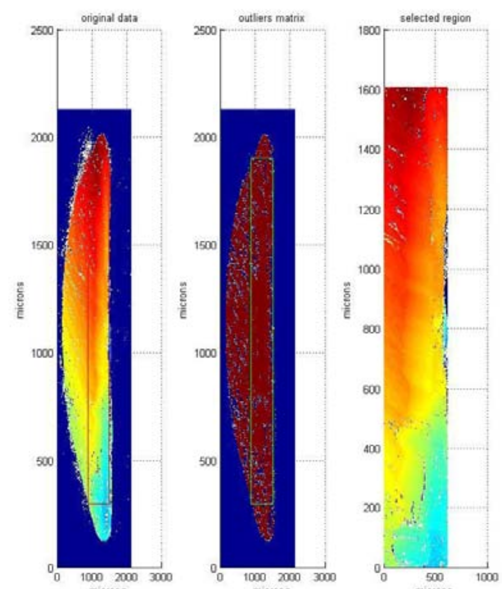

Figure 4: Selection of region of interest: raw data (left), mask with indicated region of interest (middle) and selected region of interest (right)

Normalization: The normalization module is responsible for compensating for the variations in the topographical images that result from inconsistencies during the acquisition process. Consider a simple illustrative example. Let us assume that a given tool mark sample is acquired twice, but in each case, the tool mark surface is **oriented** differently. If left uncorrected, these two data sets may be erroneously judged to be dissimilar by the correlation algorithms. The purpose of the

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normalization process is to bring these two data sets to a "level playing field." The purpose of the normalization is to apply a transformation to compensate for the fact that the tool marks under consideration were not acquired in a uniform manner.

The normalization process consists of the application of a geometric transformation to the pre-processed data in an effort to compensate for any inconsistencies resulting from the acquisition process. In other words, the goal of the normalization process is to ensure that the data is represented in a consistent way regardless of variations which may have taken place during the acquisition process. It is important to note that in order to perform the normalization process accurately, it is necessary to have knowledge of which data points can be considered reliable. Otherwise, the result of the normalization process is not consistent between different tool marks. For this reason, identification of unreliable points precedes the normalization process.

Signature Generation: The signature generation module is responsible for emphasizing those features which are specific to the tool mark under consideration (individual characteristics), while minimizing the features which may be common to all tool marks of the same type (class characteristics). This amounts to using a Gaussian band pass filter on the interpolated data to eliminate the low frequency component corresponding to the class characteristics of the tool mark. Figure 6 shows an example of the signature generation process applied to normalized data. It is important to note that the signature itself is composed of two sets of data: the Gaussian filtered data shown on the right side of Figure 6 together with its corresponding mask. These two sets of data will be used in the signature correlation step.

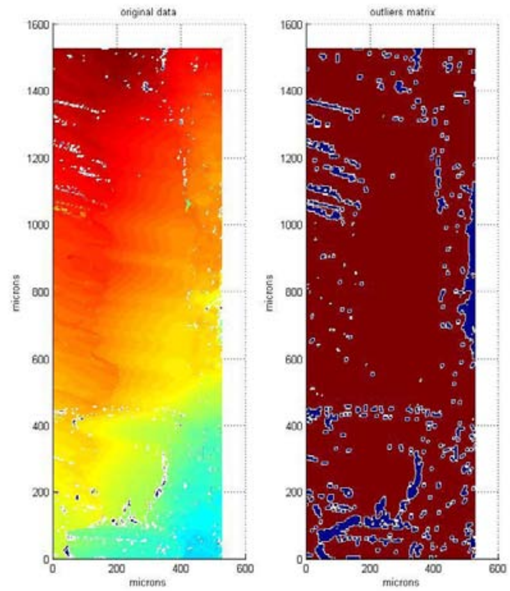

Figure 5: Data (left) and mask (right) of the region of interest at the completion of pre-processing (interpolation has not been applied to data)

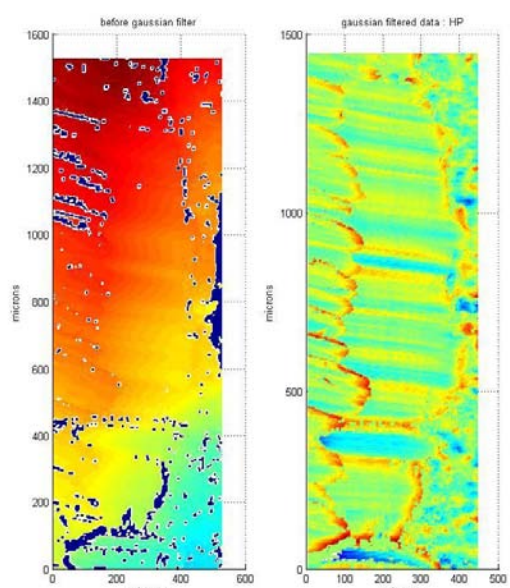

Figure 6: Data corresponding to region of interest (left) and after interpolation followed by Gaussian band pass filtering (right).

3.2.1.2.2 Signature Correlation

The signature correlation approach implemented

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in IAI's system is a 2D extension of the 1D statistical correlation coefficient computation. However, as mentioned earlier, the code developed by IAI is designed to ignore drop-outs and outliers by creating a mask together with the processed data. We can define the mask in the following manner: Given a data set $Z_{A,}$ we create a mask M_A defined as follows:

$$M_{\mathrm{A}}(i,j) = \begin{cases} 1, \text{if } (i,j) \text{ is not an outlier or dropout,} \\ 0, \text{if } (i,j) \text{ is an outlier or dropout.} \end{cases} \tag{1}$$

Further, we define $Z_A(i, j,\theta)$ and $M_A(i, j, \theta)$ as the rotated versions of Z_A and M_A respectively. Finally, we define the index set $I_A(\theta)$ as follows:

$$I_{\mathrm{A}}(\theta) = \{(i,j) \mid M_{\mathrm{A}}(i,j,\theta) = 1\}. \tag{2}$$

In other words, for a given rotation angle θ, $I_A(\theta)$ corresponds to the set of all the points on the data set $Z_A(i,j,\theta)$ that are considered valid (i.e. which are not drop-outs nor outliers). We can now define the Areal Cross Correlation Value (ACCV) between two samples A and B:

$$ACCV(\mathrm{A}, M_{\mathrm{A}}, \mathrm{B}, M_{\mathrm{B}}, \tau_x, \tau_y, \theta) = \frac{\sum_{(i,j)\in I_M} Z_{\mathrm{A}}(i,j)\, Z_{\mathrm{B}}(i-\tau_x, j-\tau_y, \theta)}{\left[\sum_{(i,j)\in I_M} (Z_{\mathrm{A}}(i,j))^2\right]^{1/2} \left[\sum_{(i,j)\in I_M} (Z_{\mathrm{B}}(i,j,\theta))^2\right]^{1/2}}, \tag{3}$$

where $I_M = I_{\mathrm{A}} \cap I_{\mathrm{B}}(\theta)$. All summations are computed only for those points that are valid (i.e., excluding drop-out or outlier points) for both Z_A and $Z_B(\theta)$. Notice that this function correlates only with respect to overlapping points. The set of overlapping points will vary due to the rotation of the data set Z_B, even if no drop-outs or outliers are present.

The *ACCV* defined in Eqn (3) is a function of τ_x, $\tau_{y,}$ and θ. In order to obtain a similarity measure between samples A and B we need to optimize with respect to τ_x, $\tau_{y,}$ and θ. The optimization of the right hand slide of Equation (3) with respect to τ_x, $\tau_{y,}$ and θ is performed in a sequential manner. The first step is to estimate the neighborhood of the optimal value of θ. Given a pair of data sets, we denote the optimal correlation value for a given relative orientation as:

$$\mathrm{corr}(\theta_i) = \max_{(\tau_x,\tau_y)\in I_\Delta} ACCF(\mathrm{A}, M_{\mathrm{A}}, \mathrm{B}, M_{\mathrm{B}}, \tau_x, \tau_y, \theta_i), \tag{4}$$

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where the index set I_Δ corresponds to the maximum lateral translations allowed, and is determined *a priori* in IAI's implementation as a percentage of the size of the tool mark. The estimate of the optimal τ_x, τ_y is computed using a frequency domain approach. As part of the first step of the optimization approach, low resolution versions of Z_A and Z_B are used to evaluate Eqn (4) at a discrete number of relative orientations defined by the set $I_\theta = \{-180, -175, \ldots 175\}$. The results of this evaluation are used to identify a neighborhood of the optimal θ. Once the neighborhood of optimal θ has been identified, the process is repeated within this neighborhood using full resolution versions of Z_A and Z_B. The peak correlation value, to be denoted as $ACCF_{max}$, is defined as:

$$ACCF_{max} = \max(\mathrm{corr}(\theta_i)), \forall\, \theta_i = I_{\theta 2}, \tag{5}$$

where the set $I_{\theta 2}$ corresponds to a set of angles within the neighborhood identified in the first step, and their resolution is 1 degree.

Figure 7 shows an example of the application of the signature correlation algorithm to a pair of matching tool marks. The left side of Figure 7 shows tool mark A (left side) and tool mark B (right side) together with the two tool marks optimally aligned (center). The plot to on the right of Figure 7 corresponds to $\mathrm{corr}(\theta_i)$. The similarity measure achieved in this comparison is 0.52.

Figure 8 shows an example of the application of the signature correlation algorithm to a pair of matching tool marks. Notice that tool mark A is the same as that used in the previous example. The similarity measure achieved in this instance is 0.26 (vs. 0.52 in the case of a matching pair).

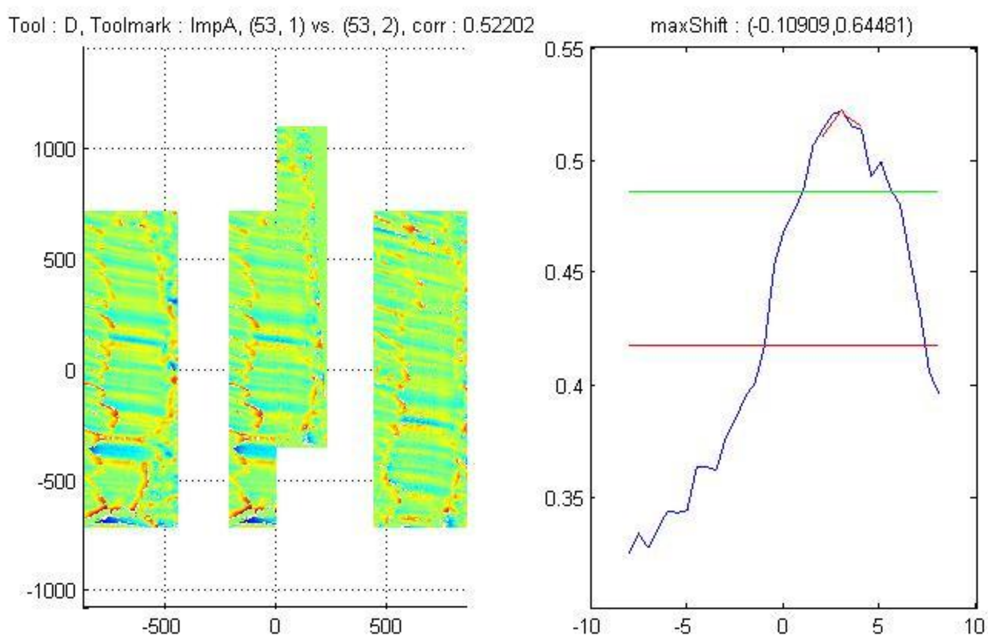

Figure 7: Similarity measure computation for pair of matching tool marks

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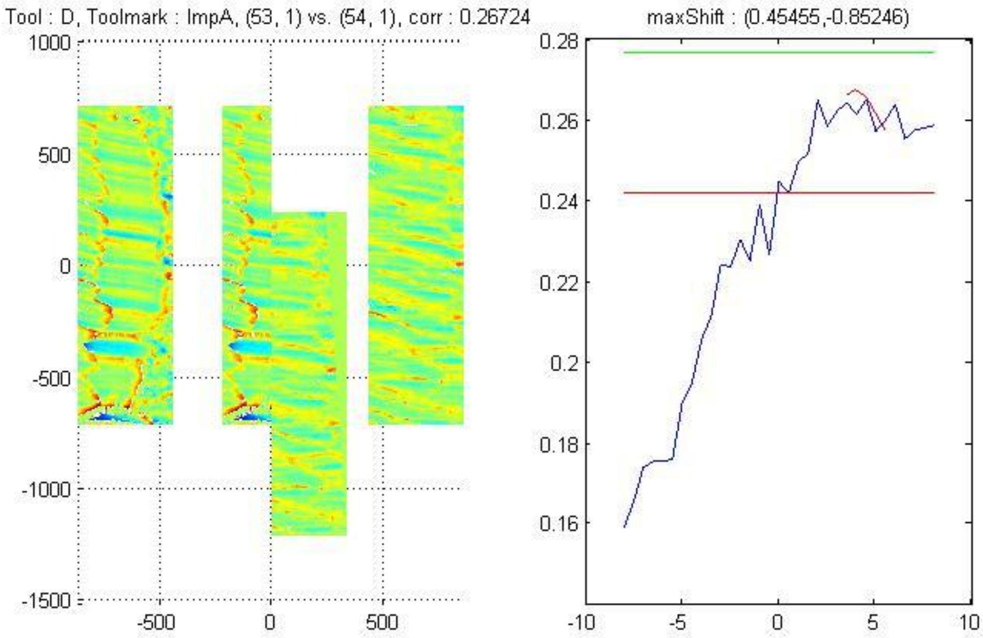

Figure 8: Similarity measure computation for pair of non-matching tool marks

As expected, the degree of similarity for a pair of non-matching tool marks is significantly lower than that obtained for a matching pair. Notice also the difference in the appearance of the plot $\text{corr}(\theta_i)$. The plot for the matching pair has a clear peak, while the plot for the non-matching pair does not have a clear peak. The shape of this plot by itself is a good indication of the similarity of the two tool marks under comparison, since the portions of this plot which do not correspond to a clear peak amount to the correlation that can be expected from the comparison of any non-matching pair.

3.2.1.2.3 Statistical Report Generation

Once all tool mark comparisons of interest are performed and all similarity measures are computed, the statistical data is summarized in a statistical report such as shown in Figure 9. The top plot of this report shows both the non-matching distribution (shown in blue) and the matching distribution (shown in red) for the tool marks under consideration. The report also includes the list of tools used in the creation of these distributions and the estimated probabilities of error if a hard threshold were to be used to decide between matching and non-matching pairs (a very commonly used hypothesis testing evaluation). In addition, considerable numerical data is included in tabular form, such as the number of matching and non-matching comparisons, their average, mean and standard deviation. Finally, this report includes all parameters associated with the pre-processing, signature generation and similarity measure calculation for the tool marks under consideration. This is done so as to guarantee that the results obtained in these computations can be reliably repeated, and as a verification tool to ensure that the comparisons are always performed under the same conditions.

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3.2.2 Sample Preparation

Figure 10 shows a photograph of the diagonal cutter used to create tool mark samples for the preliminary experiments. This diagonal cutter is manufactured by Cooper Tools (Crescent model # 542-7C). To facilitate the identification of the diagonal cutter, we marked the pair of diagonal cutter with a unique identifying number. Each side of the diagonal cutter blade was labeled using letters a, A, b, and B in a same manner for all tools, as shown in Figure 11 and Figure 12. The cutting point on the diagonal cutter blade was marked in the middle of the blade so that each tool mark was created carefully at the same position of the blade.

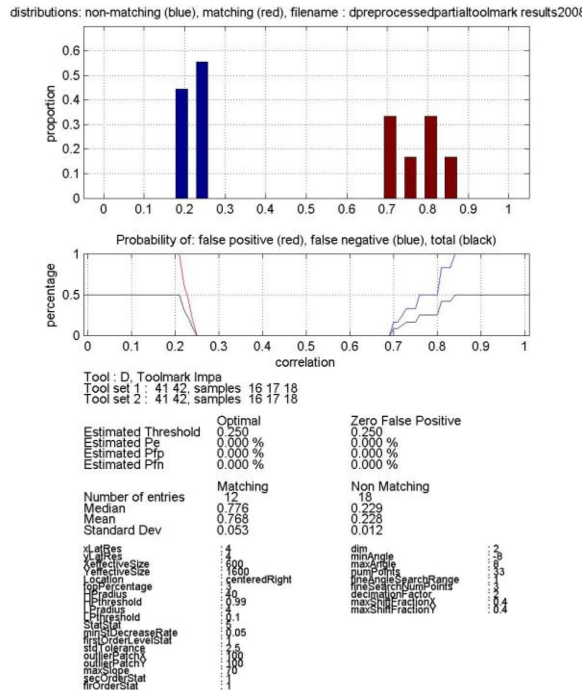

Figure 9: Example of statistical report associated with a given set of tool mark comparisons.

Based on the discussions with Mr. Paul Tangren, we selected copper wires as the media of interest for tool marks, since tool marks on copper wires are frequently found in crime scenes. For our purposes, a solid-core 12 gauge copper wire, obtained from the THHN 12-2 Romex cable, was used as the media of tool marks for all the experiments. The insulation layer of the copper wire was first removed before the tool mark was made. After the bared copper wire was straightened by hand, on one side of the copper wire, where the cut would be initiated, was marked. Subsequently, the copper wire was cut under the blade at the marked position, as shown in Figure 13. All the tool marks from diagonal cutters used in the first two phases of this study were created in such a fashion to address the changes on the tool mark due to wear and exposure. In Phase III on the other hand, we consider the more realistic case where the examiner does not know which portion of the blade is responsible for the tool mark. The detailed tools and tool marks preparation procedure followed as part of the study are included in Section 6 (Appendix A).

Figure 10: Diagonal Cutter

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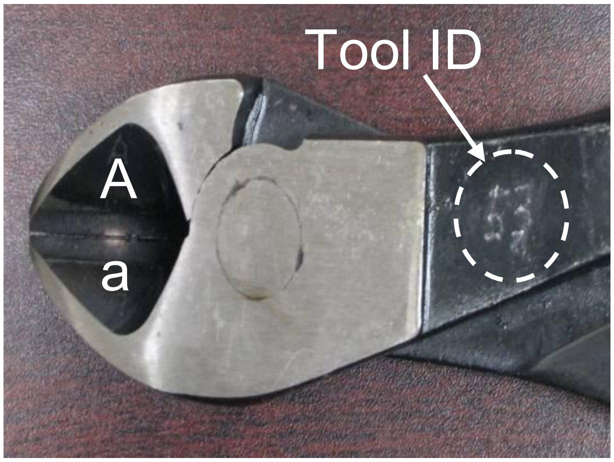

Figure 11: Picture of a tool with engraved Tool ID and blade label “A” and “a”.

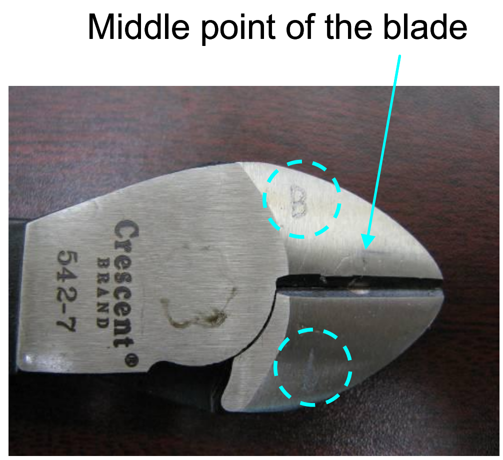

Figure 12: Picture of a tool with engraved label “B” and “b”, and the mark in the middle of the blade indicating the cutting point.

In order to simulate exposure to the environment, tool marks or tools were put into corresponding containers with salt water to mimic environment exposure. These containers were covered as shown in Figure 14 (not an air tight seal). We identified 3 concentrations of salt water for experiments of both tools and tool marks. The highest concentration is 3.5%, which is similar to that in sea water. The other two concentrations we chose are 1.75% and 0.88%, mimicking the water in any estuarine environment.

After a certain time of exposure in the salt water, the tools or tool marks were taken out. For tool marks exposure experiment, the tool marks were cleaned first by an ultrasonic cleaner before their topology images were acquired. Then they were put back into corresponding water for further exposure. For tool exposure experiment, the tools were also cleaned by the ultrasonic cleaner first. Following the cleaning, they were used to create new tool marks. Then they were put back into corresponding water for further exposure.

3.2.3 Preliminary Experiments

Having selected the tool, media, and exposure to use as part of our study, we conducted a small scale experiment to determine a reasonable time frame within which to sample the effect of tool

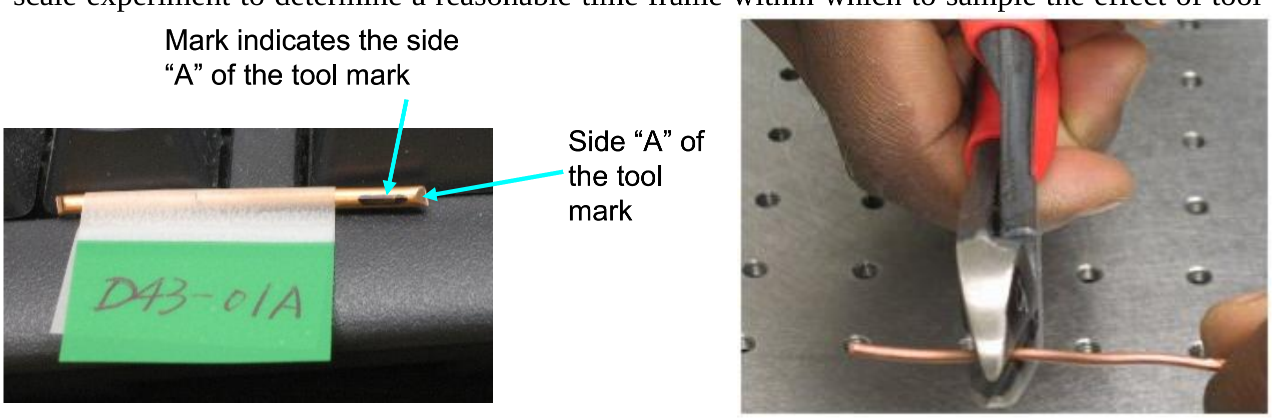

Figure 13: The copper wire media and the process of creating a tool mark from the diagonal cutter

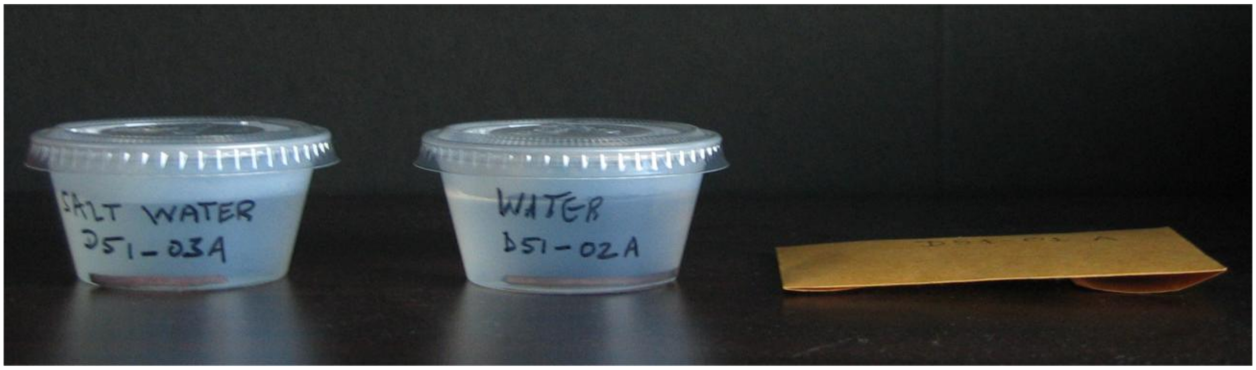

Figure 14: Environmental exposure of tool marks

and tool mark exposure. This experiment was carried out with three tool marks made from a selected diagonal cutter. As part of this small scale experiment, we have exposed a) one tool mark to concentrated salt water, b) one tool mark to normal water, c) one tool mark was not exposed, but kept in a coin envelope (see Figure 14).

Our exposure protocol for this small scale experiment was to expose the tool marks for periods of 3 weeks at a time, over a span of 19 weeks. At the end of every 3 week period, topographical data of these tool marks, exposed to the environment, were re-acquired and then the tool mark were reintroduced to the same environment in which it was exposed previously. The acquired data were stored appropriately for future analysis.

Figure 15 shows a side by side comparison of the tool marks at week 0 (no exposure) and week 14 for all three cases. The complete set of images for these three cased are shown in Section 7 (Appendix B). Based on simple visual comparison, it can be seen that the tool marks show slow degradation when they are exposed to air and tap water. In contrast, the tool marks exposed to salt water show dramatic change after the first three weeks exposure. While further exposure to the salt water deteriorates the tool mark further, the most dramatic changes seem to take place in the first 3 weeks.

To quantify the deterioration of tool marks exposed to environments, we computed the similarity measures between each pair of tools in each of the three data sets. The resulting similarity values computed are shown in Table 1.

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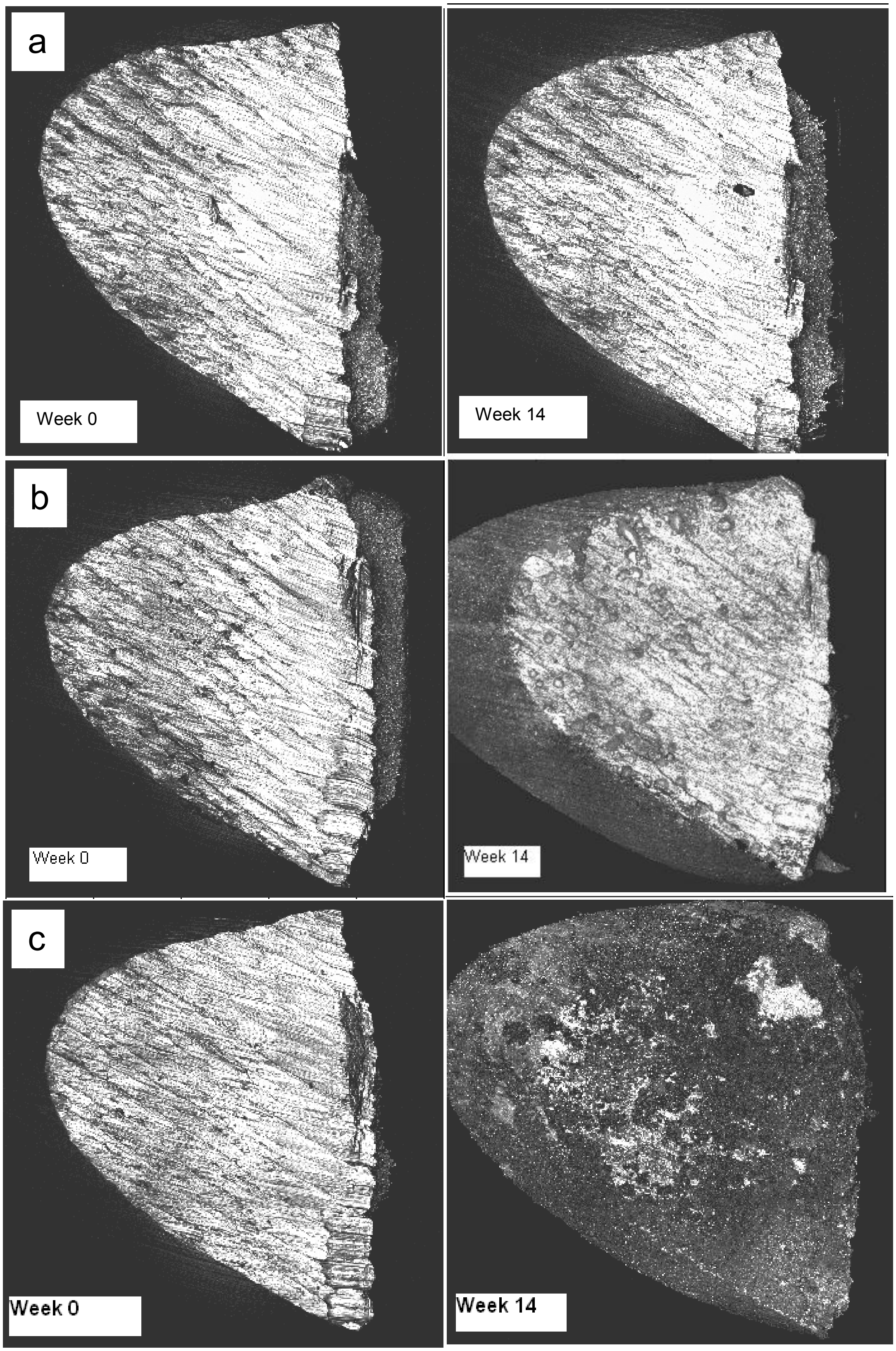

Figure 15. Comparison of topological images of toolmarks exposed to (a) air; (b) clean water; (c) salt water after week 0 (no exposure) and week 14

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Table 1. Similarity Measure among tool marks exposed to environments

Tool mark exposed to air						
TM 51 (11-16)	**Week 0**	**Week 3**	**Week 6**	**Week 9**	**Week 14**	**Week 19**
Week 0		0.978	0.969	0.965	0.936	0.914
Week 3	0.976		0.973	0.982	0.955	0.937
Week 6	0.971	0.972		0.97	0.945	0.938
Week 9	0.965	0.981	0.97		0.942	0.932
Week 14	0.936	0.953	0.943	0.94		0.969
Week 19	0.915	0.936	0.937	0.93	0.97	

Note: Correlation values for original tool mark (week 0) decrease as a function of time

Tool mark exposed to clear water						
TM 51 (21-26)	**Week 0**	**Week 3**	**Week 6**	**Week 9**	**Week 14**	**Week 19**
Week 0		0.818	0.766	0.723	0.716	0.669
Week 3	0.815		0.952	0.932	0.927	0.938
Week 6	0.762	0.956		0.944	0.943	0.948
Week 9	0.722	0.933	0.946		0.949	0.938
Week 14	0.716	0.93	0.941	0.946		0.922
Week 19	0.67	0.937	0.952	0.935	0.923	

Note: (1) Correlation values for original TM (week 0) decrease as a function of time; (2) Correlation values for all TM decrease as a function of time; (3) Lowest correlation values are observed when TM exposed to clear water are compared with the original TM

Tool mark exposed to air						
TM 51 (31-36)	**Week 0**	**Week 3**	**Week 6**	**Week 9**	**Week 14**	**Week 19**
Week 0		0.24	0.295	0.252	0.296	0.312
Week 3	0.241		0.84	0.799	0.188	0.218
Week 6	0.298	0.842		0.938	0.282	0.295
Week 9	0.253	0.796	0.941		0.277	0.277
Week 14	0.298	0.212	0.282	0.209		0.845
Week 19	0.289	0.248	0.252	0.227	0.8435	

Note: (1) Lowest correlation values observed when TMs exposed to salt water is compared with original TM (not exposed to water); (2) TM of week 4 gives low correlation values across all comparisons while correlation values for all other TMs decrease as a function of time

Figure 16 graphically summarizes the most relevant data from Table 1. Each plotted line in Figure 16 shows the similarity measure scores between the initial tool mark feature (at week 0, unexposed) and the one after certain week exposure to selected environments. The results in both Table 1 and Figure 16 agree with the visual observations as shown in Figure 15 and Appendix B.

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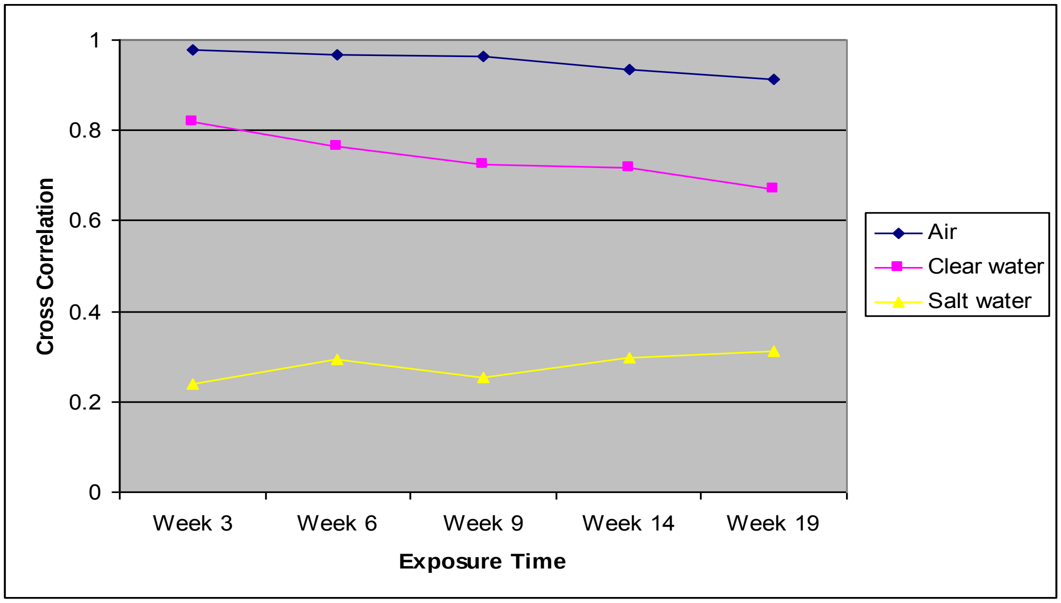

Figure 16: Similarity measure of exposed tool marks against their unexposed control.

The results of this preliminary experiment indicate that **the tool marks deteriorate very slowly in air and tap water, but dramatically in salt water**. These results validate our choice of salt water as an environmental exposure media of interest. It is because of these results that we chose 3 concentrations of salt water as environmental exposure for experiments of both tools and tool marks. The highest concentration used in this study is 3.5%, which is similar to that in the sea water. The other two concentrations used in this study are 1.75% and 0.88%, mimicking the water in the bay area.

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3.2.4 Experiment Procedures

3.2.4.1 Tool Wear Experiment Procedure

For the tool wear experiment, 3 tools were chosen (D53, D54 and D55). For tools D53 and D54, we collected samples of the first 5 cuts (cuts 1 through 5). After skipping the following 95 cuts, we collected samples of the 101^{st} to 105^{th} tool cut (cut 101 through 105). Similarly, we collected samples of cuts 201^{st} to 205^{th}, and 301^{st} to 305^{th}. For tool D55, we collected the first 20 tool marks. The reason for this distinction is that we wanted to use tools D53 and D54 to study the long terms effects of tool wear, while we selected D55 to study the short term effects of tool wear. Table 2 lists the experiment plan for tools D53, and D55. The experiment plan of tool D54 is similar to that of D53. The complete experiment plan for tool wear experiment is listed in Section 8.1 (Appendix C.1).

Table 2. Tool wear experiment plan

Tool Wear				
Tool ID	**Tool Wear**	**Tool Mark ID**	**Image Date File Name**	**Note**
D53	0	D53-01 ~ D53-05	D053-P001 Impa ~ D053-P005 Impa	The exact first 5 tool marks were discarded. Tool mark ID counting started from the 6^{th} tool mark
	100 cuts	D53-06 ~ D53-10	D053-P006 Impa ~ D053-P010 Impa	
	200 cuts	D53-11 ~ D53-15	D053-P011 Impa ~ D053-P015 Impa	
	300 cuts	D53-16 ~ D53-20	D053-P016 Impa ~ D053-P020 Impa	
D55	0	D55-01 ~ D55-20	D055-P001 Impa ~ D055-P020 Impa	D55-01 is exactly the first tool mark generated by D55

3.2.4.2 Tool Mark Exposure Experiment Procedure

For the tool mark exposure study, 3 tools (D41-D43) were selected. 5 control tool mark samples were made in sequence from every tool. 5 additional tool mark samples were made in sequence from every tool for each concentration of salt water under consideration. The exposure sampling period for each tool mark was 2 weeks (i.e. each tool mark was re-acquired at two week intervals of exposure). The process was stopped after 6 weeks because the experimental results showed a clear trend. Table 3 lists the experiment plan for tool D41 (which was identical to that of D42 and D43). The complete tool mark exposure experiment plan for all the three tools are listed in Section 8.2 (Appendix C.2).

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Table 3. Tool mark exposure experiment plan for tool D41

Tool Mark Exposure Experiment							
				Image Data File Name			
Tool ID	Tool Mark ID	Notes	Container (Salinity)	0 week	2 week	4 week	6 week
D41	D41-01 ~ D41-05	Control		D041-P001 Impa ~ D041-P005 Impa			
	D41-06 ~ D41-10	Evidence	C1 (3.5%)	D041-P006 Impa ~ D041-P010 Impa	D041-P021 Impa ~ D041-P025 Impa	D041-P036 Impa ~ D041-P040 Impa	D041-P051 Impa ~ D041-P055 Impa
	D41-11 ~ D41-15	Evidence	C2 (1.75%)	D041-P011 Impa ~ D041-P015 Impa	D041-P026 Impa ~ D041-P030 Impa	D041-P041 Impa ~ D041-P045 Impa	D041-P056 Impa ~ D041-P060 Impa
	D41-16 ~ D41-20	Evidence	C3 (0.875%)	D041-P016 Impa ~ D041-P020 Impa	D041-P031 Impa ~ D041-P035 Impa	D041-P046 Impa ~ D041-P050 Impa	D041-P061 Impa ~ D041-P065 Impa

As shown in Table 3, twenty tool marks were created by tool D41 when it was a totally new tool. They were labeled sequentially as D41-01 to D41-20. Every 5 tool marks were grouped as a set. The first set is the “control” set, and the next three sets were the “evidence” sets. After all the 4 tool mark sets were acquired, the three evidence sets were exposed to corresponding salt concentration for 2 weeks, 4 weeks and 6 weeks. Data acquisition was accomplished after each exposure period. Therefore, for D41, 20 tool marks were created, but a total of 65 tool mark images were acquired after 6 weeks exposure. We carried the same experiment procedure with tool D42 and D43.

3.2.4.3 Tool Exposure Experiment Procedure

For the tool exposure experiment, we selected tools D44 to D52. We allocated 3 tools for each of the three salt concentrations (for a total of 9 tools). For concentration 3.5%, we selected tools D44, D45 and D46, as listed in Table 4. 5 tool marks were created by each tool before initiating exposure (week 0). A new set of 5 tool marks was created by each tool after 2 weeks of exposure. This process was repeated every two weeks. The process was stopped after 6 weeks because the experimental results showed a clear trend. After 6 weeks, we obtained total 20 tool mark samples for each tool, and 60 for 3 tools from the same concentration. Similarly, tools D47-D49 were used for concentration 1.75%, and tools D50-D52 for concentration 0.88%. Table 4 shows the tool exposure experiment plan for 3.5% concentration. The complete experiment plan for tool exposure experiment is listed in Section 8.3 (Appendix C.3).

Table 4. Tool exposure experiment plan for 3.5% concentration

Tool Exposure				
Container (Salinity)	Tool ID	Tool Exposure Period	Tool Mark ID	Image Data File Name
C1 (3.5%)	**D44**	0	D44-01 ~ D44-05	D044-P001 Impa ~ D044-P005 Impa
		2 weeks	D44-06 ~ D44-10	D044-P006 Impa ~ D044-P010 Impa
		4 weeks	D44-11 ~ D44-15	D044-P011 Impa ~ D044-P015 Impa

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		6 weeks	D44-16 ~ D44-20	D044-P016 Impa ~ D044-P020 Impa
	D45	0	D45-01 ~ D45-05	D045-P001 Impa ~ D045-P005 Impa
		2 weeks	D45-06 ~ D45-10	D045-P006 Impa ~ D045-P010 Impa
		4 weeks	D45-11 ~ D45-15	D045-P011 Impa ~ D045-P015 Impa
		6 weeks	D45-16 ~ D45-20	D045-P016 Impa ~ D045-P020 Impa
	D46	0	D46-01 ~ D46-05	D046-P001 Impa ~ D046-P005 Impa
		2 weeks	D46-06 ~ D46-10	D046-P006 Impa ~ D046-P010 Impa
		4 weeks	D46-11 ~ D46-15	D046-P011 Impa ~ D046-P015 Impa
		6 weeks	D46-16 ~ D46-20	D046-P016 Impa ~ D046-P020 Impa

3.2.4.4 Partial Tool Mark Experiment Procedure

For the partial tool mark experiment, we decided to stray slightly from the original proposal. Given that the tool selected for this study is a diagonal cutter and the media under consideration copper wire, we are in fact from the outset looking at a partial tool mark! Taking a portion of this partial tool mark to create yet an even more partial tool mark did not seem like a practical or meaningful topic of study. On the other hand, the comparison of the tool marks found on a copper wire to those created on a sheet of copper do answer a much more meaningful question: **Is it possible to identify a tool mark created on copper wire by comparing it to a tool mark created on a copper sheet?** If so, whenever an evidence tool mark corresponding to a diagonal cut on a piece of wire is found in a crime scene it would be possible to create a single control tool mark by making a cut on a copper sheet (as opposed to making a variety of cuts on wire).

Based on these considerations, we performed the partial tool mark experiment as follows: We selected tools D41 and D42 (for which tool marks were created in copper wire as part of the tool mark exposure experiment) and created new, relatively large tool marks on a copper sheet as shown in Figure 17. These tool marks were compared among themselves, and also against their copper wire counterparts. The comparison of these tool marks can be better appreciated by looking at Figure 18. The left column of Figure 18 shows three too marks created on copper wire by tool D41, while the right column shows a single tool mark created by the same tool on a copper sheet (the images are not exactly to scale). The question under consideration is whether the tool marks created on the copper sheet will match those created on the copper wire. This is not necessarily so, since the action of the tool blade while cutting through a sheet of metal is not the same as when cutting through a wire.

Figure 17: Tool mark on copper sheet

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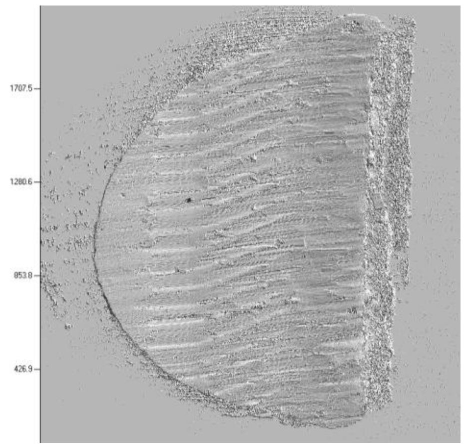
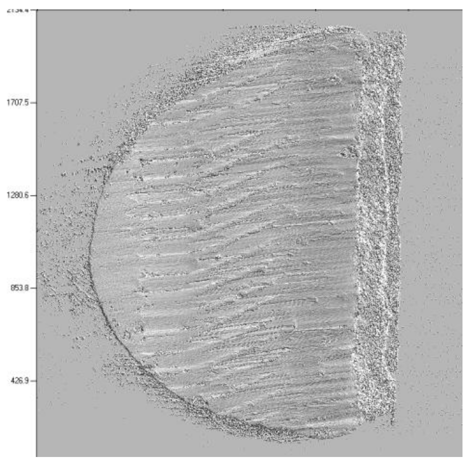
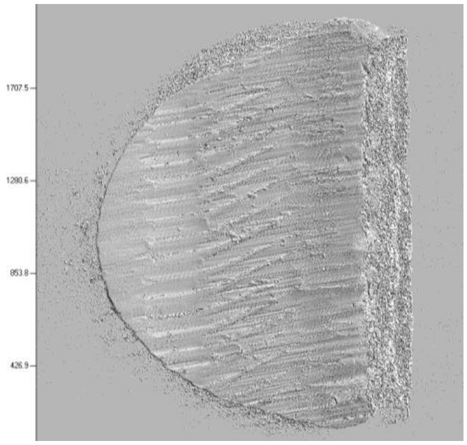


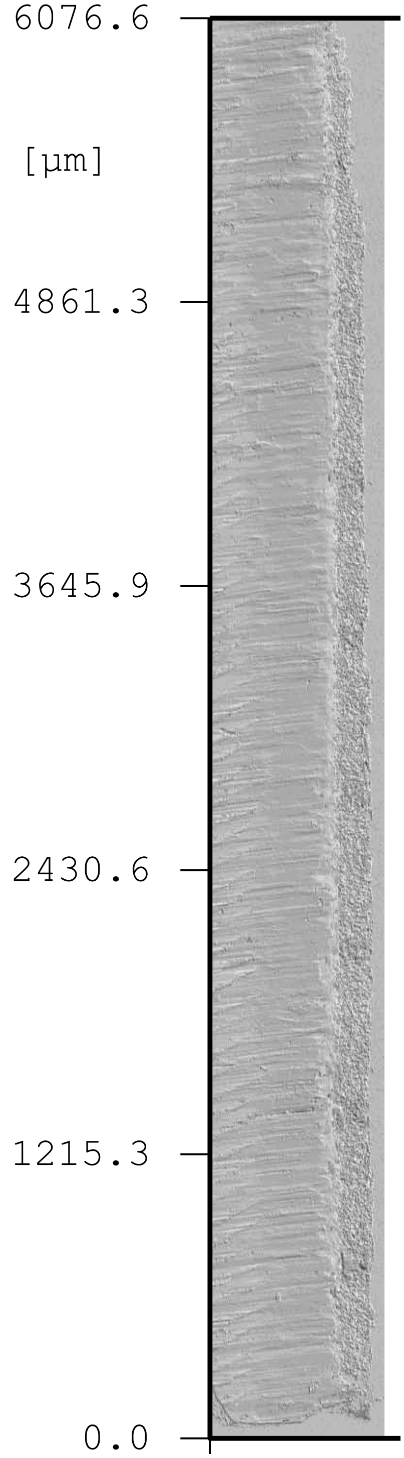
D41-16



D41-17



D41-18



D41-103

Figure 18: Comparison of copper wire and copper sheet tool marks

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3.3 Experimental Results

3.3.1 Effect of Tool Wear

3.3.1.1 Long Term Tool Wear Effect

The first question of interest is following: What is the effect of the repeated use (wear) of the tool on the tool marks created by it? A visual comparison of the topological images of the 1st, 101st, 201st and 301st tool marks created by D53 are shown side by side in Figure 19.

A visual inspection of these four images does not shed much evidence of wear in tool D53. All these tool marks appear to be very similar to each other. One thing caught our eyes is the different features shown in the 201st tool mark image. The part that is indicated with a rectangle in the 201st tool mark image is noticeably different from that in the others. The reason of this discrepancy is that while every effort was made to create the tool marks with the same portion of the blade, in some instances this was not the case. Although we marked on each tool blade the cutting point before we created any tool marks, and then the copper wire was aligned with the mark on the tool blade to create a tool mark, this alignment process is conducted visually. A 0.5mm misalignment would not be unreasonable. The size of the tool marks is on the order of just 2mm x 2mm. Therefore, it is inevitable that the cutting positions on the blade may shift from tool mark to tool mark. From Figure 19 we can tell, for the 201st tool mark, it used a higher portion of the tool blade than the other tool marks.

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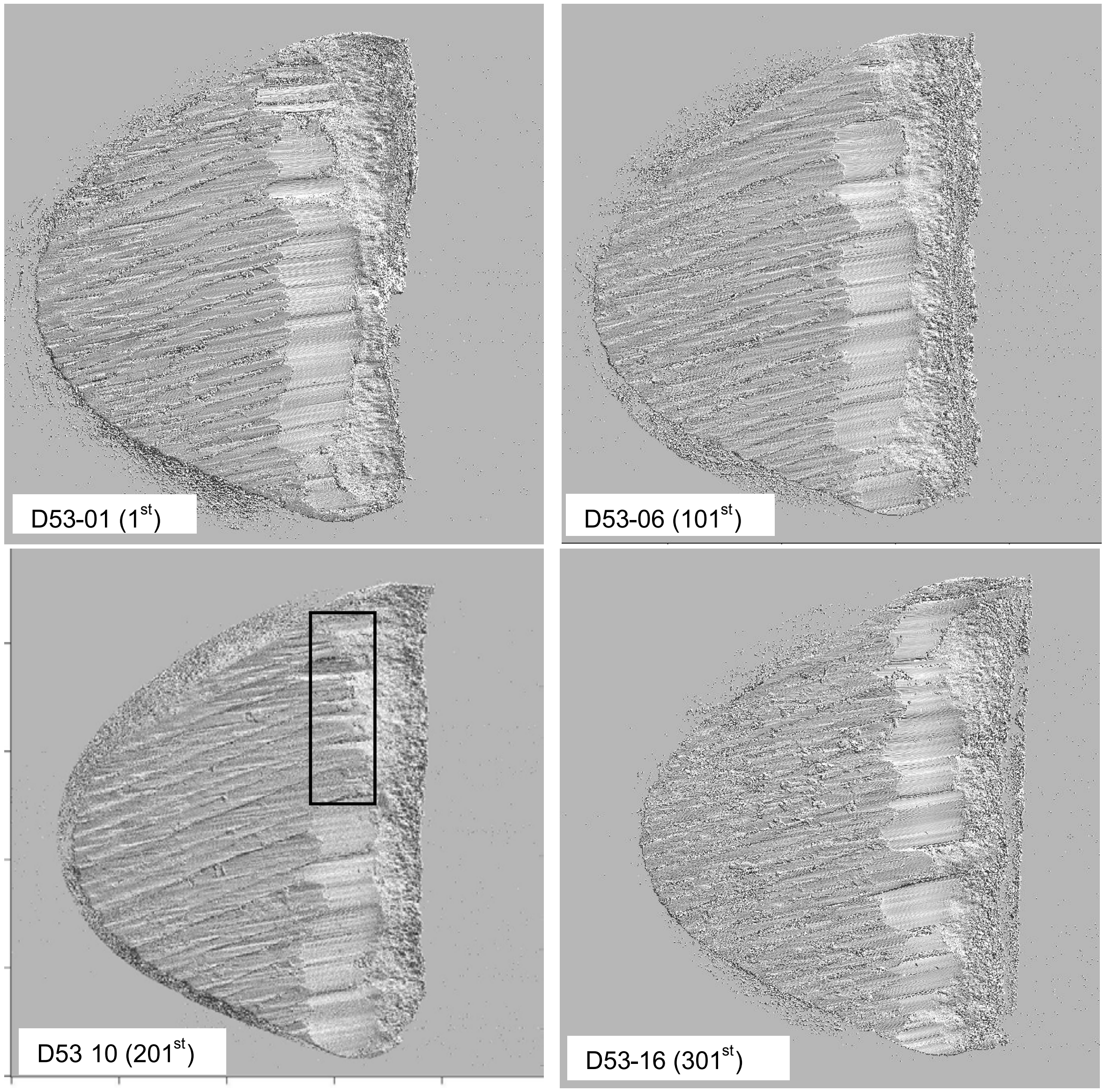

Figure 19: Topological images of tool marks No. 1, No 101, No 201 and No 301 created by tool D53

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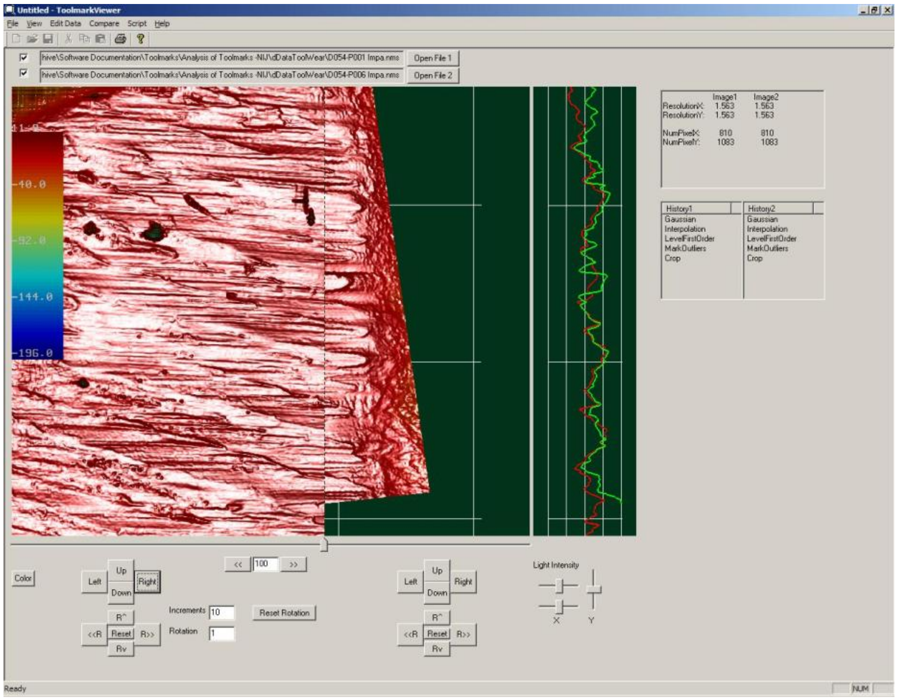

Figure 20. Visual comparison between 1st and 101st tool marks created by tool D53 using IAI's virtual comparison microscope

A visual comparison of these tool marks using Intelligent Automation Inc.'s virtual comparison microscope also reveals only minor change between the tool marks as a result of tool wear. Figure 20 shows an example of the comparison between the 1st and the 101st tool marks. **It can be seen that these two tool marks display considerable similarity, and would have been identified as originating from the same tool without difficulty**.

Figure 21 shows the distribution of the similarity measure resulting from the automated comparison of the tool marks created by tool D54. The distribution at the top of the figure corresponds to the comparison of the first set of tool marks (1st through 5th); while the distribution in the middle corresponds to the second set of tool marks (101st through 105th). The distribution at the bottom of the figure shows the comparison between the first set and the second set. The results in Figure 21 show high correlations among the "near" samples, such as 1st through 5th and 101st through 105th. While the degree of similarity resulting from the comparison of the first set with the second set is still quite high, there is a noticeable decrease in the average similarity value. **These results indicate that even while not immediately visible to the eye in Figure 19 and Figure 20, wear does have an effect on the features of the tool mark**. It is worth mentioning that the effect due to wear over 100 cuts (as in this instance) would have not precluded an examiner from making a correct identification (as can be seen in Figure 20).

An important point to keep in mind is that the diagonal cutters used to create the tool marks in this experiment were brand new. The sharp blades may be dulled quickly at the beginning, but the wear may be slowed down, or "settled", after a certain number of cuts. To explore the long term effect of tool wear on tool mark identification, we extended the experiment up to 300 cuts for both D53 and D54.

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Table 5 shows the manner in which the statistical results of the comparisons of different tool marks created by D53 and D54 were summarized for analysis. The table on the upper-left side of Table 5 summarizes the comparison of tool marks created by D41 against each other. This corresponds to a comparison of "matching" tool marks, since they were all created by tool D53. In a similar fashion, the table on the lower-right side shows the same results for tool marks created by tool D54. The table on the upper-right side in Table 5 corresponds to the comparison of tool marks created by D53 against tool marks created by D54, and is therefore a comparison of "non-matching" tool marks.

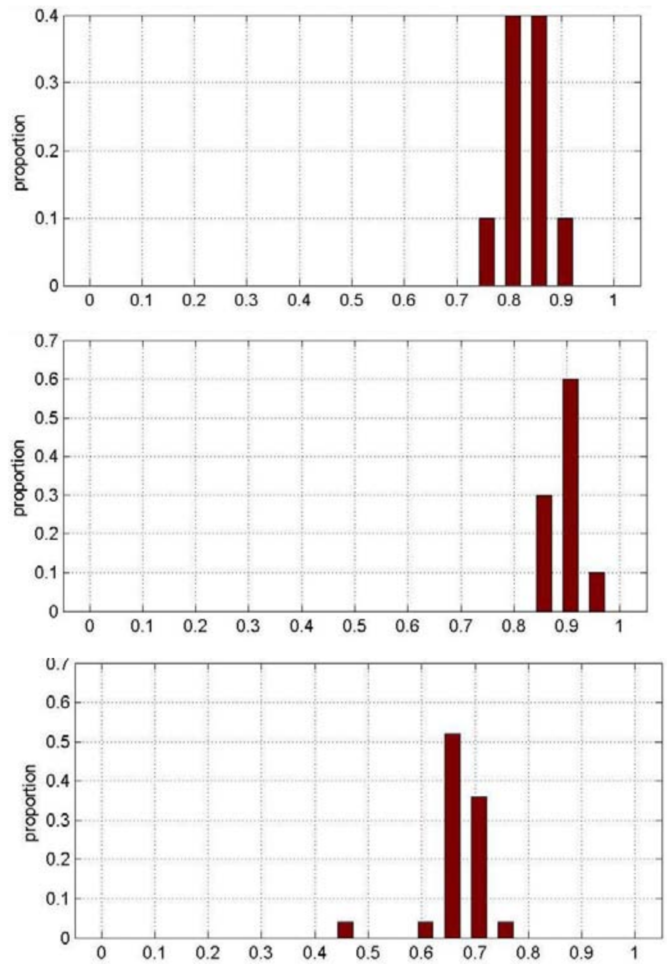

Figure 21: Comparison of the similarity measure distributions resulting from the comparison of tools 1st through 5th (top), 101st through 105th (middle) and 1st through 5th vs. 101st to 105th (bottom)

While the upper-left portion of Table 5 includes comparison of tool marks created by D53 against themselves, the tool marks involved in these comparisons are organized in groups of 5 tool marks according to the conditions under which they were created. For example, in the case of the tool wear study, the first group corresponds to the tool mark created with the new tool labeled (1-5), tool marks created after the tool has made 100 cuts (6-10), tool marks created after the tool made 200 cuts (11-15), and tool marks created after the tool has made 300 cuts (16-20). These groups of tool marks can be compared among themselves (we refer to such comparison as an "intra-group" comparison) or against a different group of tool marks (we refer to such comparison as an "inter-group" comparison). Therefore, the results corresponding to intra-group comparisons will be found in the diagonal of the table (shown grayed out), while the results of inter-group comparisons will be found on the upper right of the table. Our statistical data analysis of environmental effects on the tool mark identification reported in following sections will be based on these intra-group and inter-group comparisons.

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Table 5. Cross correlation among tool marks from D53 and D54 in tool wear experiment

53			53: 1-5 (0)	6-10 (100)	11-15 (200)	16-20 (300)
53	1-5 (0)	median	0.791	0.650	0.665	0.533
		mean	0.801	0.635	0.634	0.527
		std	0.040	0.080	0.101	0.045
	6-10 (100)	median		0.736	0.745	0.535
		mean		0.695	0.716	0.532
		std		0.126	0.117	0.060
	11-15 (200)	median			0.769	0.555
		mean			0.747	0.530
		std			0.059	0.071
	16-20 (300)	median				0.834
		mean				0.822
		std				0.027

53			54: 1-5 (0)	6-10 (100)	11-15 (200)	16-20 (300)
53	1-5 (0)	median	0.337	0.329	0.344	0.327
		mean	0.335	0.331	0.340	0.336
		std	0.032	0.027	0.034	0.033
	6-10 (100)	median		0.372	0.356	0.367
		mean		0.374	0.370	0.371
		std		0.029	0.051	0.042
	11-15 (200)	median			0.357	0.349
		mean			0.352	0.354
		std			0.027	0.024
	16-20 (300)	median				0.335
		mean				0.338
		std				0.038

54			54: 1-5 (0w)	6-10 (100)	11-15 (200)	16-20 (300)
54	1-5 (0)	median	0.826	0.666	0.658	0.656
		mean	0.829	0.658	0.668	0.634
		std	0.041	0.060	0.064	0.062
	6-10 (100)	median		0.899	0.812	0.660
		mean		0.891	0.813	0.629
		std		0.028	0.034	0.136
	11-15 (200)	median			0.894	0.789
		mean			0.879	0.738
		std			0.031	0.127
	16-20 (300)	median				0.809
		mean				0.830
		std				0.060

The data shown in Table 5 is difficult to analyze without some graphical representation. Figure 22 summarizes in a graphical manner the result of the intra-group comparison for both tools D53 and D53 (the data used to generate these plots corresponds to the shaded entries of Table 5). The upper two lines in Figure 22 correspond to the statistical distribution for the matching cases. These plots show the similarity within the same set of tool marks from the same tool is very high and fairly stable. It does not change as the tool wears out. This makes sense because the five tool marks were created in sequence – and tool wear is an accumulating process that is only observable after certain amount of cuttings. By contrast, the lower line in Figure 22 shows the low similarity measure among tool marks from different tools (non-matching).

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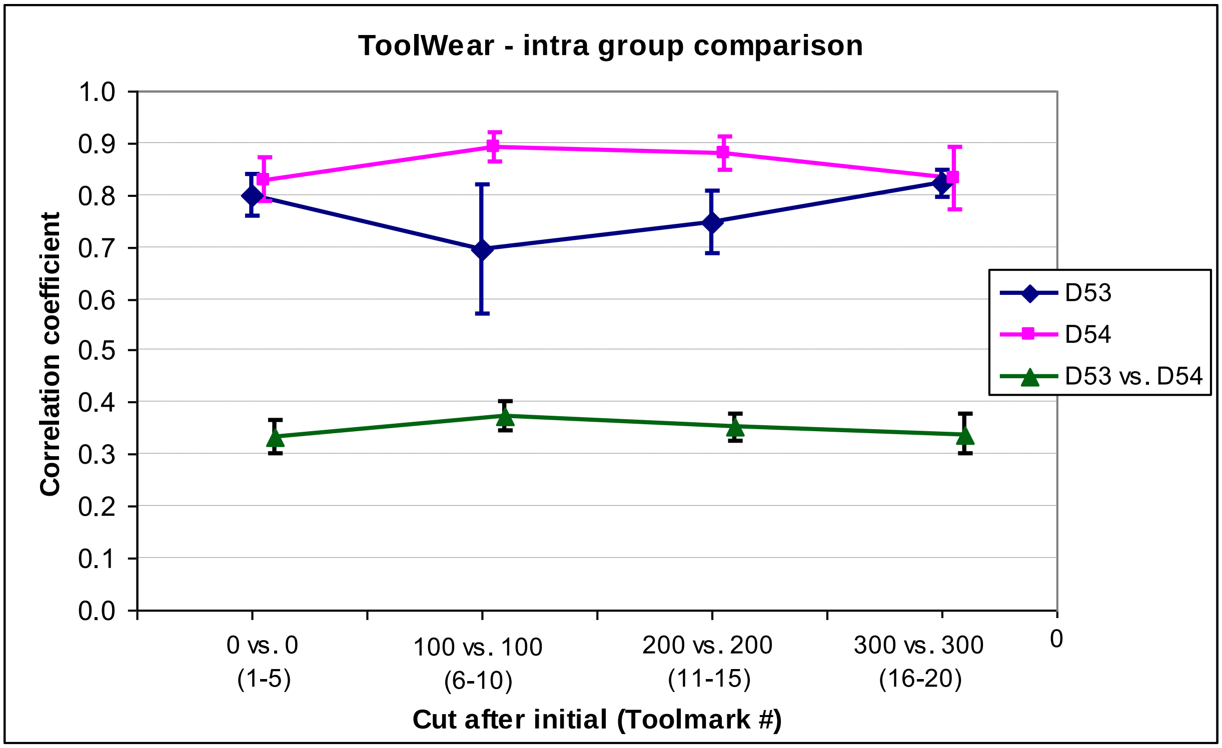

Figure 22. Tool wear intra-group comparison (D53, D54)

Figure 23 shows the inter-group comparison of the first set of tools (after 0 cuts) against themselves, the second (after 100 cuts), third (after 200 cuts) and fourth (after 300 cuts) sets for each of D53 and D54. One can see that the similarity measure resulting from these comparisons decreases proportionally to the wear of the tool, indicating that tool wear does result in measurable changes on the tool marks. However, even after 300 cuts the matching distributions are still significantly separate from the non-matching comparison, as can be seen by comparing against the non-matching distribution shown in the lower line in Figure 23. Not surprisingly, the non-matching distributions are insensitive to tool wear.

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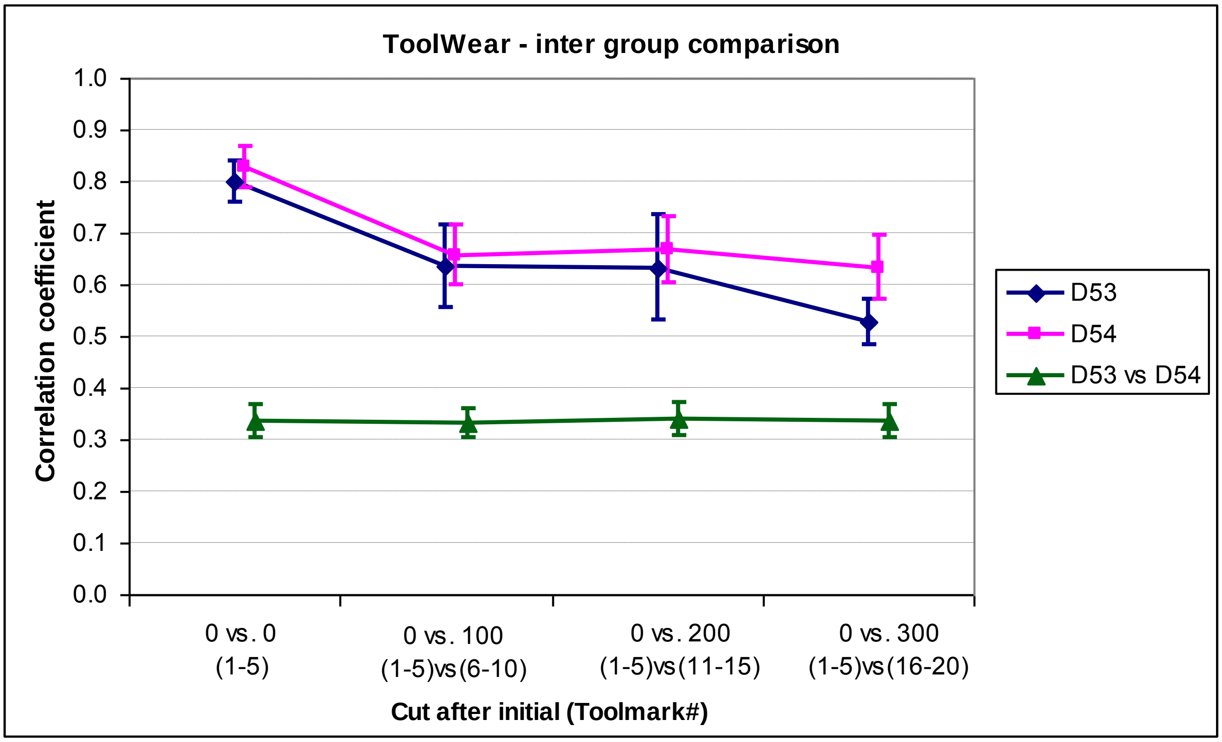

Figure 23. Tool wear inter-group comparison (D53, D54)

3.3.1.2 Initial Tool Wear Effect

The results in Figure 23 suggest that the most significant change of tool blade (and consequently of the similarity measure of tool marks) takes place within the first 100 cuts. Given that the tool wear experiments were conducted with new tools, and under the assumption that the tool blades were sharp when new, it is logical to assume that the blade sharpness decreases more rapidly as the tool is used, and then in a slower manner after it dulls out. We believe that the fine features in a sharp tool are more likely to wear out than the coarse features found in a dull tool. To test this hypothesis and determine how quickly these changes take place, we added a new diagonal cutter (tool D55) to our study and created 20 new tool marks. The images of the first three tool marks (1^{st} – 3^{rd}) and the 10^{th} tool mark created by tool D55 shown in Figure 24. The complete first 10 images from tool D55 are shown in Section 9.1 (Appendix D.1).

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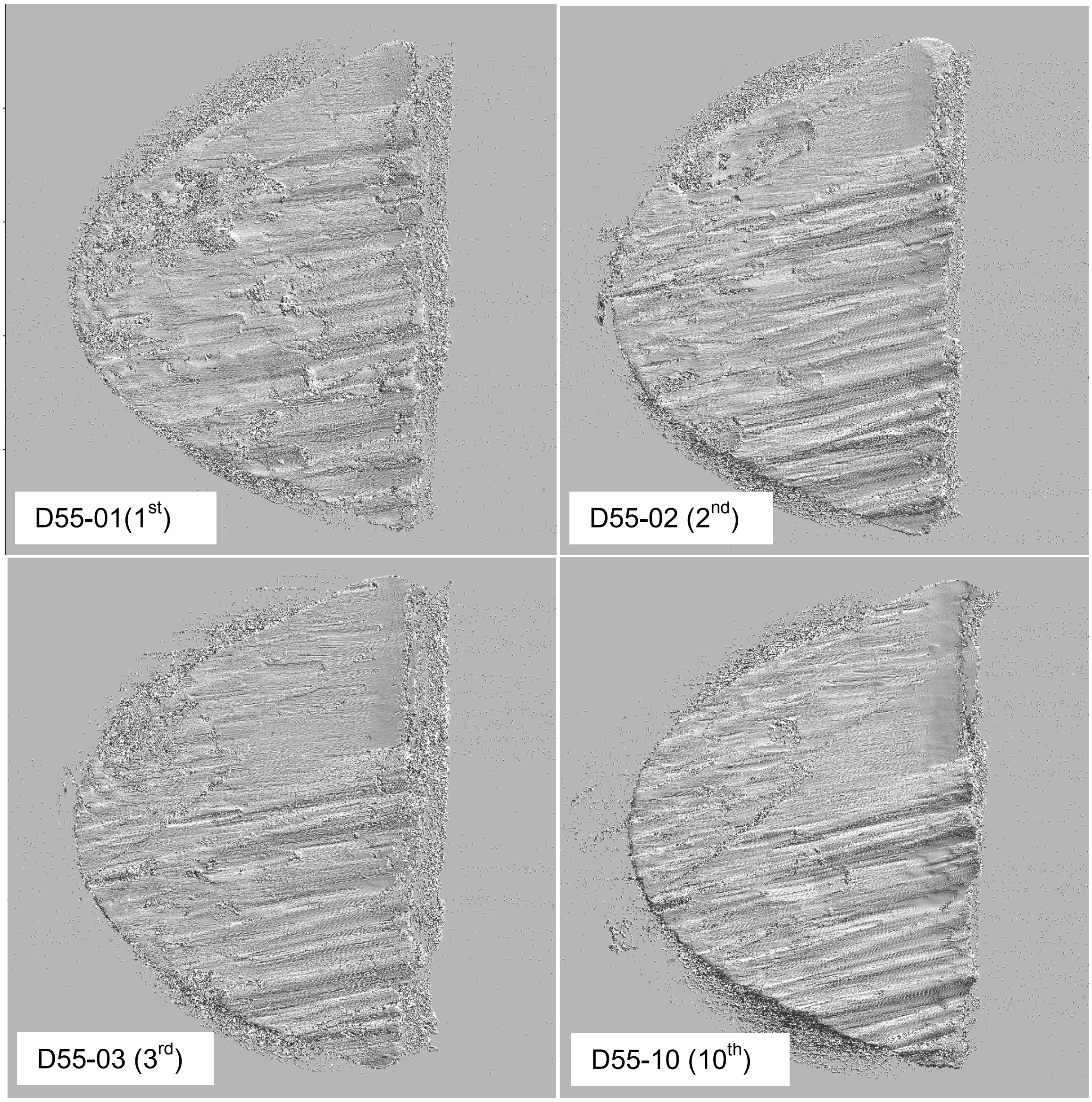

Figure 24: Comparison of topological images of 1st-3th and 10th tool marks from D55

To quantitatively study the trend of tool wear, we calculated the similarity measure between the 1st tool mark against the following 19 tool marks, as well as the 20th versus the preceding 19 tool marks. The results are shown in Figure 25 and Figure 26. Even though there are variations in the similarity values among the first 20 tool marks in both figures, a trend of decline in Figure 25 and a trend of climbing in Figure 26 can be observed. In other words, as the tool is used more and more, the tool marks are less and less similar to the 1st tool mark and more and more similar to the 20th tool mark.

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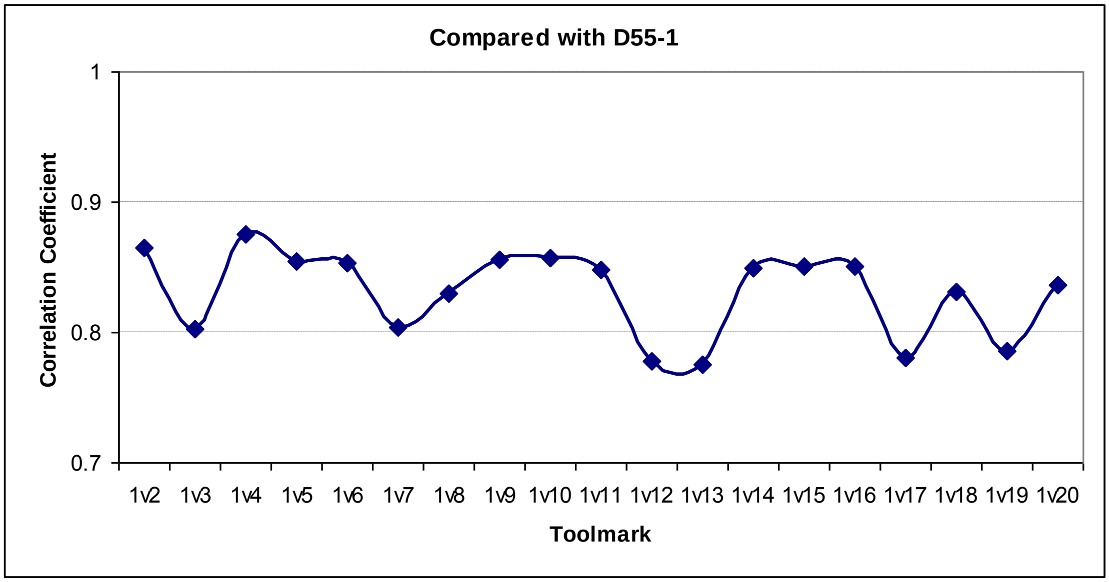

Figure 25. Wear effect on tool mark comparison within the first 20 cuttings of tool D55 (compared with the 1st tool mark)

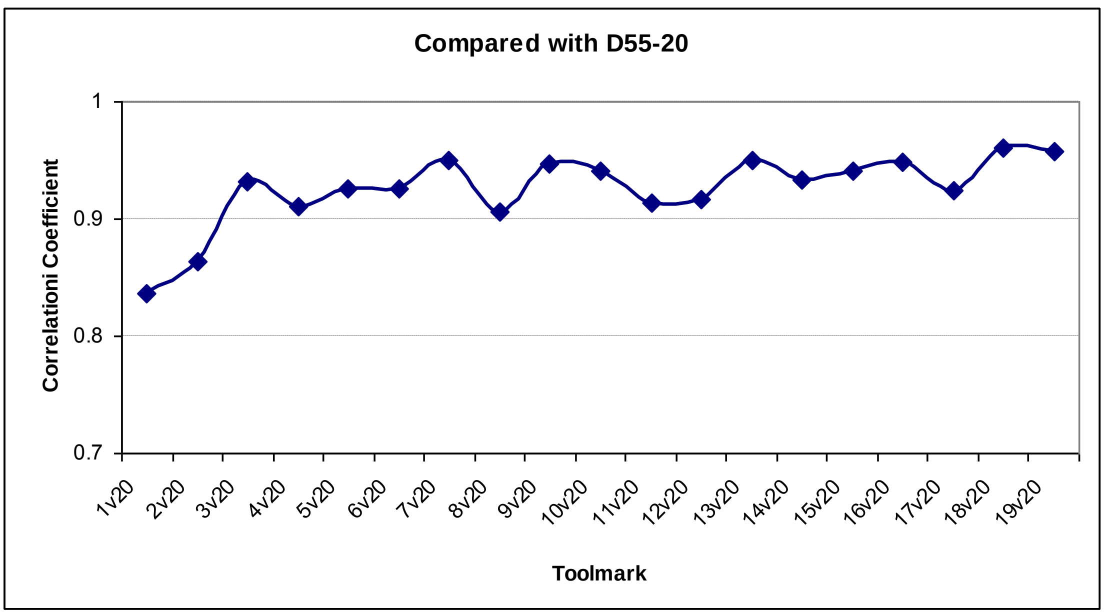

Figure 26. Wear effect on tool mark comparison within the first 20 cuttings of tool D55 (compared with the 20th tool mark)

Figure 27 shows the result of comparing every two consecutive tool marks within the first 20 tool marks from D55. It can be seen that the similarity measure between 1st and 2nd, and 2nd and 3rd cuts is quite lower for the other pairs. But after the 3rd tool mark, the curve stabilizes and remains more or less constant. This result shows that for tool D55 the majority of the wear effect took place within the first few cuts (**within the first two or three cuts**).

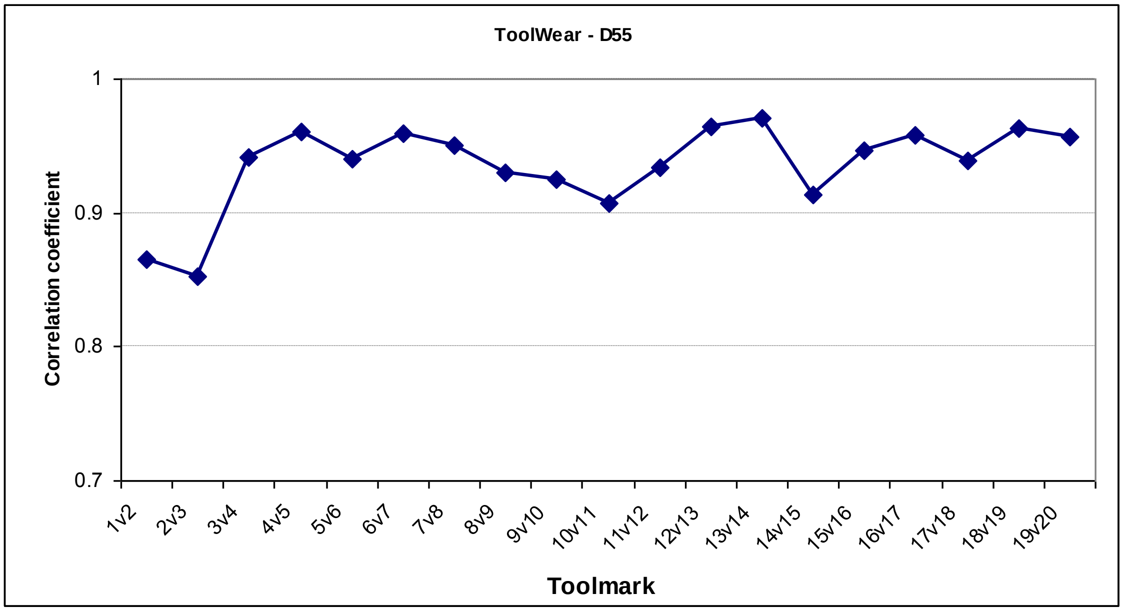

Figure 27. Wear effect on tool mark comparison within the first 20 cuttings of tool D55 (Compare every two consecutive tool marks)

In order to extend our set of data for the initial tool wear study, we also used data from the tool mark exposure experiment. As the reader may recall, in tool mark exposure experiment, 20 tool marks were created with each of the new tools D41, D42 and D43. Therefore, the first 20 tool marks from each of these three tools can be analyzed in the same manner as in the case of D55. The results of the intra-group comparison are shown in Figure 28 and the results of inter group comparison are shown in Figure 29.

From Figure 28, one can see that for D55, the similarity measure within the first set (1-5) is lower than within the other sets. This is consistent with our previous discussion regarding the variation of the tool marks due to the initial wear of the tool. However, judging by the results obtained with tools D41, D42 and D43 it would seem that the behavior of tool D55 is less than typical. Compared with the results of tools D41, D42 and D43, the similarity measures attained by tool D55 are significantly higher, show lower standard deviation, and display a consistent trend. The curves of D43 in both Figure 28 and Figure 29 have greater fluctuation at the second data point.

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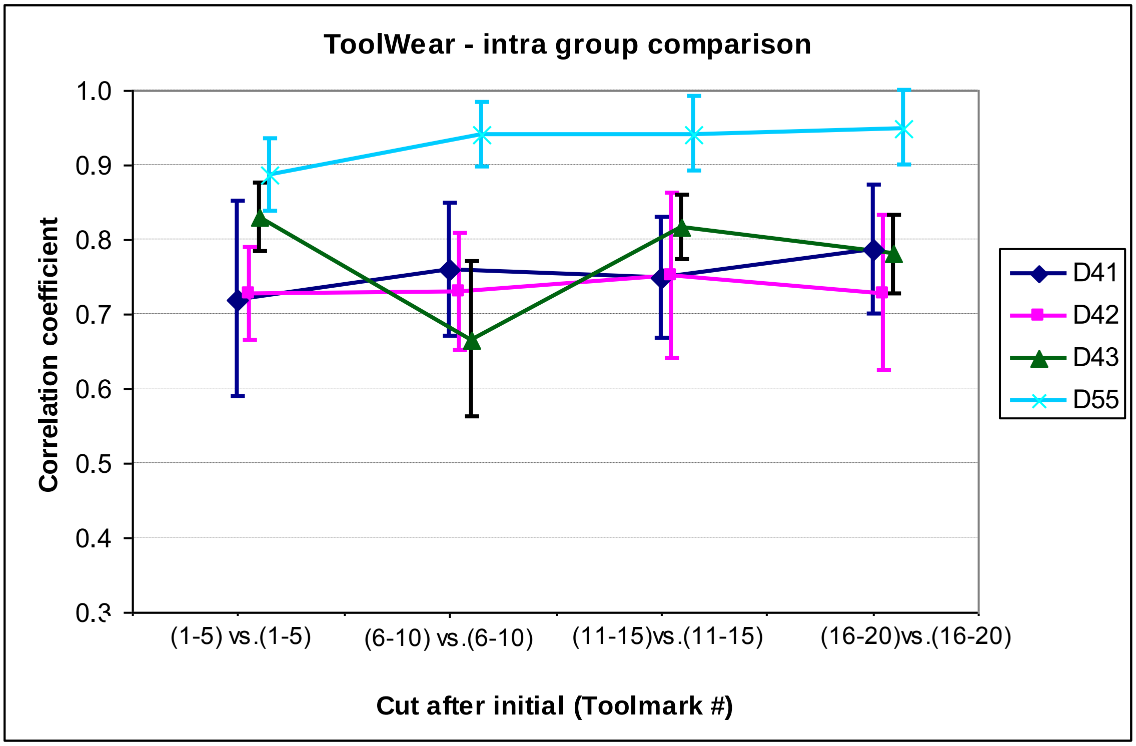

Figure 28. Tool wear intra group comparison (D55, D41-D43)

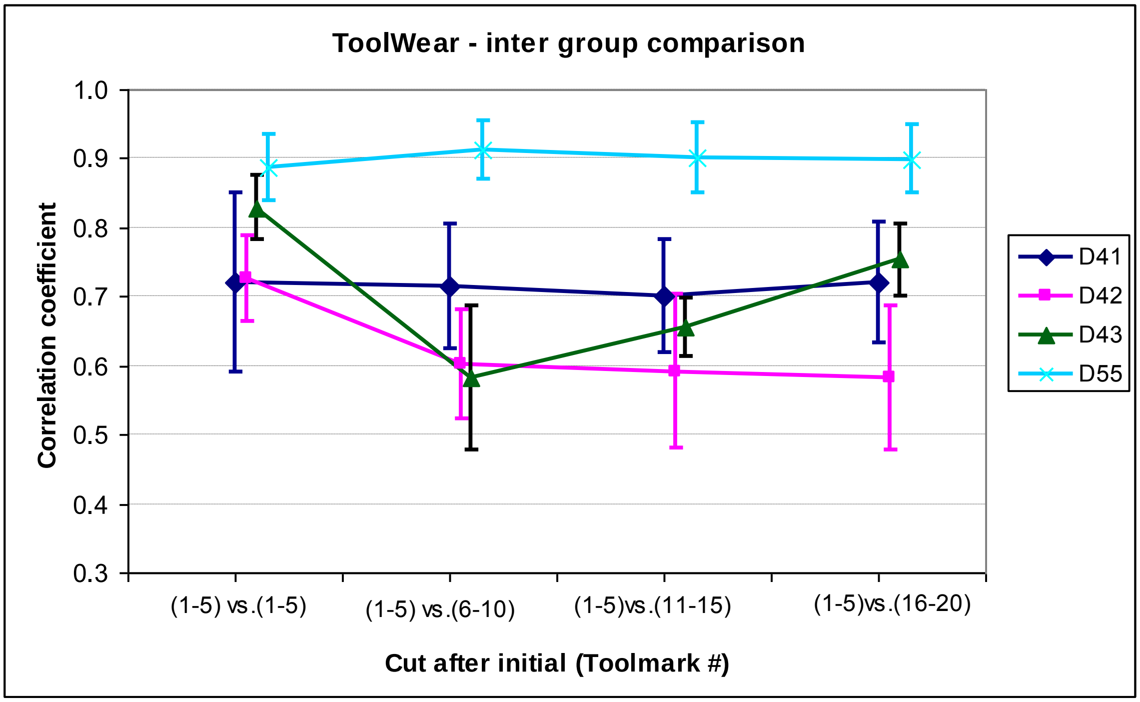

Figure 29. Tool wear inter group comparison (D55, D41-D43)

The same analysis conducted for tool D55 was undertaken for tools D41-D43. The results for all the four tools are shown in Figure 30 to Figure 32.

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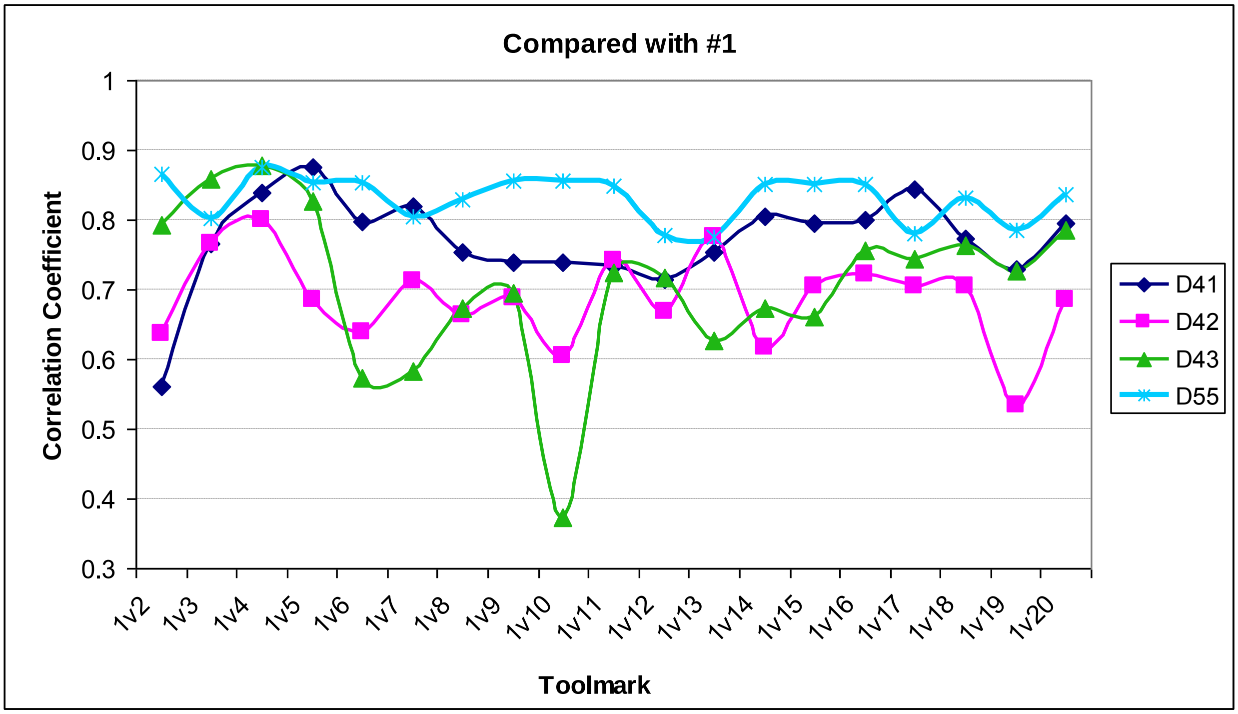

Figure 30. Comparison between the 1st tool mark with all the following 19 tool marks

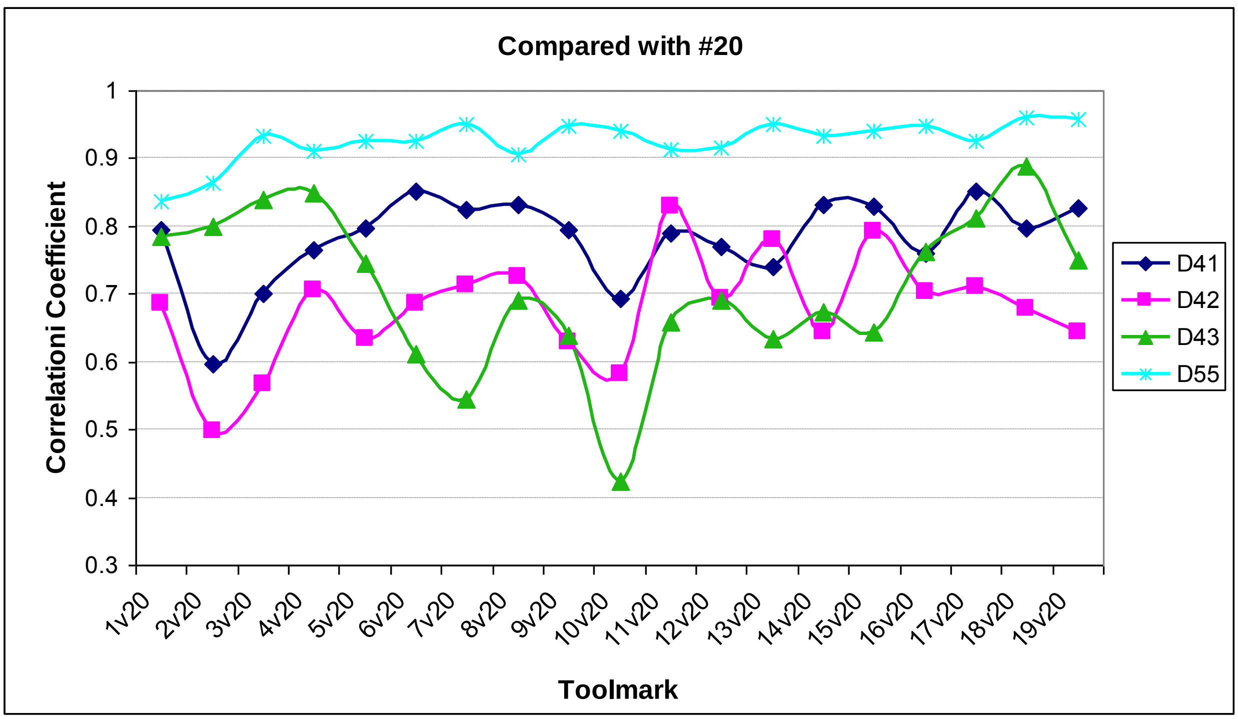

Figure 31. Comparison between the 20th tool mark with all the preceding 19 tool marks

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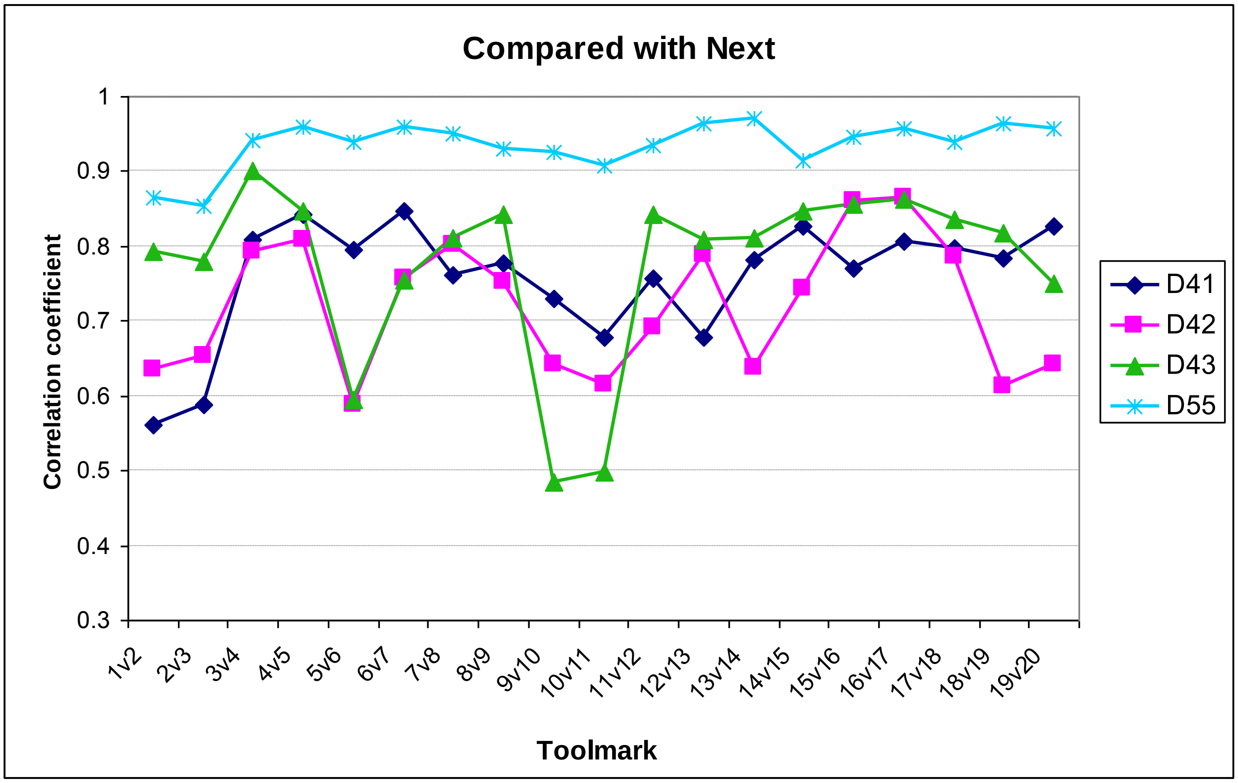

Figure 32. Comparison between every two consecutive tool marks within the first 20

Compared with curves corresponding to tool D55, the results obtained for tools D41 to D43 show lower similarity values and much higher standard deviations. The reason for this difference seems to be that the feature found on the tool marks created by tool D55 are unusually strong. In other words, these features are unusually large. To illustrate this difference, compare the features shown in Figure 24 (corresponding to tool D55) with those shown in Figure 33 (corresponding to tool D43). Nevertheless, we still see some common trends between these tools. Most significantly, behavior of all tools is quite similar in Figure 32, where each tool mark is compared to its following tool mark. **Based on Figure 32 we notice that the lowest similarity measures result from the first two comparisons (1st vs 2nd, and 2nd vs. 3rd tool mark). This means that the most significant change in the tool mark takes place within the first 3 cuts, after which the behavior of the tool seems to settle.** The most noteworthy exception to this behavior corresponds to tool mark D43-10. We therefore decided to take a close look at this particular tool mark as compared to its counterparts.

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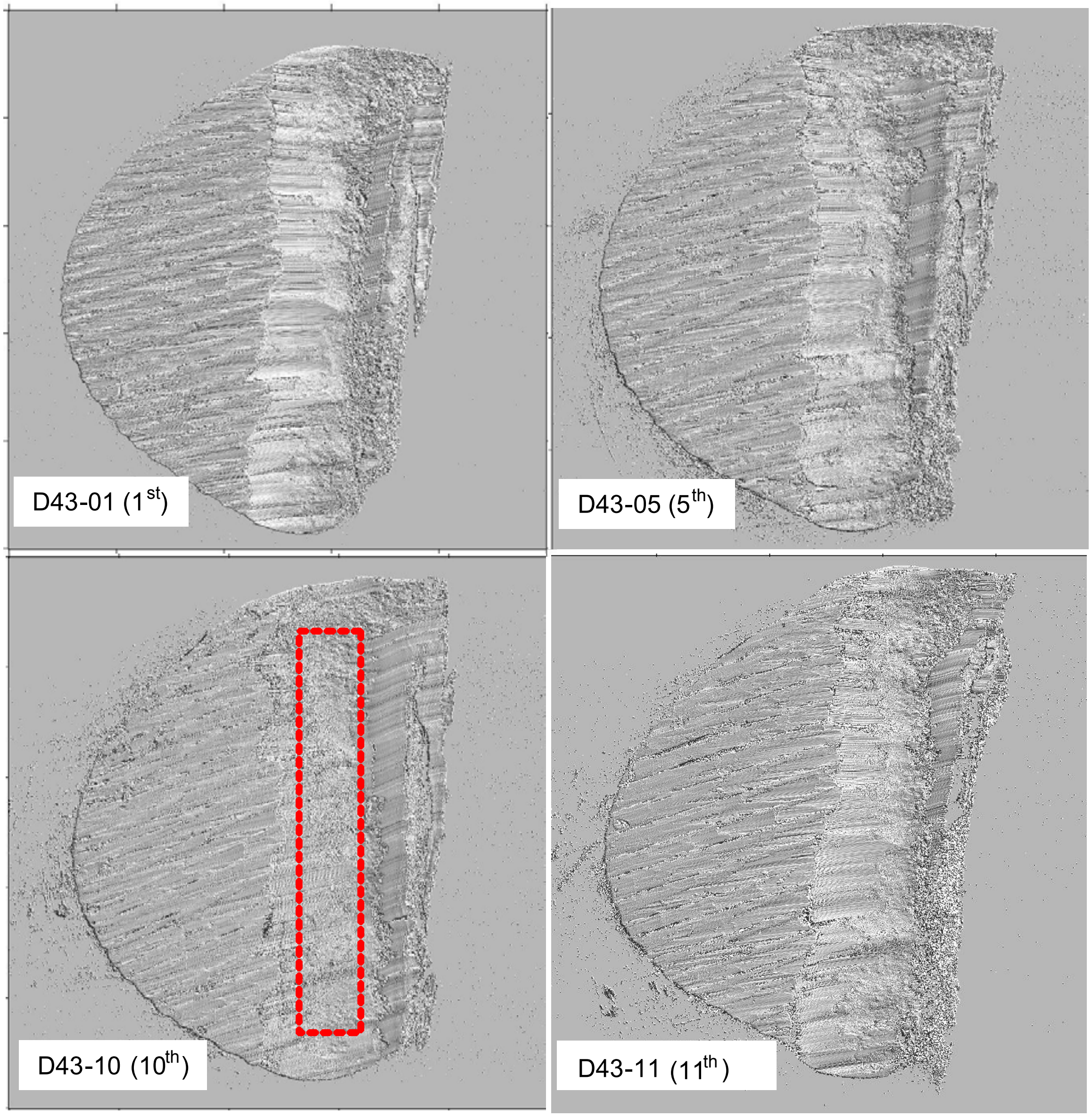

Figure 33. Tool mark images from D43

In all three figures above, the comparison of between D43-10 and any other tool mark results a much lower similarity score than other comparisons. Specifically, the '1v10' point in Figure 30, the '10v20' point in Figure 31, the '9v10' and '10v11' points in Figure 32. After careful inspection of the first 20 tool mark images from D43, it was found that the tool mark image of D43-10 (the 10^{th} cut) shows some abnormity (see Figure 33, where the 1^{st}, 5^{th}, 10^{th} and 11^{th} tool mark for tool D43 are shown). The area indicated by a rectangle in tool mark D43-10 is the area used by the automated comparison software. Based on Figure 33, we can see that those features which are rather rich and distinct in tool marks 1, 5 and 11 are very unclear in D43-10, especially in the area for comparison. The abnormity of D43-10 image is most likely caused by the uncertainty in the manual cutting process or in the data acquisition process. The complete first 10 tool mark images from D43 are shown in Section 9.2 (Appendix D.2).

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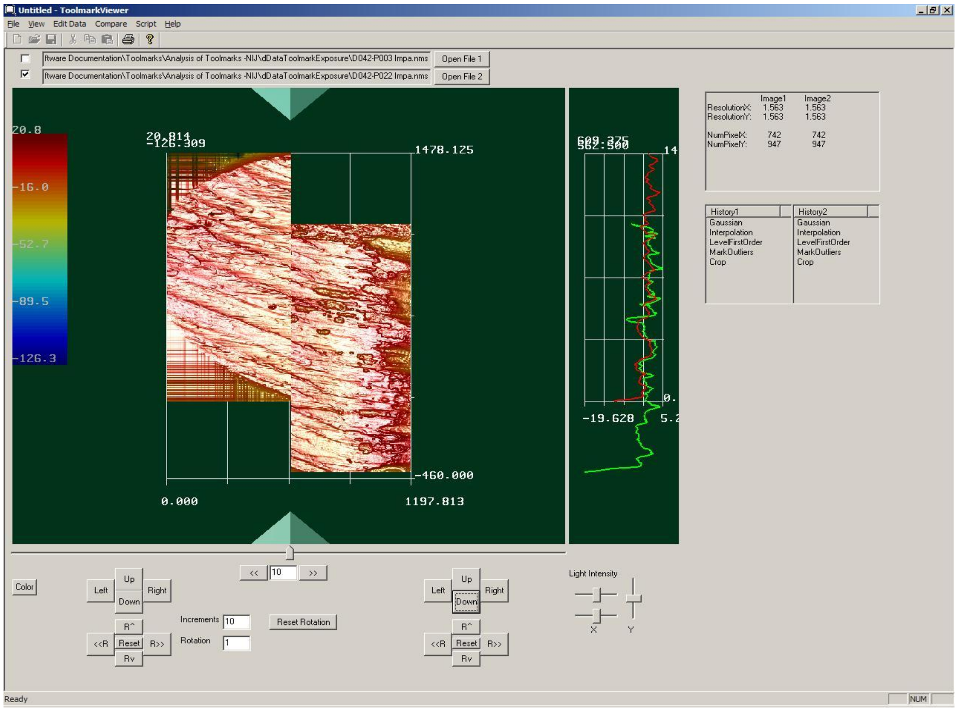

Figure 34: Comparison of tool marks before (left side) and after (right side) exposure to salt water in two weeks

3.3.2 Effect of Tool Mark Exposure

3.3.2.1 Tool Mark Exposure Time Effect

As discussed in our preliminary experiment (see Section 3.2.3), the effect of exposure can be seen in a tool mark as early as 3 weeks. Figure 34 shows the side-by-side comparison using IAI's virtual comparison scope between a control tool mark and a tool mark exposed to sea-like water for two weeks (tool D42). The two tool marks can be seen to have significant common features under the virtual comparison microscope, even though the salt water deteriorates the tool marksto a noticeable degree. Therefore, the tool marks that have been exposed to the salt water for 2 weeks should be identifiable. Would these tool marks still be identifiable after 6 weeks? To quantitatively answer this question, we calculated the cross correlation among all the tool marks acquired after 2 weeks, 4 weeks and 6 weeks for each tools and each concentration. As an example, the cross correlation among tool marks from D41 and D42 with 3.5% salt concentration is given in Table 6. Similar to the analysis method we used in the Tool Wear study, the upper left table in Table 6 compared the matching tool marks from D41, and the lower right table compares the matching tool marks from D42, while the upper right table compares tool marks from D41 against tool marks from D42, which is referred to as a comparison of "non-matching" tool marks. We completed similar tables for all the three tools and all the concentrations.

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Table 6: Cross correlation among tool marks from D41 and D42 in tool mark exposure experiment with 3.5% salt concentration

41 (rows) vs. 41 (columns)

41		control (1-5)	0w (6-10)	2w (21-25)	4w (36-40)	6w (51-55)
control (1-5)	median	0.774	0.743	0.506	0.350	0.325
	mean	0.720	0.714	0.498	0.353	0.340
	std	0.130	0.090	0.100	0.098	0.114
0w (6-10)	median		0.761	0.465	0.304	0.296
	mean		0.759	0.490	0.316	0.299
	std		0.048	0.107	0.092	0.058
2w (21-25)	median			0.534	0.521	0.470
	mean			0.551	0.502	0.470
	std			0.110	0.195	0.191
4w (36-40)	median				0.444	0.470
	mean				0.402	0.449
	std				0.158	0.217
6w (51-55)	median					0.338
	mean					0.370
	std					0.153

41 (rows) vs. 42 (columns)

41		control (1-5)	0w (6-10)	2w (21-25)	4w (36-40)	6w (51-55)
control (1-5)	median	0.289	0.297	0.256	0.271	0.238
	mean	0.294	0.300	0.262	0.269	0.250
	std	0.036	0.029	0.044	0.036	0.045
0w (6-10)	median		0.301	0.242	0.273	0.246
	mean		0.302	0.255	0.284	0.254
	std		0.041	0.040	0.042	0.028
2w (21-25)	median			0.299	0.298	0.272
	mean			0.301	0.311	0.283
	std			0.053	0.043	0.047
4w (36-40)	median				0.338	0.284
	mean				0.331	0.281
	std				0.053	0.057
6w (51-55)	median					0.273
	mean					0.276
	std					0.046

42

42 (rows) vs. 42 (columns)

42		control (1-5)	0w (6-10)	2w (21-25)	4w (36-40)	6w (51-55)
control (1-5)	median	0.726	0.605	0.416	0.378	0.310
	mean	0.727	0.601	0.420	0.401	0.330
	std	0.062	0.079	0.098	0.077	0.064
0w (6-10)	median		0.722	0.552	0.439	0.296
	mean		0.730	0.549	0.448	0.340
	std		0.071	0.123	0.083	0.117
2w (21-25)	median			0.441	0.378	0.318
	mean			0.441	0.408	0.354
	std			0.095	0.174	0.140
4w (36-40)	median				0.387	0.294
	mean				0.400	0.394
	std				0.080	0.205
6w (51-55)	median					0.252
	mean					0.255
	std					0.028

Figure 35 shows the results of inter-group comparison of all the tool mark sets from 3.5% salt water. The upper three lines show the distribution of the similarity measure resulting from the comparison of the control tool marks against the exposed tool marks (which were exposed to salt water for varying amounts of time). As expected, the longer the exposure to salt water, the lower the similarity measure between the control set and the exposed sets. **Not surprising the duration of the exposure has a significant effect on the tool marks.** The lower three lines in Figure 35 show the cross comparison between the tool marks from different tools (non-matching). The non-matching curves are relatively stable at a similarity measure of about 0.3, with less fluctuation and small standard deviation compared with the matching curves. The distances between the matching distribution curves (upper three curves) and the non-matching curves (lower three curves) are indicative of the separation of the matching and non-matching distributions associated with the probability of correct tool mark identification (the bars associated with each data point correspond to one standard deviation). We observed that after 4 weeks of exposure, the matching and non-matching distribution overlap significantly, indicating that these tool marks would become challenging to identify or match after 4 weeks of exposure to 3.5% salt water.

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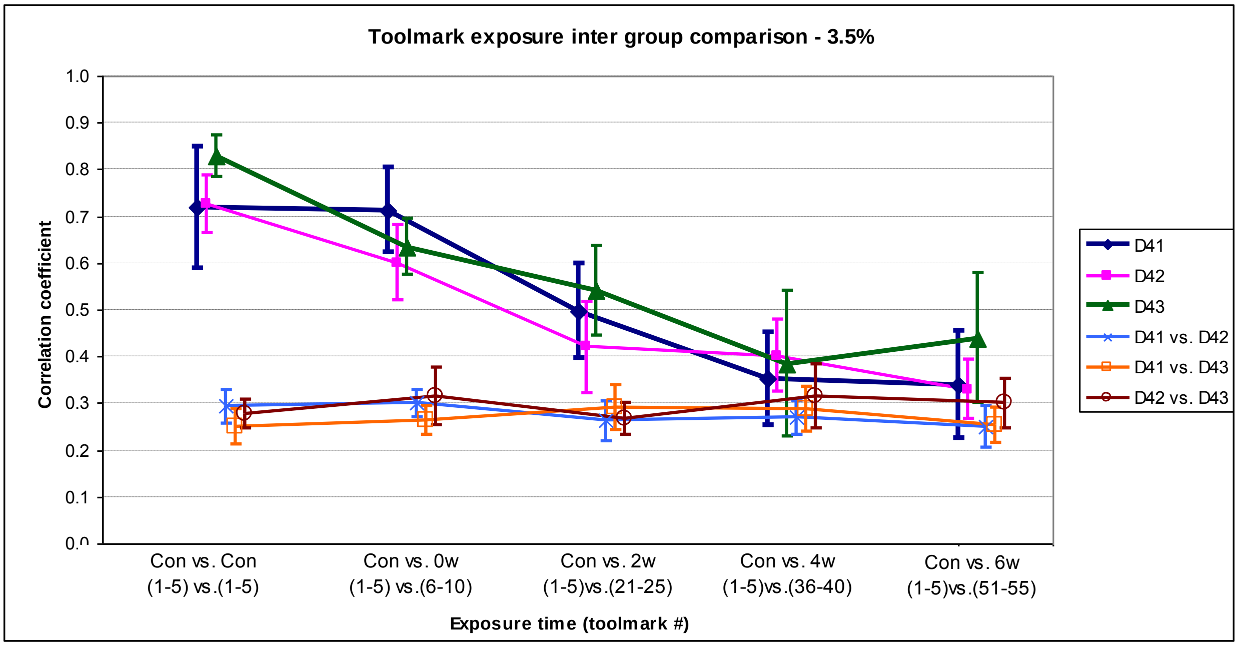

Figure 35. Inter group comparison of tool marks exposed to 3.5% salt water

In the same way, we processed the data of tool marks exposed to salt water of concentrations 1.75% and 0.88%, and the results are shown in Figure 36 and Figure 37 respectively. In Figure 36 and Figure 37, we observed the same trend as in Figure 35. The upper three curves decline along exposure time, but not as fast as in Figure 35. The curves settle at higher levels than in Figure 35, indicating that the 1.75% salt water deteriorates the tool marks to a less severe extent than 3.5% salt water. Comparing Figure 36 (1.75%) and Figure 37 (0.88%), the matching curves (the upper three curves) in Figure 37 (0.88%) differentiate themselves from the non-matching (the lower three curves) for longer periods of exposure than in Figure 36 (1.75%). Even after 6 weeks, the matching distributions are still fairly separable from the non-matching distributions. **Not surprisingly, we conclude that the concentration of the exposure media has significant influence on the deterioration of the tool marks**.

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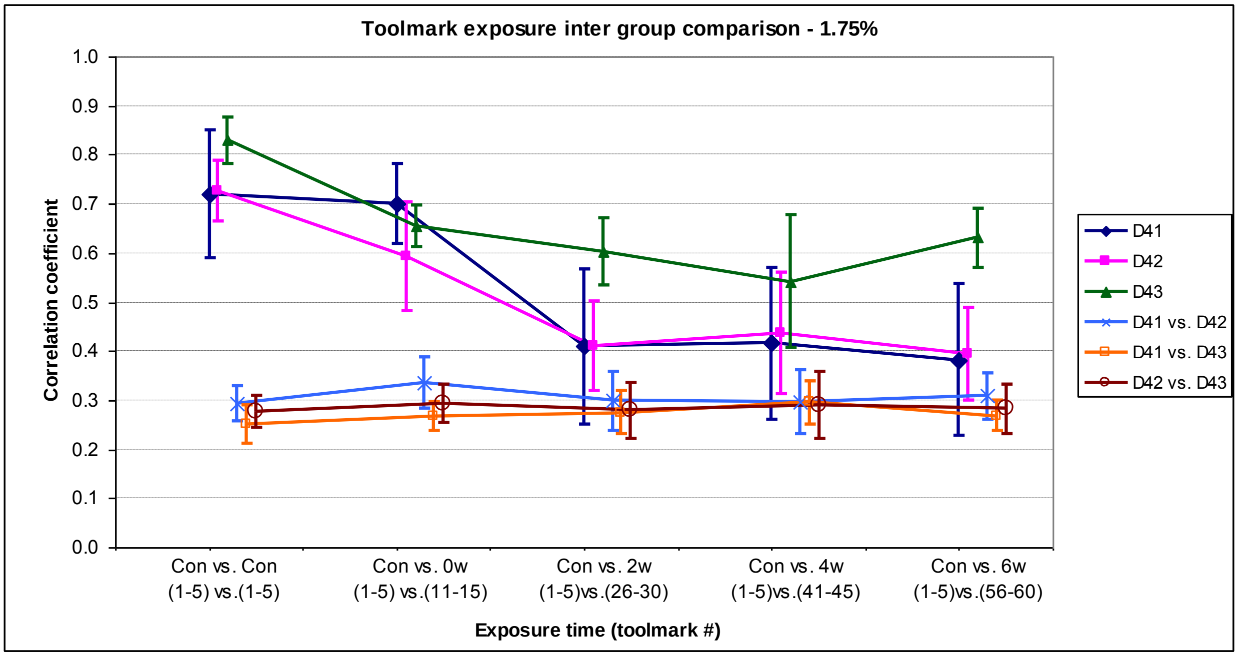

Figure 36. Inter group comparison of tool marks exposed to 1.75% salt water

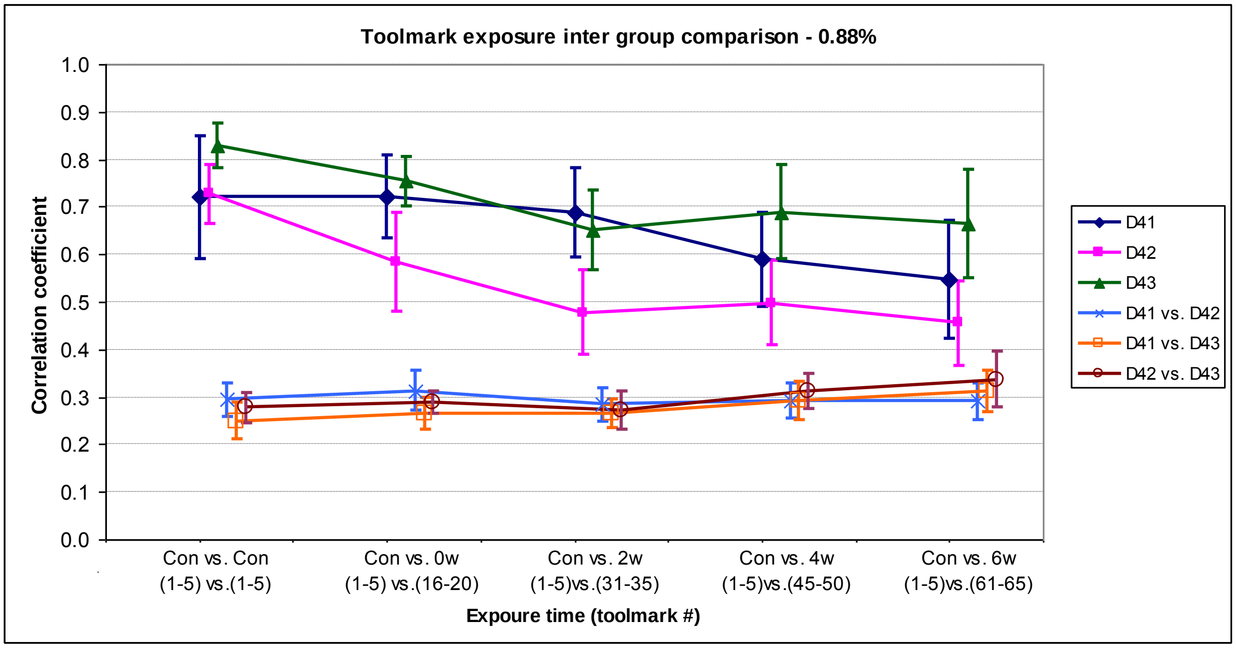

Figure 37. Inter group comparison of tool marks exposed to 0.88% salt water

We further conducted the intra-group comparison within each set of tool marks. Figure 38 shows the intra-group comparison for 3.5% concentration for three tools, D41, D42 and D43. Figure 39 and Figure 40 show the results for 1.75 and 0.88% concentration respectively. In all three plots, the similarity within each set of tool marks decreases with the exposure time increase. The lower three curves in each figure correspond to the non-matching similarity measure, which result from comparing the tool marks of different tools. Again, we can clearly see the effect of different salt

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concentration. For 3.5% concentration, after 4 weeks of exposure, the average of the distribution of the similarity measure of matching tool marks in all three curves drops to a level as to be difficult to separate from the distribution of the non-matching similarity measures. But for 0.88% concentration, the matching curves are still clearly distinguishable from the non-matching curves. Similar to the non-matching curves in the inter-group comparison, the non-matching curves in the intra-group comparison are relatively stable and insensitive to exposure time, which means the 5 tool marks from the same set do not become any more similar to each other due to the corrosion of salt water (this may seem like an obvious statement, but there are arguments which state that the longer a set of tool marks are corroded, the more similar they may become). For 1.75% concentration, D42 and D43 stayed above the non-matching curves after 2 weeks (D41 drops quickly and mixes with the non-matching curves after 2 weeks). For 0.88% concentration, all the matching similarity measure distributions remain easily differentiable from the non-matching distributions.

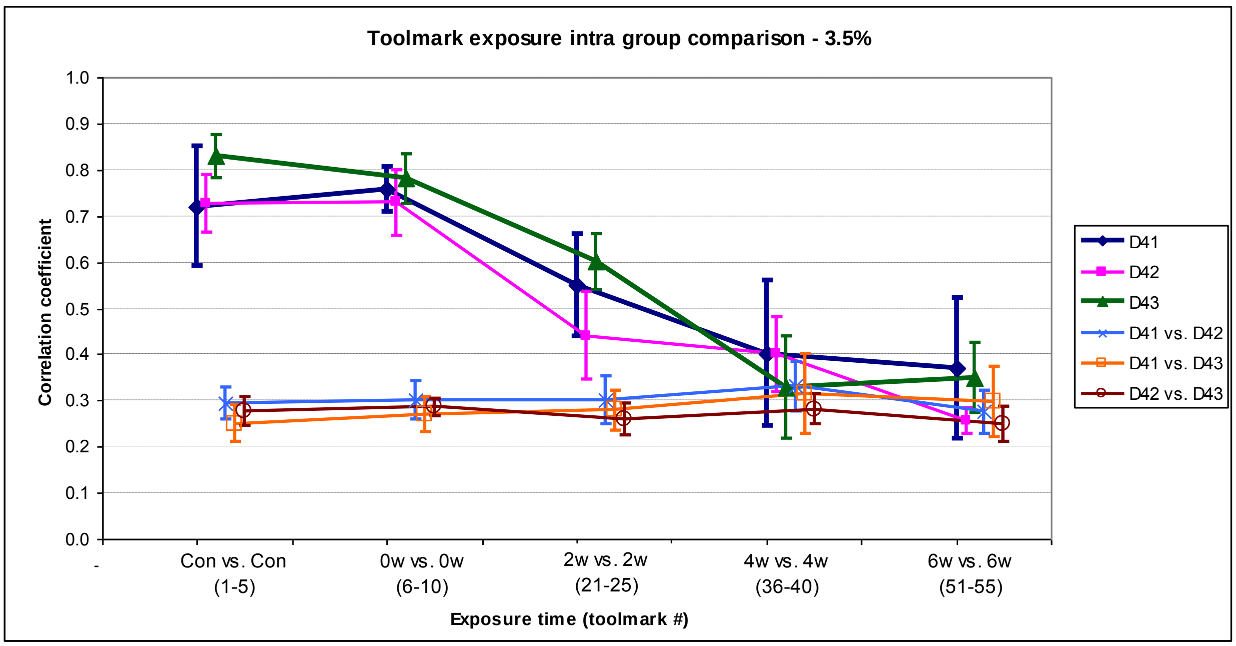

Figure 38. Intra group comparison of tool marks exposed to 3.5% salt water

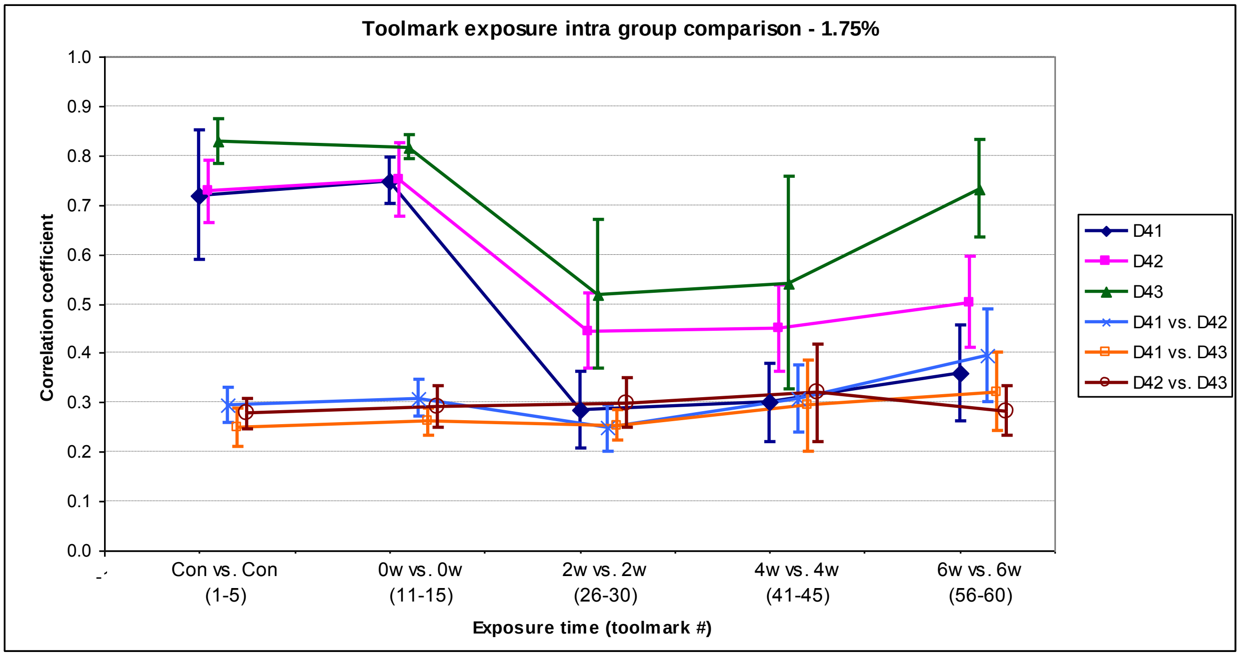

Figure 39. Intra group comparison of toolmarks exposed to 1.75% salt water

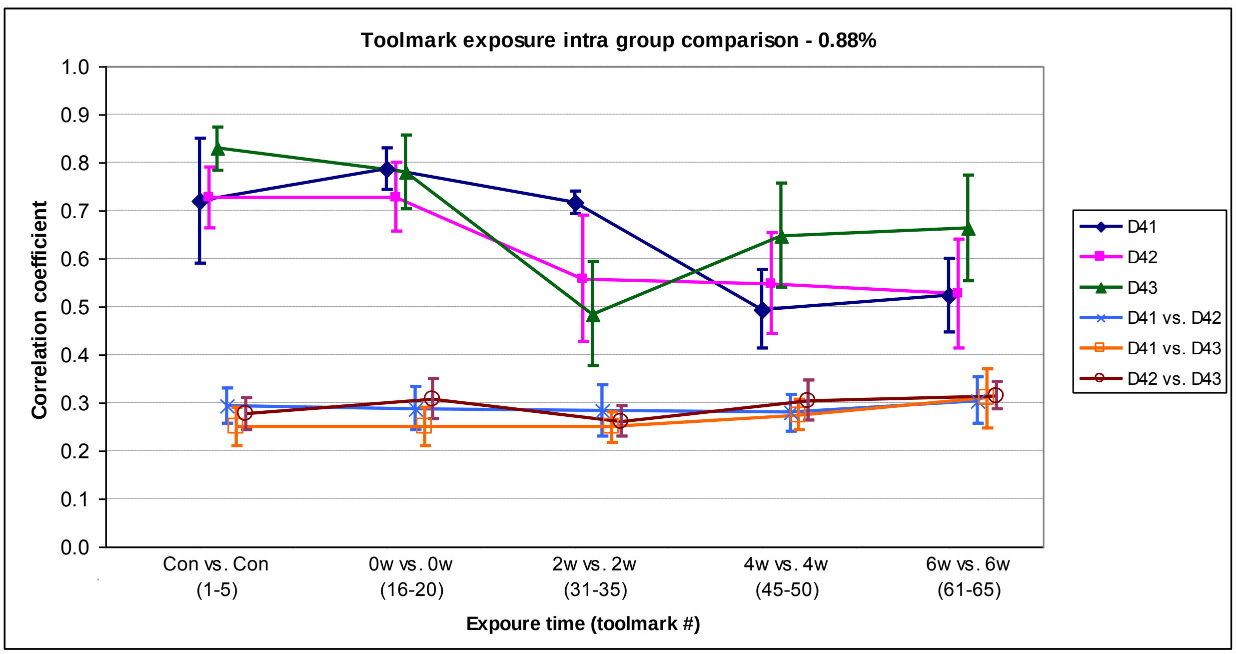

Figure 40. Intra group comparison of tool marks exposed to 0.88% salt water

The fact that the average values of the distributions resulting from the intra-group comparison decrease with the exposure time is an interesting phenomena. After all, why would tool marks subjected to the same conditions (i.e. same exposure) be less and less similar? We speculate that as the tool marks are exposed longer and longer, their features fade away as they got corroded, leaving less and less features for comparison (or at the very least diminishing the magnitude of the features).

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3.3.2.2 Tool Mark Exposure Salt Concentration Effect

The relative effect of the salt water concentration can be better appreciated by observing the results of the inter-group comparison curves of the three tools. This phenomenon is shown in Figure 41 for tool D41, Figure 42 for tool D42, and Figure 43 for tool D43. In all three plots, the curves corresponding to the distribution of the similarity measures for tools exposed to 3.5% exposure concentration have the lowest mean value, those corresponding to 1.75% exposure concentration curves are in the middle and those corresponding to 0.88% exposure concentration curves are at the top, indicating the effects of the salt water is more significant as the concentration increases.

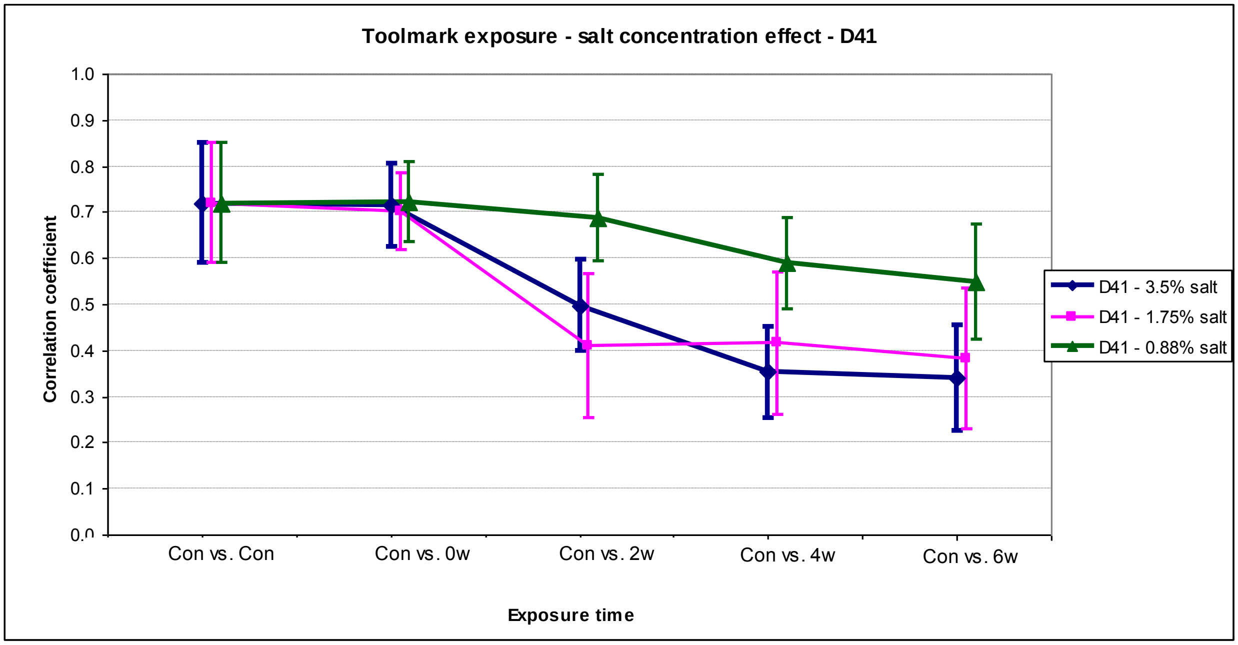

Figure 41. Salt concentration effect on tool marks from Tool D41

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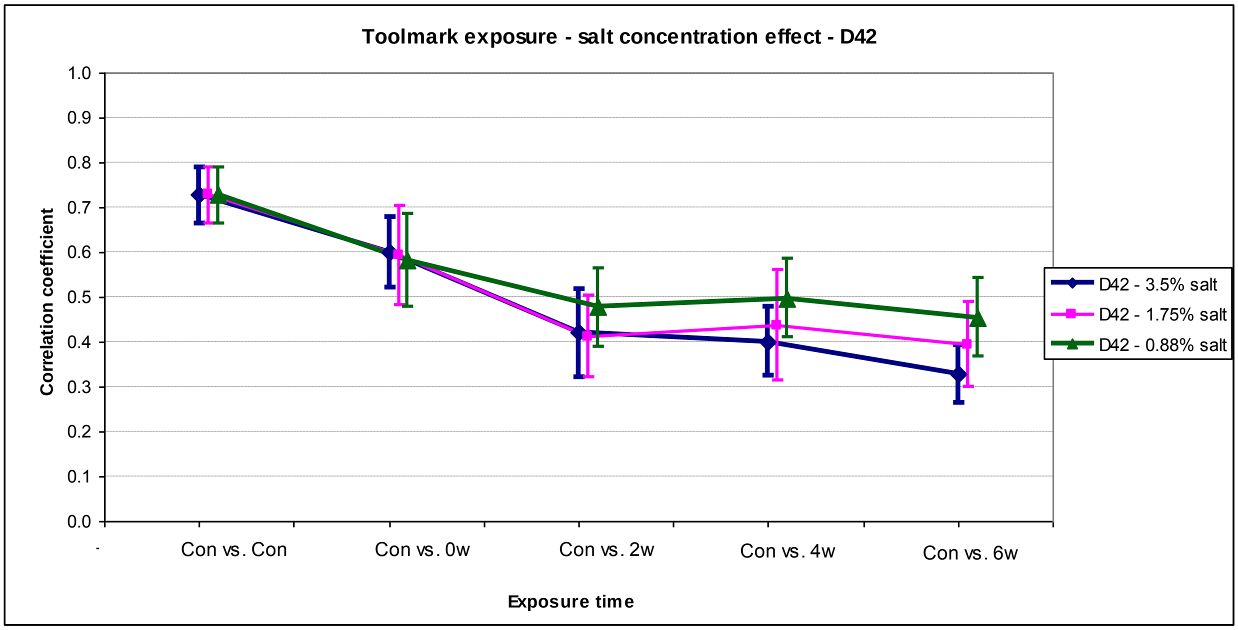

Figure 42. Salt concentration effect on tool marks from Tool D42

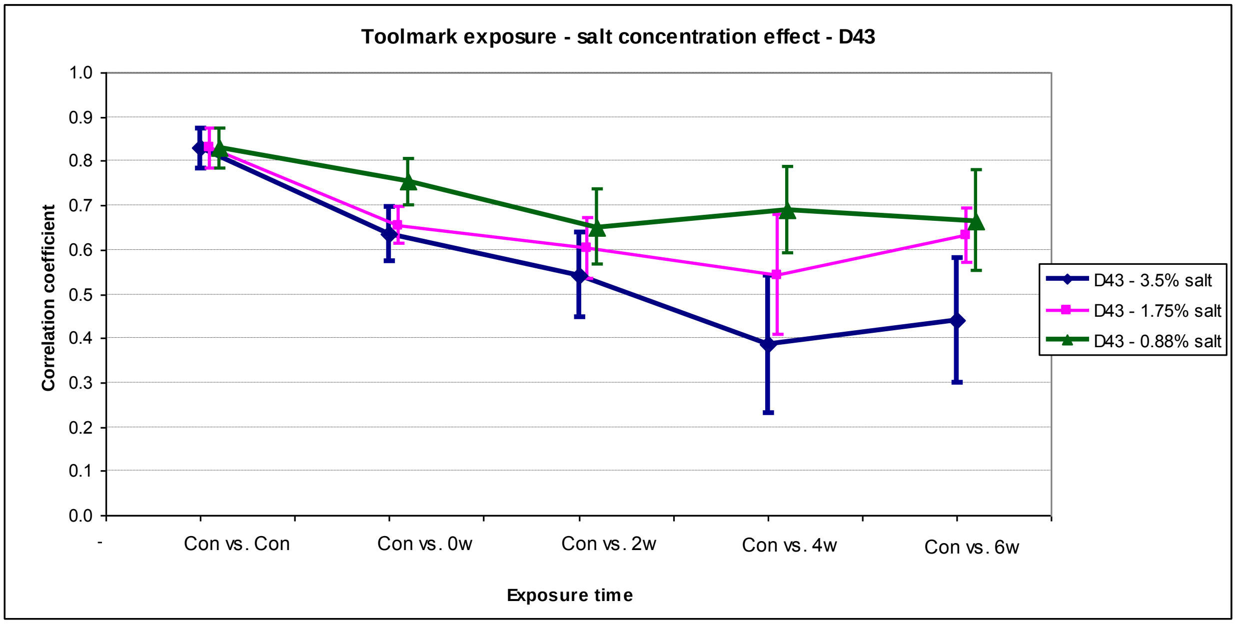

Figure 43. Salt concentration effect on tool marks from Tool D43

The tool mark exposure experiment results clearly show that the effects of the salt water on the features found on the tool marks are consistent with our expectation. **The deterioration of the tool mark features is not only proportional to the exposure time, but also it is proportional to the salt concentration.** The exposure to salt water of concentration similar to those of sea

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water significantly deteriorates the tool mark features in a time frame of approximately four weeks.

3.3.3 Effects of Tool Exposure

3.3.3.1 Tool Exposure Time Effect

In the tool exposure experiment, tools (as opposed to their tool marks) were exposed to salt water of three different concentrations, 3.5% (tool D44, D45 and D46), 1.75% (tool D47, D48 and D49) and 0.88% (tool D50, D51 and D52). A set of tool marks were created by each tool after 2 weeks, 4 weeks and 6 weeks of exposure (as well as a control set, or 0 weeks set, which was created before the tools were exposed at all). Each set of tool marks includes 5 tool marks. Following the same procedure used in tool mark exposure data analysis, we processed all the inter-group and intra-group comparisons among different sets of tool marks. Figure 44 to Figure 46 show results of the inter-group comparison among sets of tool marks created from tools that were exposed to salt water of concentrations of 3.5%, 1.75%, and 0.88% respectively. These results show that in as little as 2 weeks of exposure to salt water, the similarity measure of the matching pairs drop to the level of that of the non-matching pairs. This indicates that the tools would be challenging to identify after 2 weeks in either 1.75% or 0.88% salt water. The results for 3.5% seem to depart from the other two concentrations. We notice that the curves corresponding to tools D44 and D46 did not drop to the non-matching level as tool D45 did. We believe that this discrepancy is most likely due to the specific characteristics of tools D44 and D46. In other words, that the blades of these tools have especially strong features (i.e. physically large features which survived a considerable amount of corrosion).

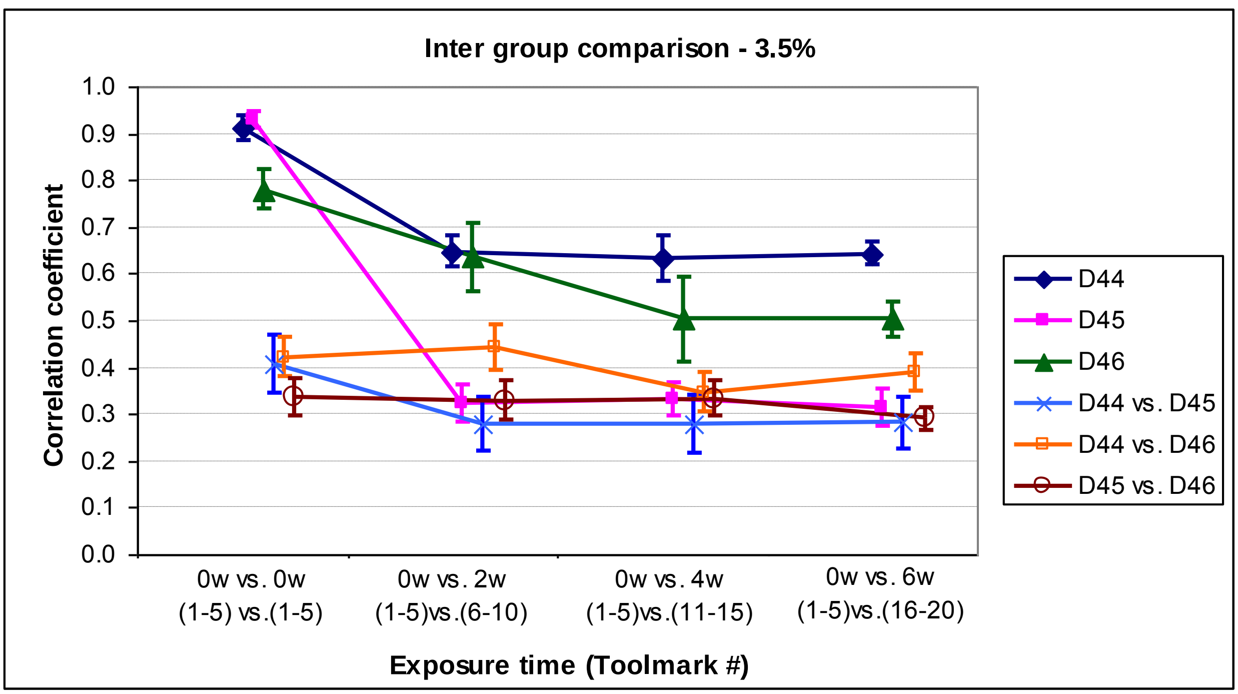

Figure 44. Inter group comparison of tool marks from tools exposed to 3.5% salt water

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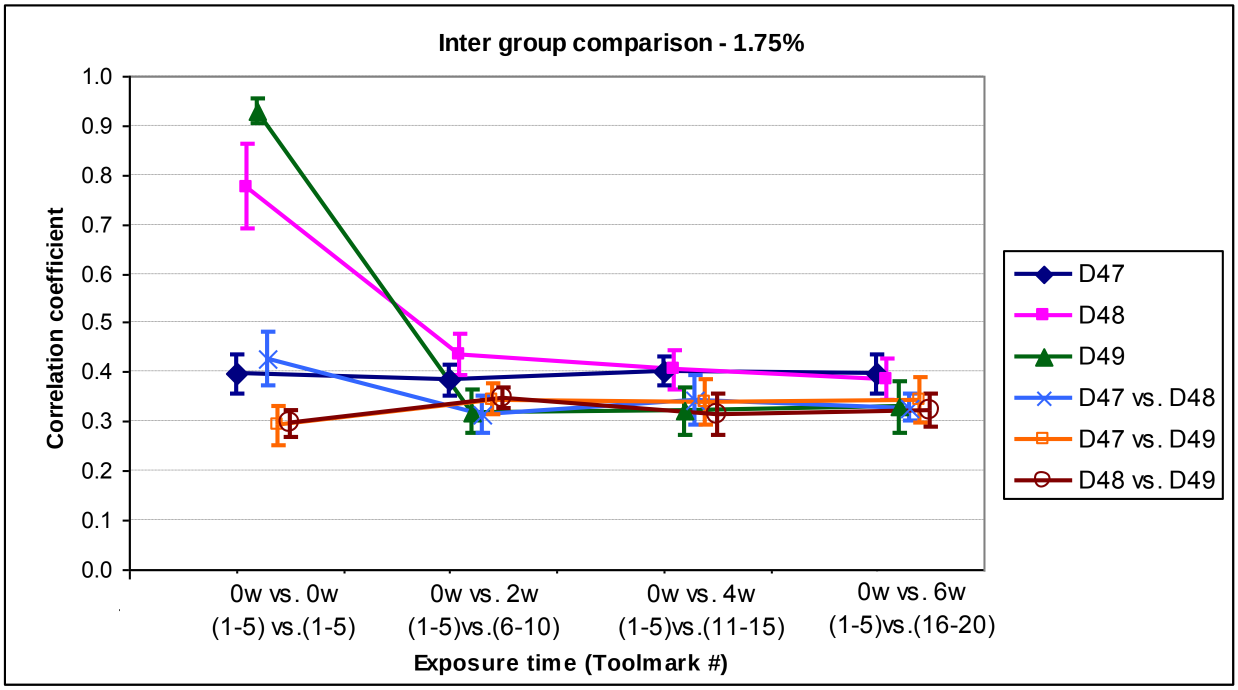

Figure 45. Inter group comparison of tool marks from tools exposed to 1.75% salt water

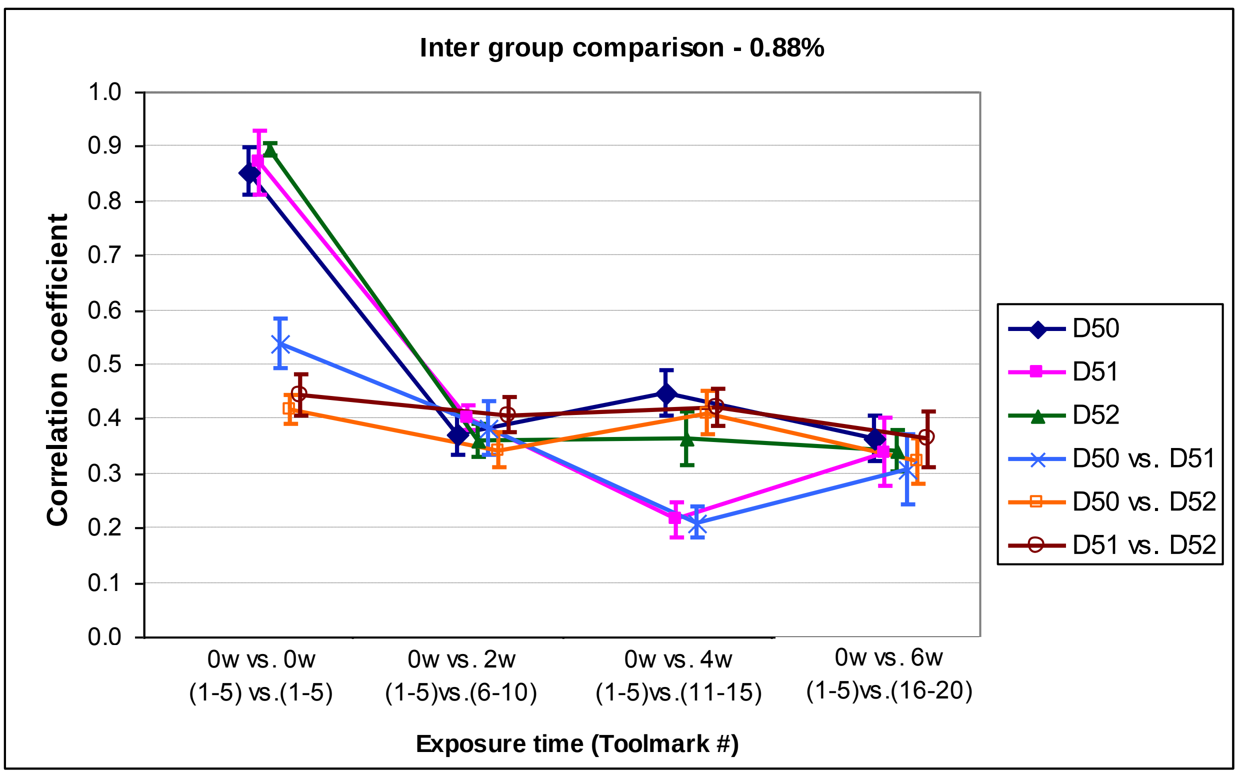

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Figure 46. Inter group comparison of tool marks from tools exposed to 0.88% salt water

The intra-group comparison among each set of tool marks with different salt concentrations are shown in Figure 47 to Figure 49. In all three figures, the similarity measure of the matching curves stay flat without dropping as the exposure time increases. This behavior is different from that observed in the case of the intra-group comparison of tool marks obtained as part of the tool mark exposure experiment. The explanation to this difference is due to the fact that for the case of tool mark exposure, the salt water deteriorates the five tool marks in the same set independently, which decreases the similarity within them. **But in the case of tool exposure, the five tool marks corresponding to the same set are created by the same tool (which has been subjected to exposure). Since each set is created by the same tool, these tool marks are very similar to each other, resulting in high intra group similarity measure values**.

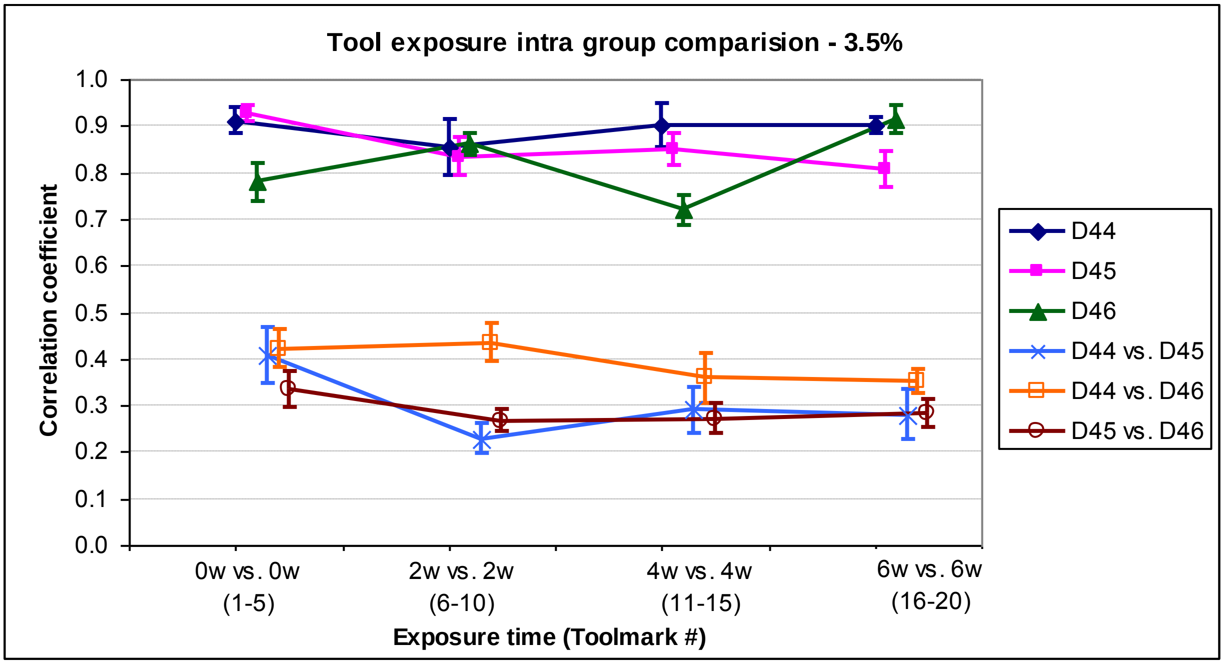

Figure 47. Intra group comparison of tool marks from tools exposed to 3.5% salt water

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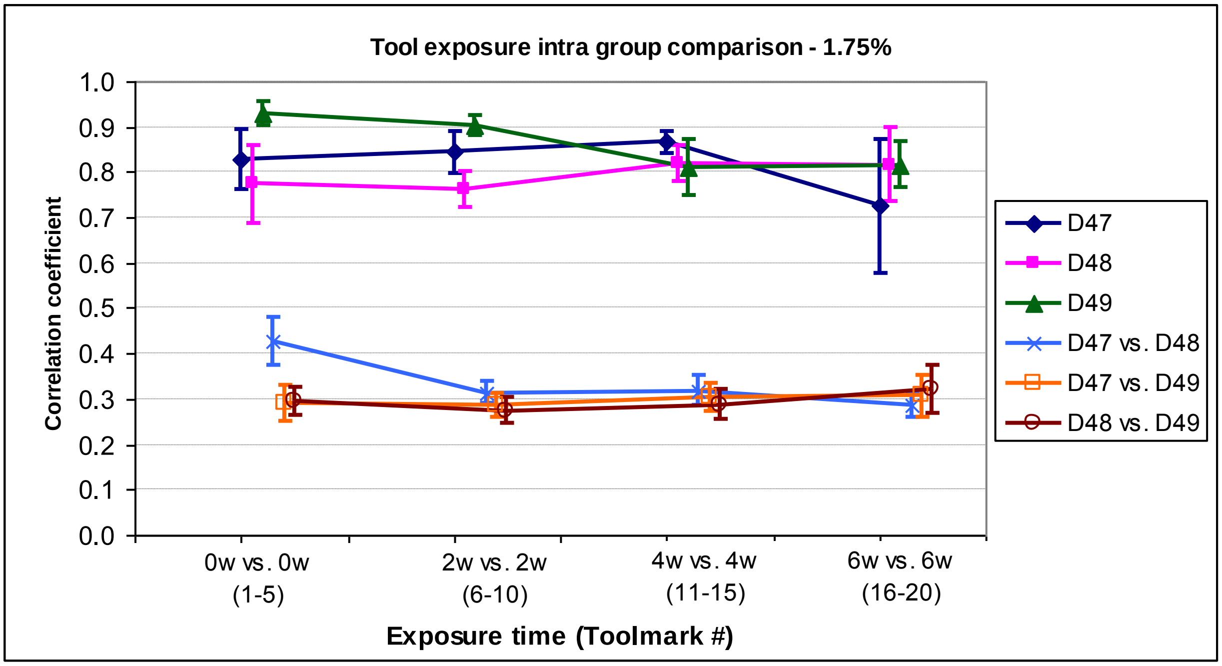

Figure 48. Intra group comparison of tool marks from tools exposed to 1.75% salt water

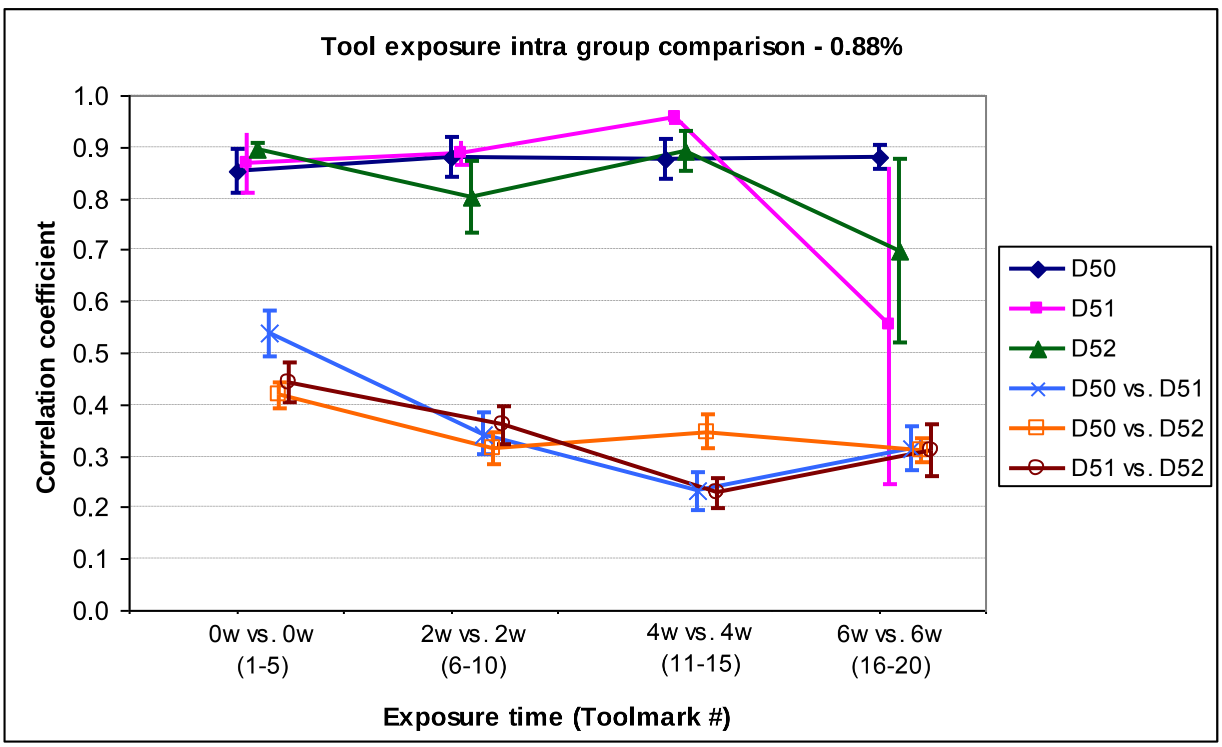

Figure 49. Intra group comparison of tool marks from tools exposed to 0.88% salt water

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Of all the results regarding reported above, one anomaly caught our attention. Figure 49 shows the intra-group comparison of tool exposure in 0.88% water, where the average of the distribution corresponding to the last data point in curve D51 shows a dramatic drop and an abnormally high standard deviation. To investigate possible reasons for this phenomenon, we first performed a visual inspection of the tool mark images D51-16 through D51-20 (which are the tool marks used to compute the last data point in curve D51). These images are shown in Figure 50. Visual inspection of these tool marks does not reveal much. For this reason, we took a close look at the similarity measure values of every comparison pair within the D51-16 to D51-20 group. All the correlation coefficient values within this group are listed in Figure 51. As highlighted in yellow in Figure 51, all the comparison between D51-16 and any other tool mark image results in an unusually low correlation coefficient (around 0.2, while all the other correlation coefficients are close to 0.8 or so). It turns out that the correlation of D51-16 with any other tool in the set results in a very low correlation coefficient, making D51-16 the most likely candidate for being the outlier (tool mark number 16 of tool D51). The last data point of the curve corresponding to D52 in Figure 49 also displayed an abnormal standard deviation (although less remarkable than the last point associated with D51). With the same method we checked the correlation coefficient value within the D52-16 to D52-20 group, and found D52-20 to be the outlier. Once the two outliers were removed from each group, the cross correlation were calculated again. The modified intra group comparison for 0.88% concentration is plotted in Figure 53, which appears to be significantly more reasonable.

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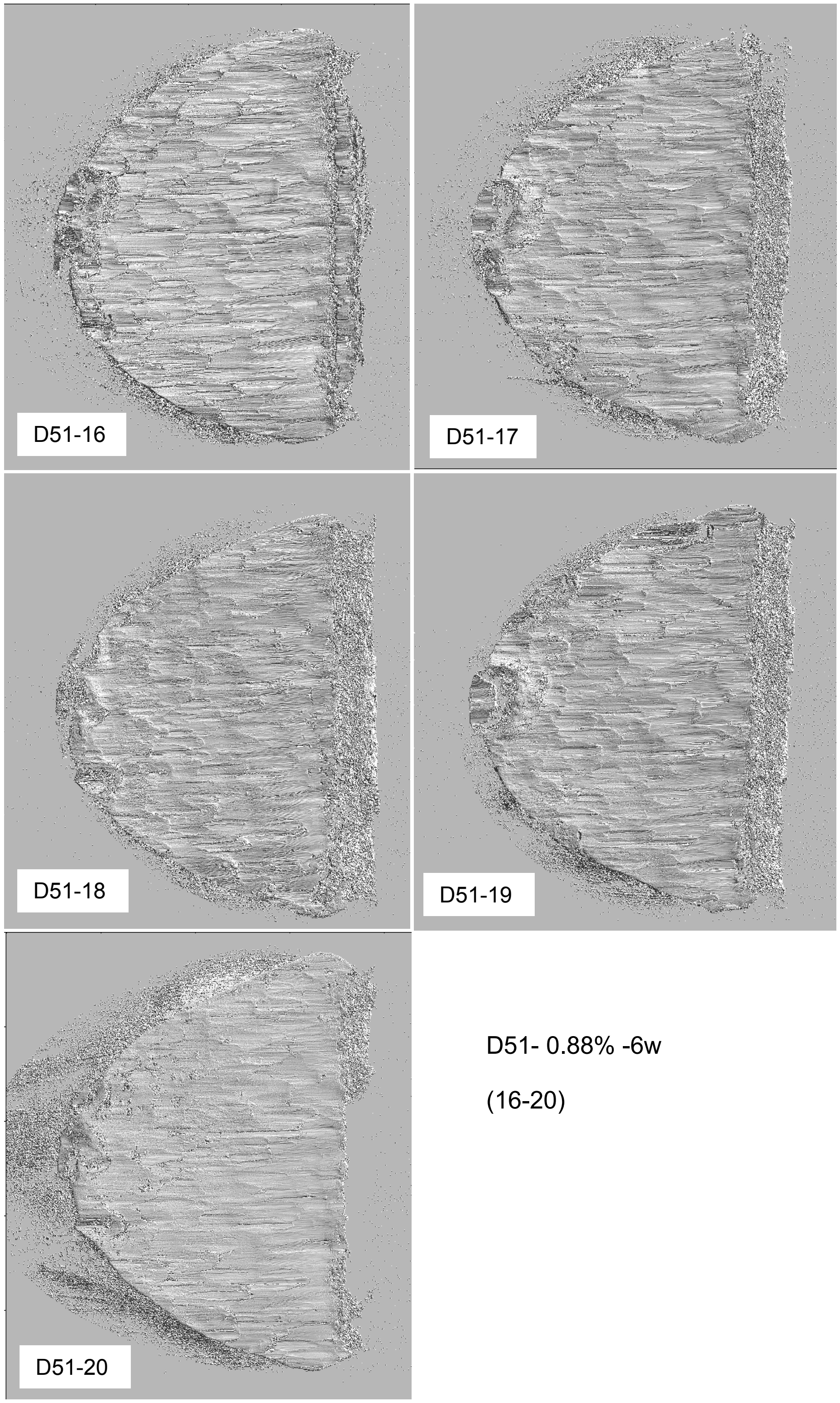

Figure 50: The tool mark images from D51 after exposed in 0.88% salt water for 6 weeks

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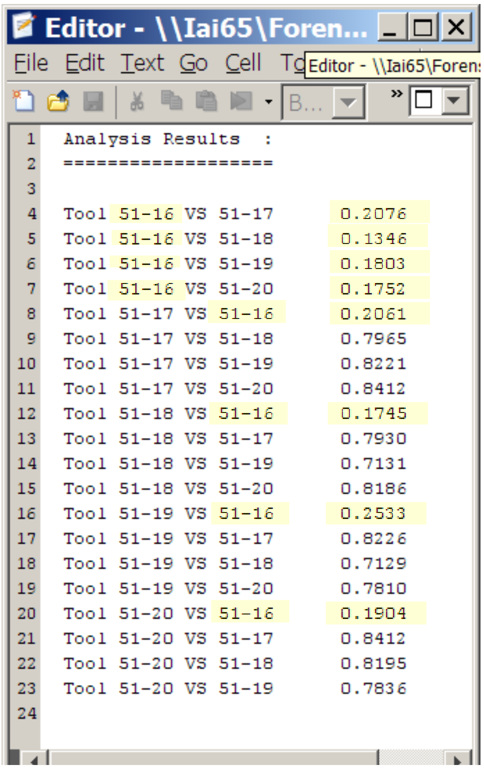

Figure 51. Correlation coefficient values within D51-16 to D51-20 group

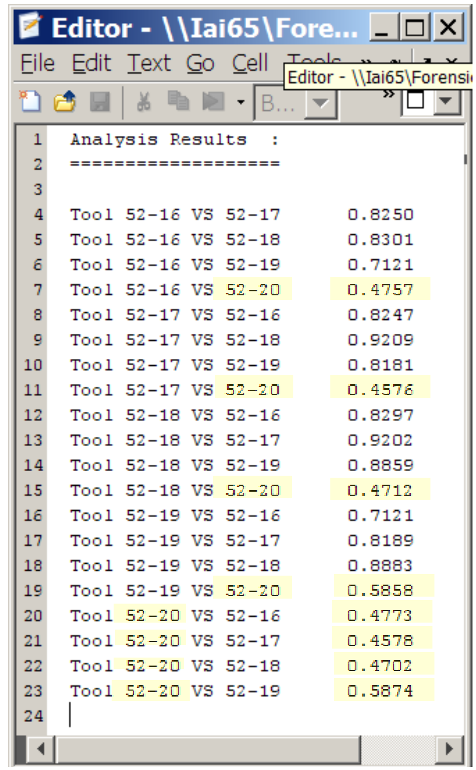

Figure 52. Correlation coefficient values within D52-16 to D52-20 group

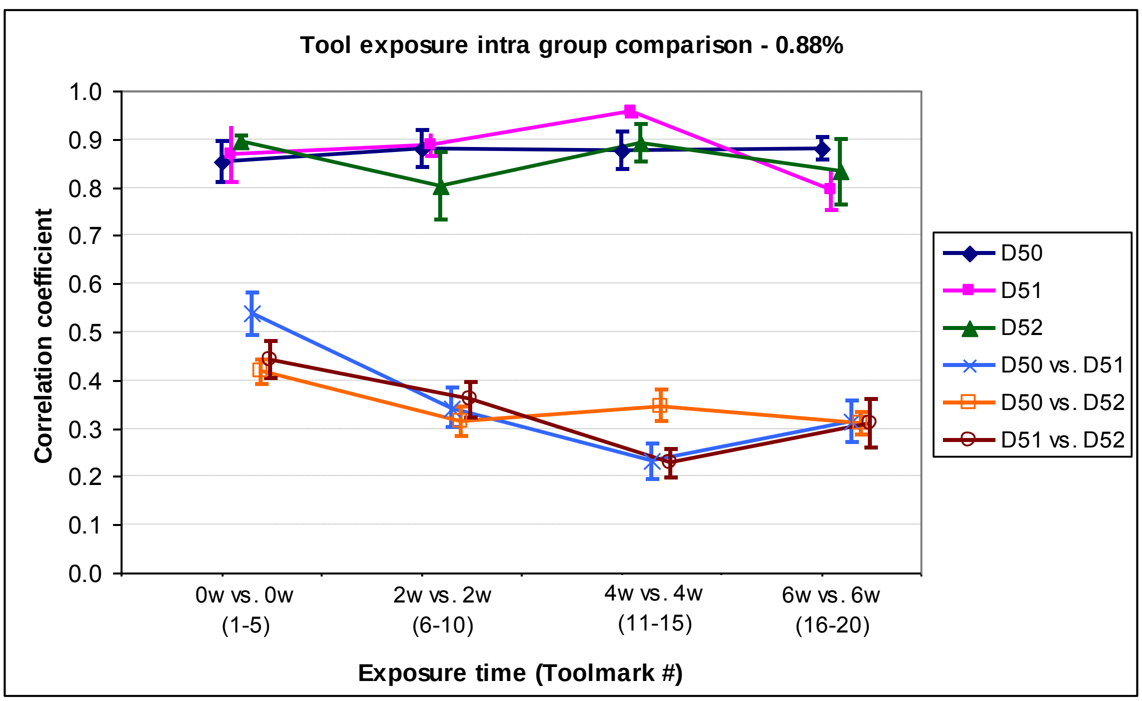

Figure 53. Modified intra group comparison of tool marks from tools exposed to 0.88% salt water (@6w, D51(17-20), D52(16-19))

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3.3.3.2 Tool Exposure Salt Concentration Effect

The intra-group comparison figures of different salt concentrations are plotted together in Figure 54 to show the relative effect of the salt water concentration. The inter-group comparison figures are plotted together in Figure 55. In both figures, curves of the 3.5% concentration are plotted in blue; curves of the 1.75% are plotted in red, and 0.88% in green. **It is evident that for tool exposure, different salt concentrations almost make no difference on the intra-group comparison.** Moreover, the concentration seems to make little difference in the inter-group comparison.

The fact that the concentration of the salt water has virtually no effect in the intra-group comparison is not surprising, since each set of tools under comparison are created by the same tool (albeit an exposed tool, but still the same tool for all tool marks). The fact that the salt water concentration has little effect on the inter-group comparisons might be surprising. **The fact is that most of the change in the tool marks takes place during the first two weeks for all concentrations**. In other words, even for the lowest salt concentration of .88% the tool's working surface has changed enough to make the tool marks significantly different to those created when the tools were new. It is worth remembering that the tools used in this study were brand new tools, so that the drastic change between a brand new and sharp tool and an exposed one should be significant.

Appendix F.1 shows the topographical images corresponding to the tool marks created by tool D43 as the tool was exposed over different periods of time at a concentration of 1.75%. As can be seen in these images, the change of the tool marks is very pronounced between week 0 (brand new tool, unexposed) and week 2 (tool exposed for two weeks). However, the change in the tool marks is not as pronounced as the tool continues to be exposed (for example, between week 2 to week 4). This can be explained by the fact that the tool's working surface will experience the most significant change at the beginning of the exposure. After the first two weeks, the blade of the tool does not seem to change significantly even though the tool continues to be exposed. **In other words, there seems to be a "settling" of the change of the tool's working surface**.

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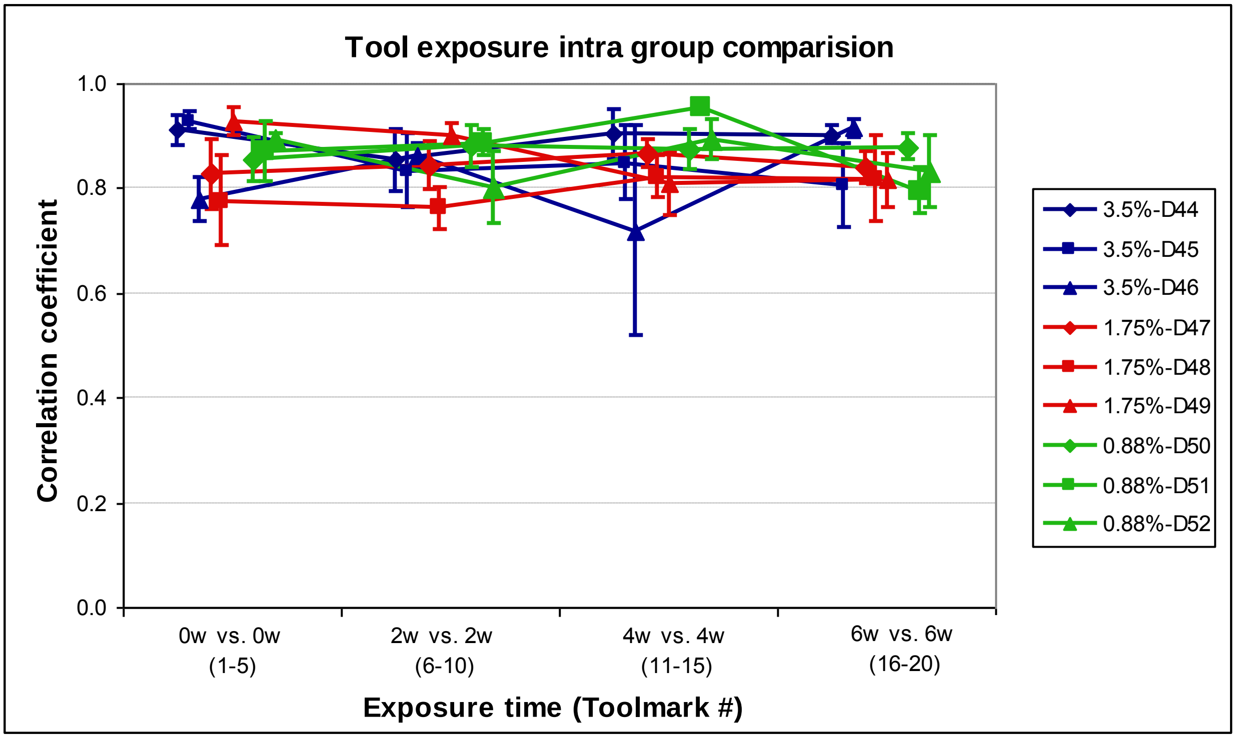


Figure 54. Tool exposure intra group comparison

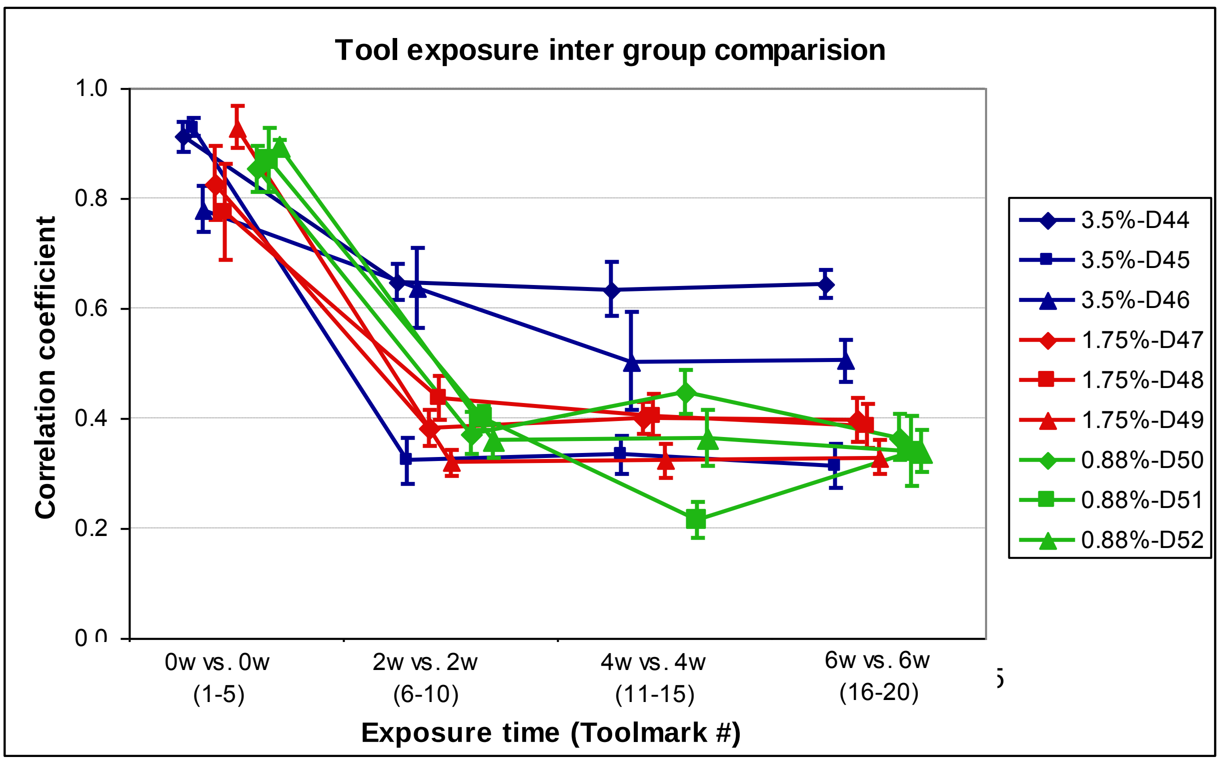


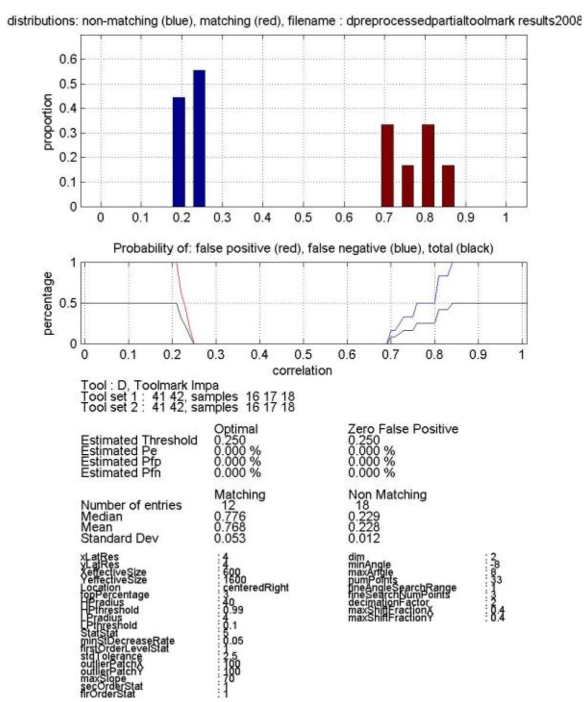
Figure 55. Tool exposure inter group comparison

3.3.4 Effect of Partial Tool Mark

For the partial tool marks experiment, the question of interest is whether a tool mark created by a diagonal cutter on a copper wire can be matched to a tool mark created by the same tool on a copper sheet. In order to answer this question, we begun by created three tool marks on a copper sheet as shown in Figure 17 for each of D41 and D42. These tool marks were labeled D41-101, D41-102 and D41-103 for tool D41, and, D42-101, D42-102 and D42-103 for tool D42.

Figure 57 shows the matching and non-matching distributions resulting from the comparison of the tool marks created by D41 and D42 on **copper sheet**. For comparison purposes, Figure 56 shows the matching and non-matching distributions resulting from the comparison of tool marks created by the same tools on **copper wire**. As can be seen from these plots, the distributions are very similar, indicating that the tool marks created on copper wire, even though much smaller in size, provide as much information to allow for discrimination between matching and non-matching pairs as those created on copper sheet (it should be noted that for the purposes of this study, we have the benefit of tool marks created under controlled conditions).

Figure 58 shows the matching and non-matching distributions resulting from the comparison of tool marks created by D41 and D42, **where in this instance we are comparing tool marks created on copper wire against tool marks created on copper sheet**. The first and most important observation is that these distributions are quite distinct (non-overlapping), indicating that the use of copper sheets in the identification of diagonal cutter tool marks on copper wire



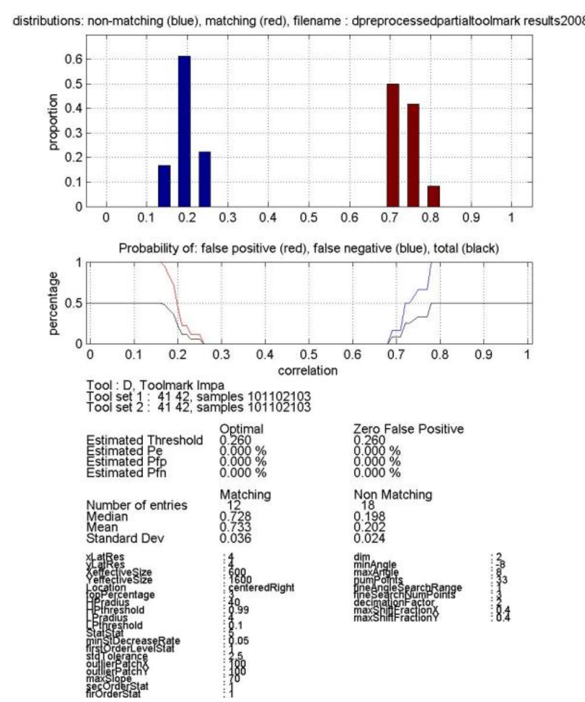


Figure 56: Distribution of matching and non-matching similarity measures for tool marks created on copper wire using D41 and D42

Figure 57: Distribution of matching and non-matching similarity measures for tool marks created on copper sheet using D41 and D42

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should be feasible. In addition, notice that the median of the matching distribution resulting from the comparison of tool marks on wire against sheet is lower (0.56) than that obtained when tool marks on wire are compared among themselves (0.78) or tool marks on sheet are compared among themselves (0.73). This should not be surprising, as the interaction between the diagonal cutter and the copper media is expected to be slightly different when cutting a wire than when cutting a sheet.

These results are quite meaningful, for two reasons:

a) These results **indicate that the identification of diagonal cutter tool marks on wire can be achieved by comparing against a tool mark made on a copper sheet. Nevertheless, it is also apparent that the best way to make a comparison is to duplicate the conditions under which the original tool mark was created**. This is a well known practice among firearms and tool marks examiners.

b) These results also indicate that **the system used in this study could be of significant assistance to tool mark examiners**. In most cases, whenever a tool marks examiner needs to assess whether a given tool mark was created by a given diagonal cutter he/she does not know where on the blade could the tool mark have been made. **These results indicate that the system used in this study could assist the examiner by quickly identifying the location along the diagonal cutter's blade where the tool mark could have been created**.

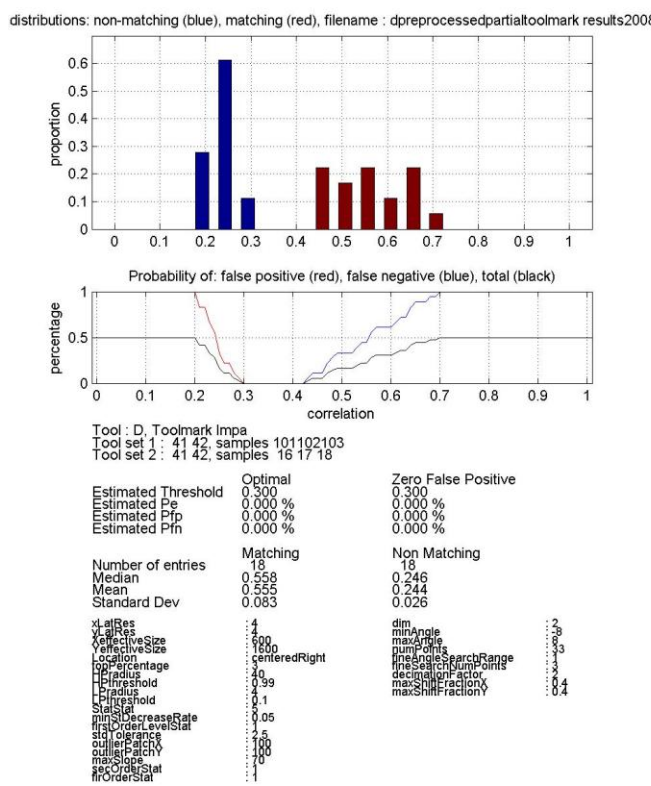

Figure 58: Distribution of matching and non-matching similarity measures of tool marks created on copper wire against tool marks created on copper sheet. Each of the comparisons considered in these distributions correspond to one tool mark created on a copper wire vs. a tool mark created on a copper sheet.

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4. Conclusions

The results of the present study strengthen the scientific foundations of tool mark identification in a variety of areas. However, it is important to consider the extent to which these results apply to other tools of the same type (tools of similar action). Strictly speaking, the conclusions of this study apply to the specific tool considered in this study. However, it is worth noting that the tools used in this study were selected - among other reasons - because there is nothing unique or unusual about them. In fact, to the best of our knowledge, they are fairly generic and representative of any tool of their type (in terms of quality or manufacture). Therefore, while only extensive research of all brands and models of tools can guarantee the accuracy of all encompassing conclusions, the author is confident that while the **detailed** results presented in this study may not repeat for all tools of the same type, the **general trends** observed for this tool will be repeated for all similar tools. With this in mind, the conclusions of the present study can be summarized as follows:

- The results of our preliminary experiment indicate that the tool marks deteriorate very slowly in air and tap water, but dramatically in salt water (see Figure 16). These results validate the choice of salt water as an environmental exposure media of interest.
- The study of tool wear effect unveils the fact that the most significant wear of a cutting tool (such as a diagonal cutter) takes place within the first individual cuts (one or two). After that, the effect of tool wear slows down rapidly as the working surface of the tool settles. Based on our experiments, we could verify that the tool marks created by diagonal cutters are easily identifiable after 300 cuts (see Figure 23). While we did not go beyond 300 cuts, the rate of change of the similarity measure between tool marks seems to indicate that identification should be possible well beyond this number of cuts. On the other hand, while the rate of change of the tool's working surface is slow, there is evidence that tool marks created in close proximity to each other (after a small number of cuts) will be more similar than tool marks created many cuts apart (see Figure 27).
- The study of tool mark exposure confirms our expectations that identification of a tool mark exposed to the environment becomes more challenging in a manner proportional to the time of exposure (see for example Figure 35) and the corrosiveness of the exposure media (see for example Figure 41). In as short time as 4 weeks of exposure to 3.5% salt water, the matching and non-matching distribution of tool mark similarity measures overlap significantly, indicating that these tool marks would become challenging to identify. In the case of 1.75% salt water identification becomes challenging somewhat later (perhaps between 4 and 6 weeks, see Figure 36), while in the case of 0.88% salt water concentration identification appears to be possible even after 6 weeks (see Figure 37).
- The study of tool exposure, the time frame at which the identification of tool marks becomes challenging is even shorter than in the case of tool mark exposure. In as little as 2 weeks of exposure to salt water the distribution of the matching similarity measure overlaps significantly with the non-matching distribution for all concentrations, indicating

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that these tool marks would be challenging to identify (see Figure 44, Figure 45, Figure 46). Not surprisingly, the tool marks created while the tool is at a given level of exposure (intra group comparisons) are easily identifiable among themselves (see Figure 48, Figure 49, Figure 50).

- The study of partial tool marks validates the premise that a partial tool mark can provide satisfactory ground for identification; just as reliable as a complete tool mark (see Figure 56 and Figure 57). In addition, it validates the fact that the identification of diagonal cutter tool marks on wire can be achieved by comparing against a tool mark made on a copper sheet (see Figure 58). Nevertheless, it is also apparent that the best way to make a comparison is to duplicate the conditions under which the original tool mark was created. This is a well known practice among firearms and tool marks examiners

It is important to understand the results of this study in the appropriate context. While the above statements are significant, it is important to remember that ultimately each tool and tool mark is unique and it may behave in unique ways. Take for example the case of tool exposure, 3.5% concentration (Figure 44). Notice that the matching distribution of the inter-group comparison of tool marks corresponding to tool D44 (and to a lesser extent D46) did not behave in the same manner as the corresponding matching distributions of all other tools tested in this experiment. While for all other tools the matching distributions become overlapped with their corresponding non-matching distribution as exposure time increased, this was not the case for D44. **This indicates that the tool marks created by D44 could have been identified even after being exposed to salt water at 3.5% concentration for 6 weeks, and perhaps longer!** This contradicts the behavior of all other tool marks in the tool exposure experiment. Is it possible that the media used to create these tool marks was different from all other? No, because the same length of wire was used to make all tool marks. We speculate that the reason for this behavior is that the features found on the blade of this tool have an abundance of relatively large features (perhaps in a similar way as D55 as discussed in Section 3.3.1.2), therefore transferring large features to the tool marks created by it. Such features would be affected to a lesser degree by exposure than small features, which are the norm among other tools. In other words, the finishing of the blade of tool D44 is rougher than normal.

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6. Appendix A: Preparation of Tool marks

The following protocol should be followed with each tool and tool mark preparation.

1. Label tool with Tool ID as “Dxx” on the handler (See Figure 59) with engraver. Notice that the letter “D” is omitted on the handler.

2. Label blades “A” and “a” as Figure 59 shows. Make sure the labels are far enough from the blade so that they will not interfere with the tool mark areas.

3. Flip the tool, label blades “B” and “b” as Figure 60 shows. Make sure “B” and “A” are both on the upper side of the blade.

4. Mark the cutting point on the blade in a middle position as Figure 60 shows. Make sure the mark is far enough from the blade so that it will not interfere with the tool mark areas. All the following cuttings will be carried at this cutting point of the blade as the mark indicates.

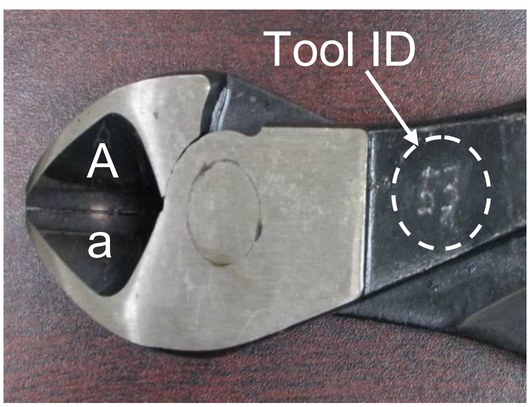

Figure 59: Picture of a tool with engraved Tool ID and blade label “A” and “a”.

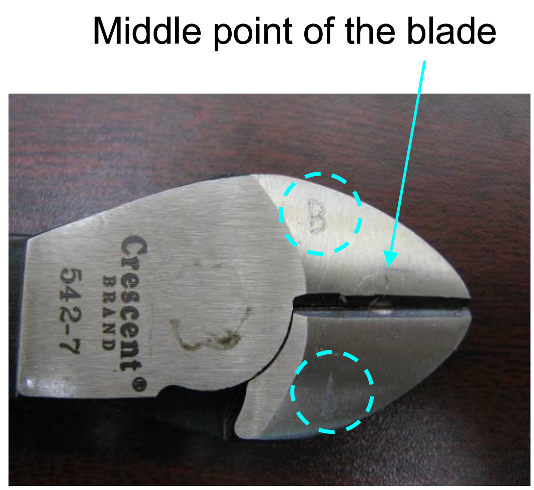

Figure 60: Picture of a tool with engraved label “B” and “b”, and middle mark of the blade.

5. Clean tool with appropriate de-greaser (possible acetone).

6. Cut the copper wire 5 times at the cutting point to get rid of the black paint and grease on the blades. Visually check the tool mark to make sure that the last (5^{th}) tool mark carries no paint on it, otherwise cutting once more and check again or more until the tool mark is clear. Normally 5 cuttings are enough.

The following steps are to prepare the control tool mark set which contains five tool marks.

8. Put the copper wire at the position of the marked cutting point of the blade, with blade “B” and “b” facing outside, i.e., facing the wire section that will be removed, and cut the wire. Make sure to remember the tool mark side generated by the blade “A”.

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9. Mark on the wire surface at the "A" side of the tool mark using permanent marker, as shown in Figure 61. Make sure not to mark in the tool mark area.

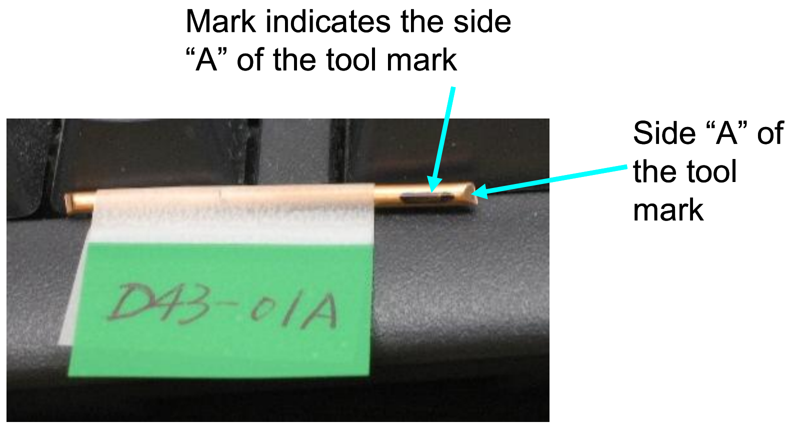

Figure 61: Picture of a control tool mark

10. Label the tool mark ID as Figure 61 shows. The tool mark ID is in form DXX-XXA. The two digits before '-' indicates the tool ID which is used to generate the tool mark, and the two digits after '-' indicates the tool ID. The letter "A" indicates that the tool mark side marked on the wire surface is generated by the side "A" of the tool. The first tool mark ID is DXX-01A.

11. Cut the other end of the wire (left side in Figure 61). Make sure to mark the "A" side on the next toolmark.

12. Label an envelope with the same tool mark ID labeled on the current cut loose tool mark (DXX-XXA). Put the tool mark into the envelope.

13. Repeat step 8 to step 12, generate more tool marks. Usually a set of toolmarks consist 5 toolmarks. Group and store these 5 toolmarks together.

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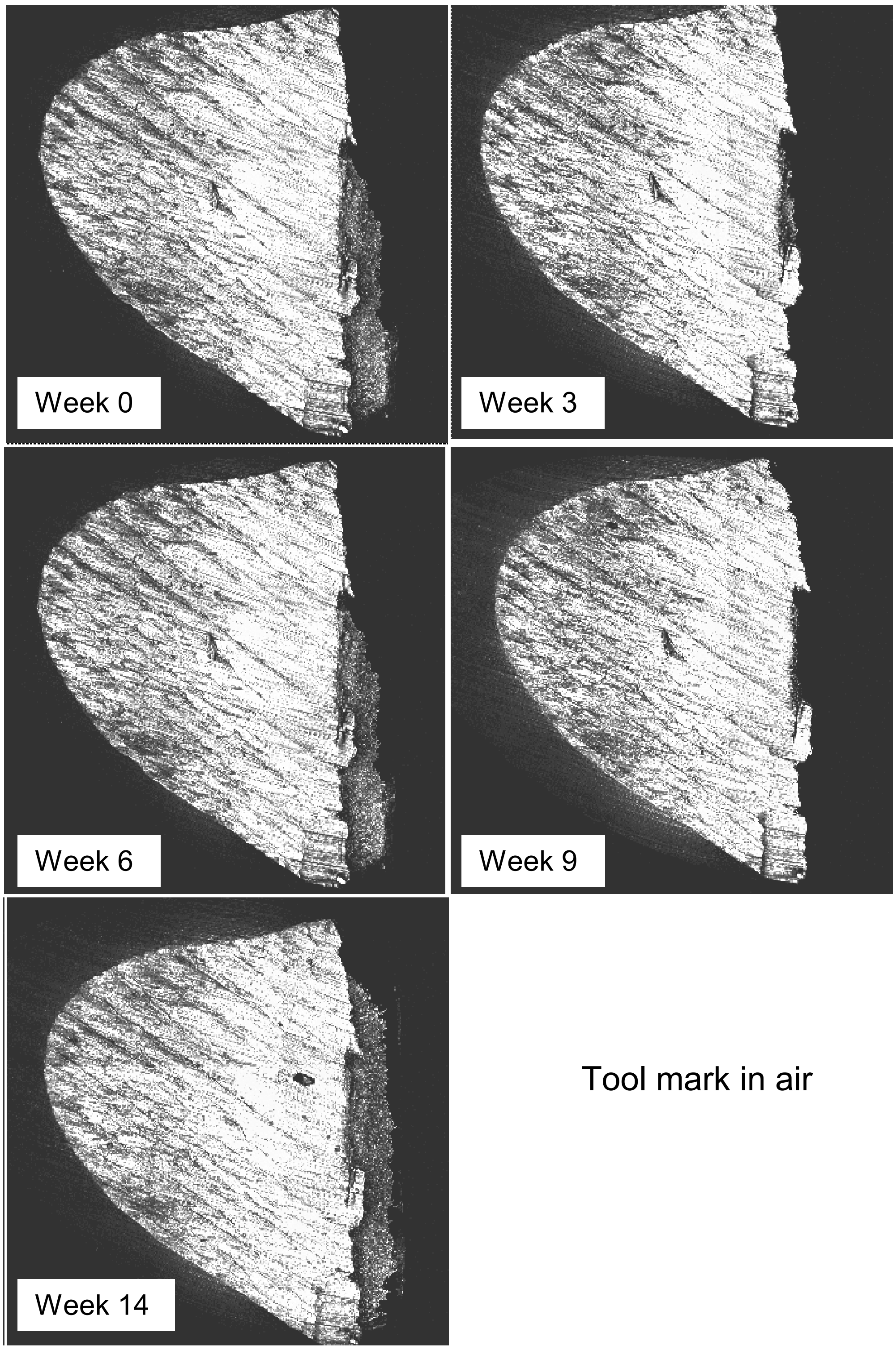
7. Appendix B: Images of tool Marks from the preliminary experiment

C.1. Exposure to air



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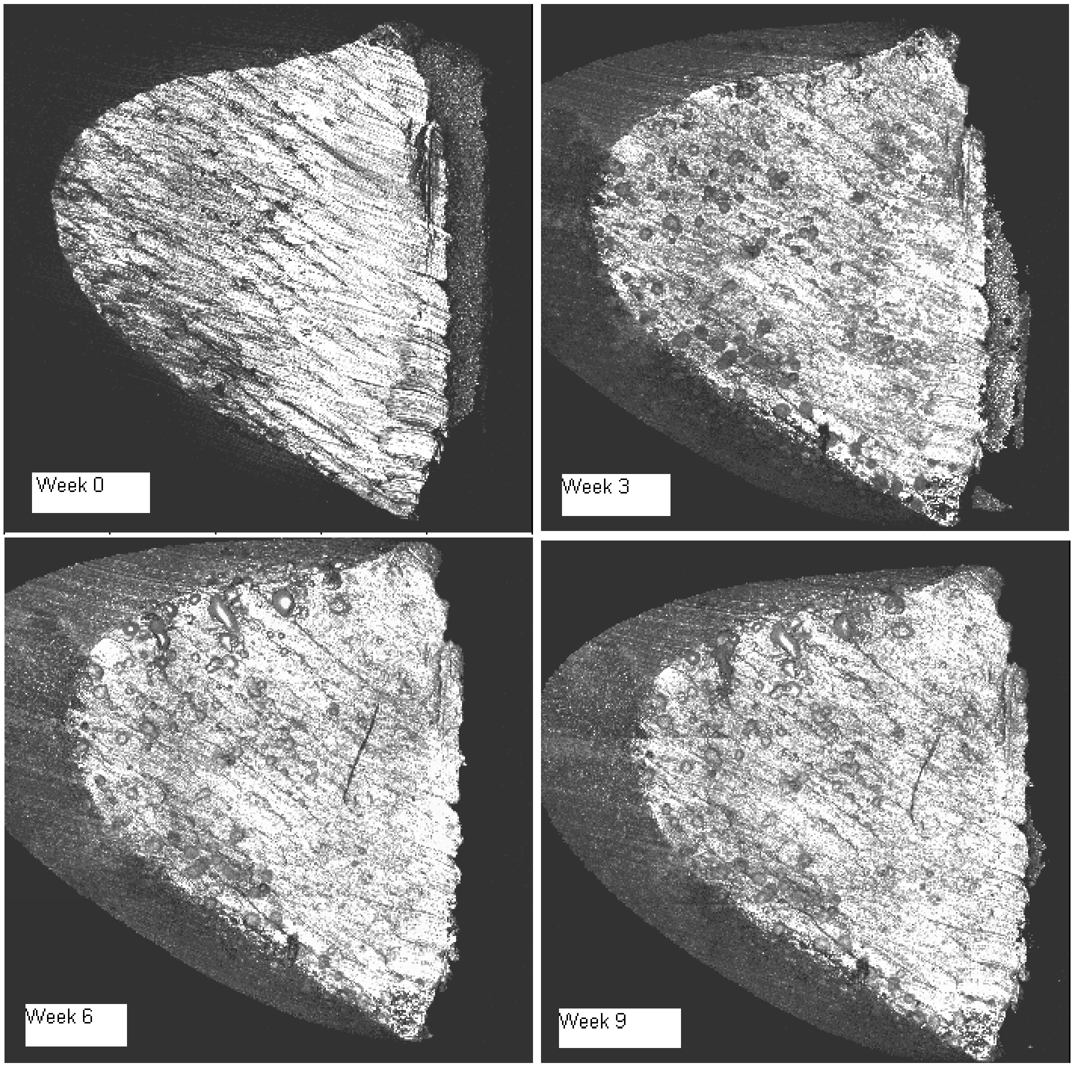
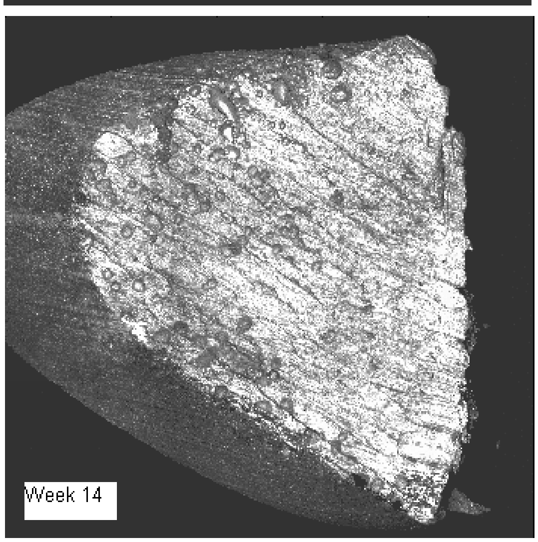
C.2. Exposure to clean water





Tool mark in clean water

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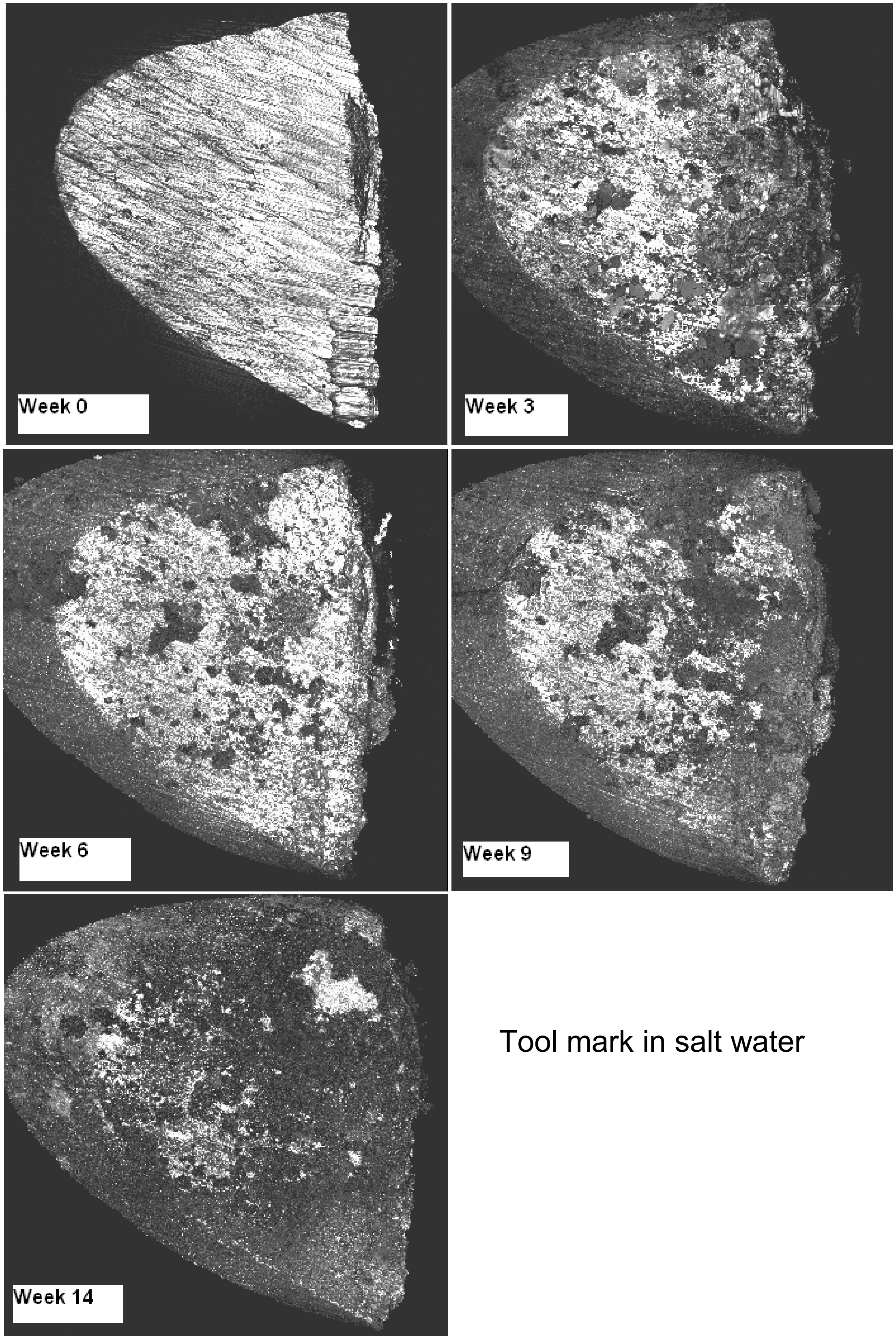
C.3. Exposure to salt water



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8. Appendix C: Experiment Plan

8.1 Appendix C.1: Tool wear experiment plan

Tool Wear				
Tool ID	**Tool Wear**	**Tool Mark ID**	**Image Date File Name**	**Note**
D53	0	D53-01 ~ D53-05	D053-P001 Impa ~ D053-P005 Impa	The exact first 5 toolmarks were discarded. Toolmark ID counting started from the 6th toolmark
	100 cuts	D53-06 ~ D53-10	D053-P006 Impa ~ D053-P010 Impa	
	200 cuts	D53-11 ~ D53-15	D053-P011 Impa ~ D053-P015 Impa	
	300 cuts	D53-16 ~ D53-20	D053-P016 Impa ~ D053-P020 Impa	
D54	0	D54-01 ~ D54-05	D054-P001 Impa ~ D054-P005 Impa	The exact first 5 toolmarks were discarded. Toolmark ID counting started from the 6th toolmark
	100 cuts	D54-06 ~ D54-10	D054-P006 Impa ~ D054-P010 Impa	
	200 cuts	D54-11 ~ D54-15	D054-P011 Impa ~ D054-P015 Impa	
	300 cuts	D54-16 ~ D54-20	D054-P016 Impa ~ D054-P020 Impa	
D55	0	D55-01 ~ D55-20	D055-P001 Impa ~ D055-P020 Impa	D55-01 is exactly the first toolmark generated by D55

8.2 Appendix C.2: Tool mark exposure experiment plan

Tool Mark Exposure Experiment							
				Image Data File Name			
Tool ID	**Tool Mark ID**	**Notes**	**Container (Salinity)**	**0 week**	**2 week**	**4 week**	**6 week**
D41	D41-01 ~ D41-05	Control		D041-P001 Impa ~ D041-P005 Impa			
	D41-06 ~	Evidence	C1 (3.5%)	D041-P006 Impa	D041-P021 Impa	D041-P036 Impa	D041-P051 Impa

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	D41-10			~ D041-P010 Impa	~ D041-P025 Impa	~ D041-P040 Impa	~ D041-P055 Impa
	D41-11 ~ D41-15	Evidence	C2 (1.75%)	D041-P011 Impa ~ D041-P015 Impa	D041-P026 Impa ~ D041-P030 Impa	D041-P041 Impa ~ D041-P045 Impa	D041-P056 Impa ~ D041-P060 Impa
	D41-16 ~ D41-20	Evidence	C3 (0.875%)	D041-P016 Impa ~ D041-P020 Impa	D041-P031 Impa ~ D041-P035 Impa	D041-P046 Impa ~ D041-P050 Impa	D041-P061 Impa ~ D041-P065 Impa
D42	D42-01 ~ D42-05	Control		D042-P001 Impa ~ D042-P005 Impa			
	D42-06 ~ D42-10	Evidence	C1 (3.5%)	D042-P006 Impa ~ D042-P010 Impa	D042-P021 Impa ~ D042-P025 Impa	D042-P036 Impa ~ D042-P040 Impa	D042-P051 Impa ~ D042-P055 Impa
	D42-11 ~ D42-15	Evidence	C2 (1.75%)	D042-P011 Impa ~ D042-P015 Impa	D042-P026 Impa ~ D042-P030 Impa	D042-P041 Impa ~ D042-P045 Impa	D042-P056 Impa ~ D042-P060 Impa
	D42-16 ~ D42-20	Evidence	C3 (0.875%)	D042-P016 Impa ~ D042-P020 Impa	D042-P031 Impa ~ D042-P035 Impa	D042-P046 Impa ~ D042-P050 Impa	D042-P061 Impa ~ D042-P065 Impa
D43	D43-01 ~ D43-05	Control		D043-P001 Impa ~ D043-P005 Impa			
	D43-06 ~ D43-10	Evidence	C1 (3.5%)	D043-P006 Impa ~ D043-P010 Impa	D043-P021 Impa ~ D043-P025 Impa	D043-P036 Impa ~ D043-P040 Impa	D043-P051 Impa ~ D043-P055 Impa
	D43-11 ~ D43-15	Evidence	C2 (1.75%)	D043-P011 Impa ~ D043-P015 Impa	D043-P026 Impa ~ D043-P030 Impa	D043-P041 Impa ~ D043-P045 Impa	D043-P056 Impa ~ D043-P060 Impa
	D43-16 ~ D43-20	Evidence	C3 (0.875%)	D043-P016 Impa ~ D043-P020 Impa	D043-P031 Impa ~ D043-P035 Impa	D043-P046 Impa ~ D043-P050 Impa	D043-P061 Impa ~ D043-P065 Impa

8.3 Appendix C.3: Tool exposure experiment plan

Tool Exposure				
Container (Salinity)	**Tool ID**	**Tool Exposure Period**	**Tool Mark ID**	**Image Data File Name**
C1 (3.5%)	**D44**	0	D44-01 ~ D44-05	D044-P001 Impa ~ D044-P005 Impa
		2 weeks	D44-06 ~ D44-10	D044-P006 Impa ~ D044-P010 Impa
		4 weeks	D44-11 ~ D44-15	D044-P011 Impa ~ D044-P015 Impa
		6 weeks	D44-16 ~ D44-20	D044-P016 Impa ~ D044-P020 Impa
	D45	0	D45-01 ~ D45-05	D045-P001 Impa ~ D045-P005 Impa
		2 weeks	D45-06 ~ D45-10	D045-P006 Impa ~ D045-P010 Impa
		4 weeks	D45-11 ~ D45-15	D045-P011 Impa ~ D045-P015 Impa
		6 weeks	D45-16 ~ D45-20	D045-P016 Impa ~ D045-P020 Impa

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	D46	0	D46-01 ~ D46-05	D046-P001 Impa ~ D046-P005 Impa
		2 weeks	D46-06 ~ D46-10	D046-P006 Impa ~ D046-P010 Impa
		4 weeks	D46-11 ~ D46-15	D046-P011 Impa ~ D046-P015 Impa
		6 weeks	D46-16 ~ D46-20	D046-P016 Impa ~ D046-P020 Impa
C2 (1.75%)	**D47**	0	D47-01 ~ D47-05	D047-P001 Impa ~ D047-P005 Impa
		2 weeks	D47-06 ~ D47-10	D047-P006 Impa ~ D047-P010 Impa
		4 weeks	D47-11 ~ D47-15	D047-P011 Impa ~ D047-P015 Impa
		6 weeks	D47-16 ~ D47-20	D047-P016 Impa ~ D047-P020 Impa
	D48	0	D48-01 ~ D48-05	D048-P001 Impa ~ D048-P005 Impa
		2 weeks	D48-06 ~ D48-10	D048-P006 Impa ~ D048-P010 Impa
		4 weeks	D48-11 ~ D48-15	D048-P011 Impa ~ D048-P015 Impa
		6 weeks	D48-16 ~ D48-20	D048-P016 Impa ~ D048-P020 Impa
	D49	0	D49-01 ~ D49-05	D049-P001 Impa ~ D049-P005 Impa
		2 weeks	D49-06 ~ D49-10	D049-P006 Impa ~ D049-P010 Impa
		4 weeks	D49-11 ~ D49-15	D049-P011 Impa ~ D049-P015 Impa
		6 weeks	D49-16 ~ D49-20	D049-P016 Impa ~ D049-P020 Impa
C3 (0.88%)	**D50**	0	D50-01 ~ D50-05	D050-P001 Impa ~ D050-P005 Impa
		2 weeks	D50-06 ~ D50-10	D050-P006 Impa ~ D050-P010 Impa
		4 weeks	D50-11 ~ D50-15	D050-P011 Impa ~ D050-P015 Impa
		6 weeks	D50-16 ~ D50-20	D050-P016 Impa ~ D050-P020 Impa
	D51	0	D51-01 ~ D51-05	D051-P001 Impa ~ D051-P005 Impa
		2 weeks	D51-06 ~ D51-10	D051-P006 Impa ~ D051-P010 Impa
		4 weeks	D51-11 ~ D51-15	D051-P011 Impa ~ D051-P015 Impa
		6 weeks	D51-16 ~ D51-20	D051-P016 Impa ~ D051-P020 Impa
	D52	0	D52-01 ~ D52-05	D052-P001 Impa ~ D052-P005 Impa
		2 weeks	D52-06 ~ D52-10	D052-P006 Impa ~ D052-P010 Impa
		4 weeks	D52-11 ~ D52-15	D052-P011 Impa ~ D052-P015 Impa
		6 weeks	D52-16 ~ D52-20	D052-P016 Impa ~ D052-P020 Impa

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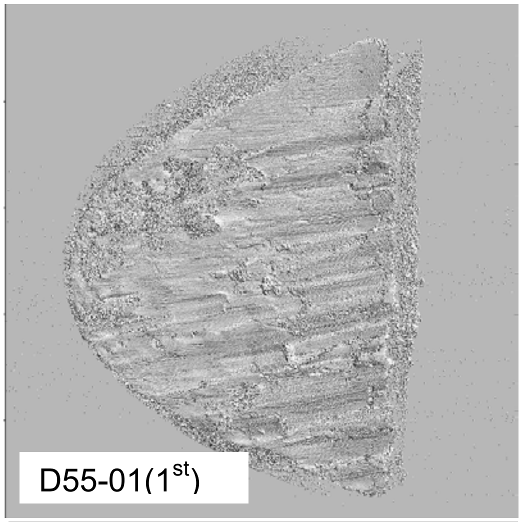
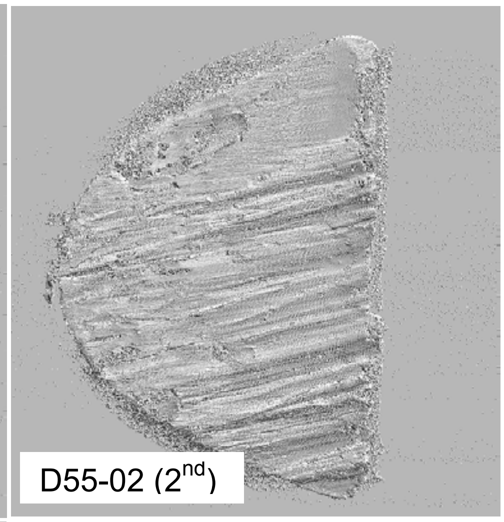
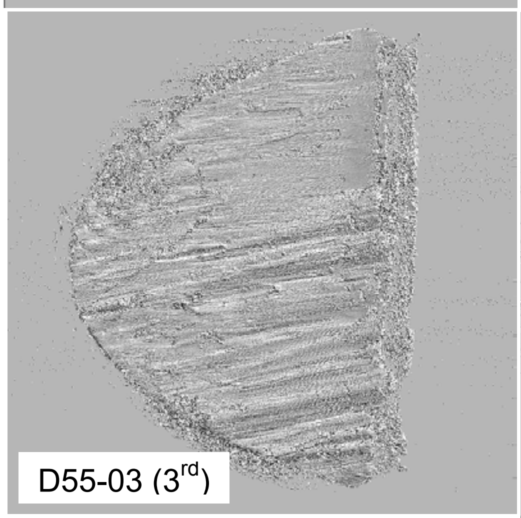
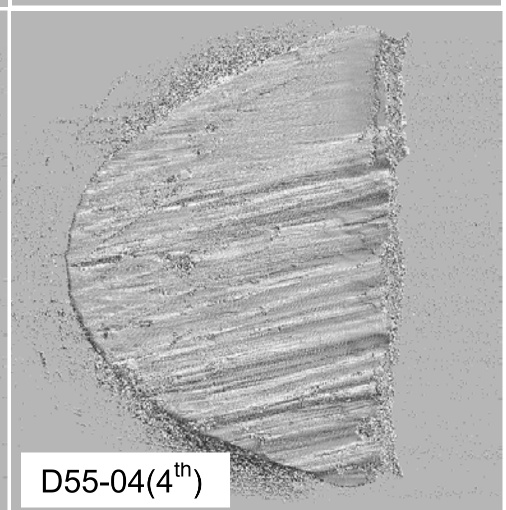
9. Appendix D: Images of tool marks from the tool wear experiment

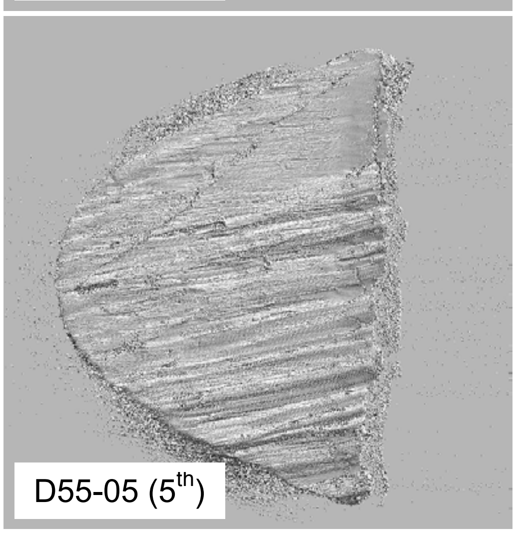
9.1 Appendix D.1: Comparison of topological images of tool marks from D55











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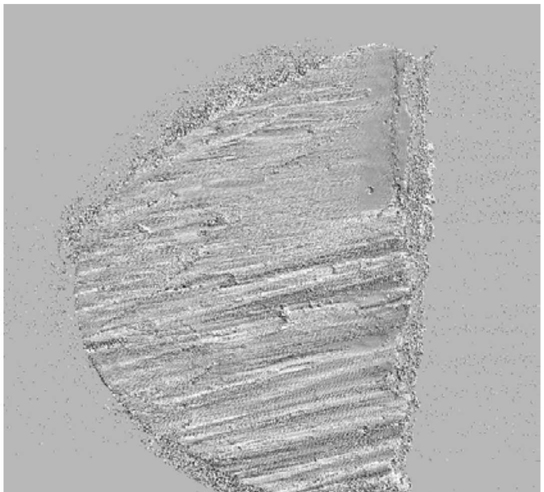
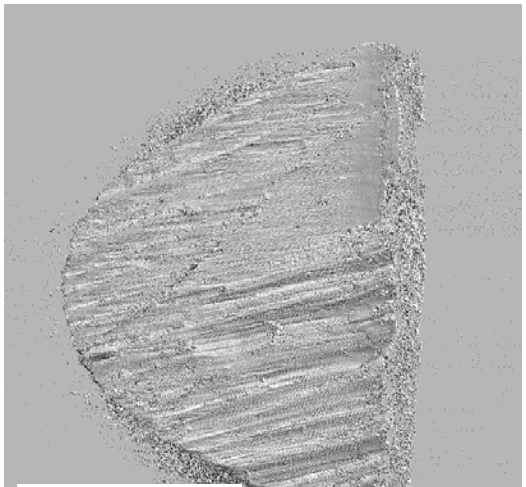
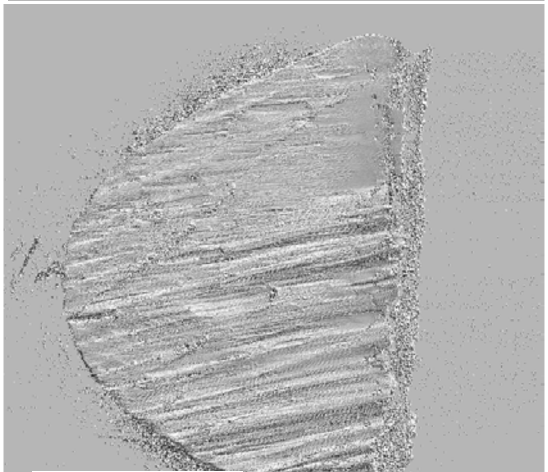
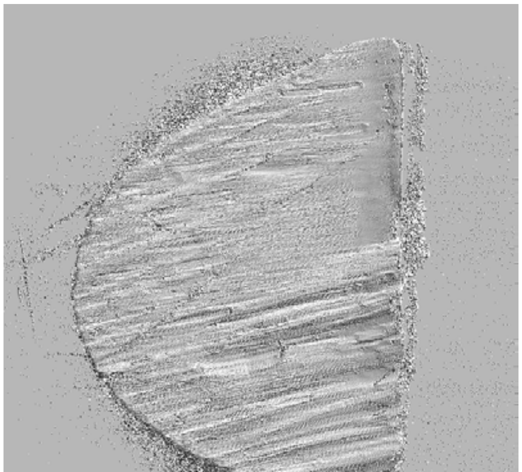
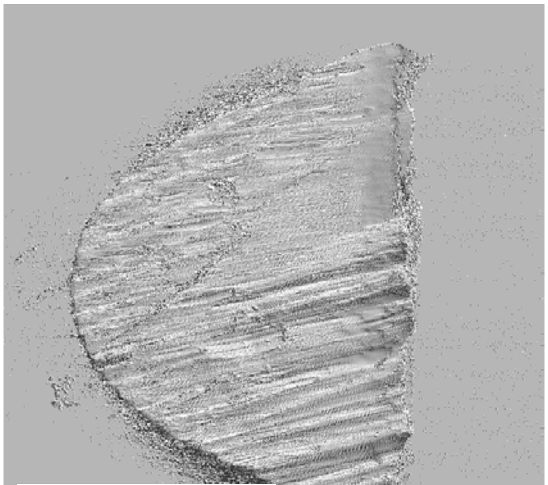

D55-06(6th)


D55-07 (7th)


D55-08 (8th)


D55-09 (9th)


D55-10 (10th)

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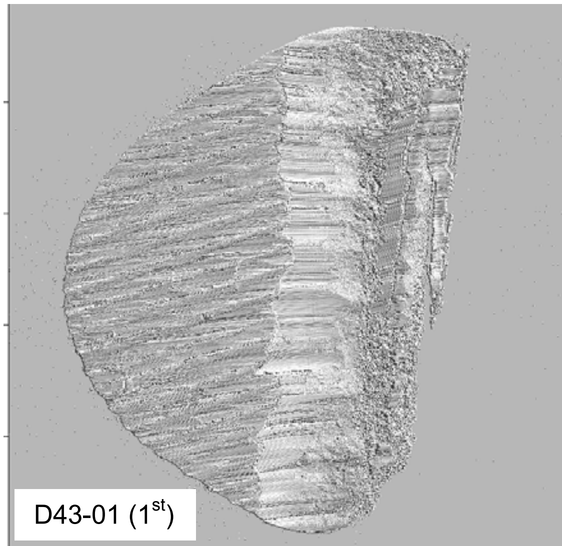
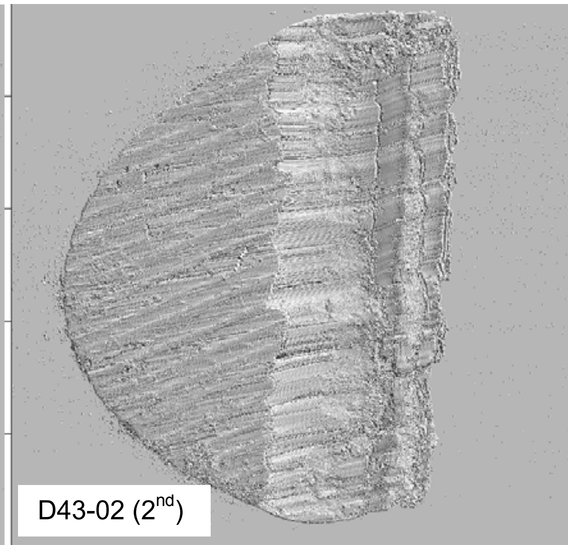
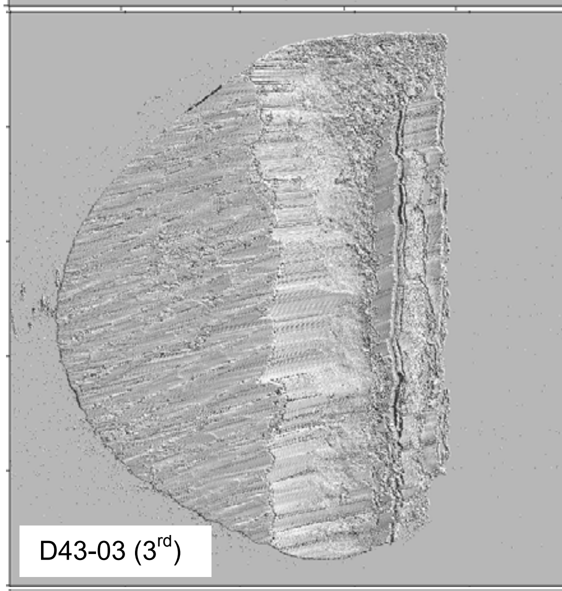
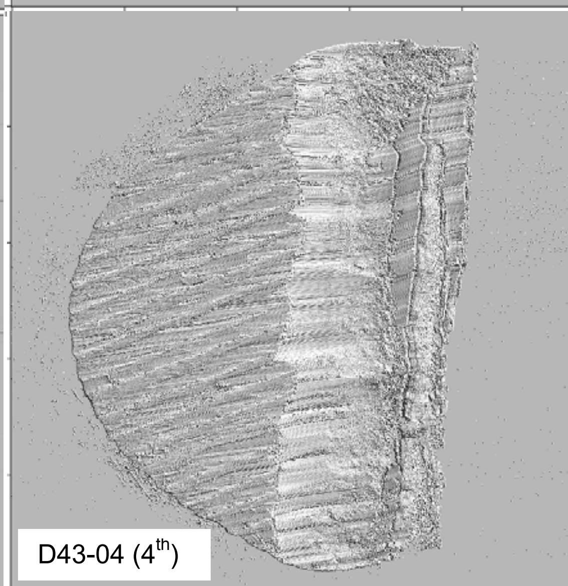
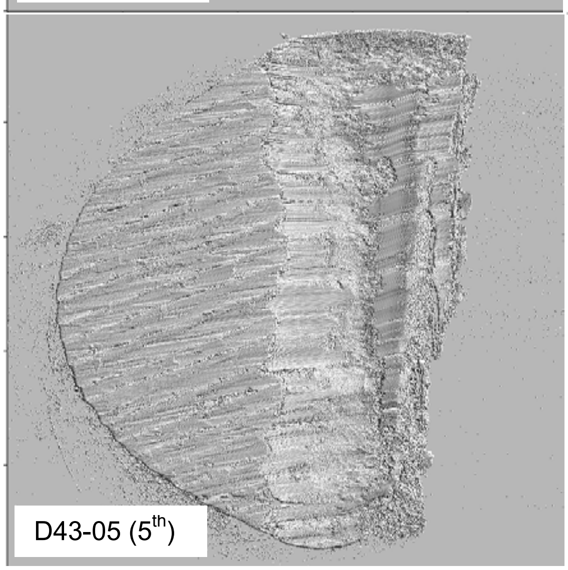
9.2 Appendix D.2: Comparison of topological images of tool marks from D43


D43-01 (1st)


D43-02 (2nd)


D43-03 (3rd)


D43-04 (4th)


D43-05 (5th)

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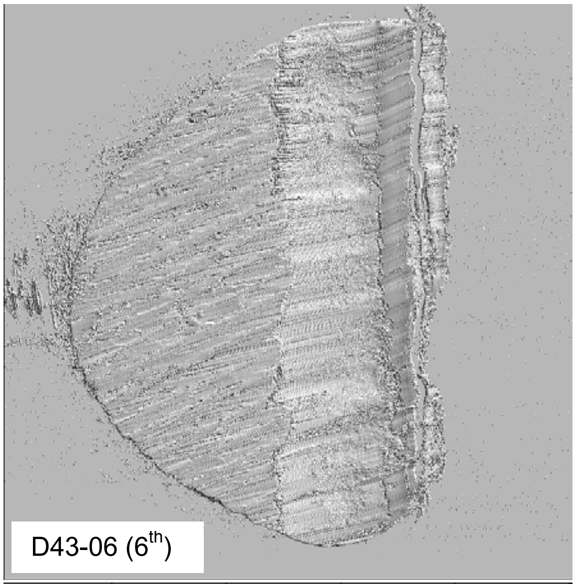
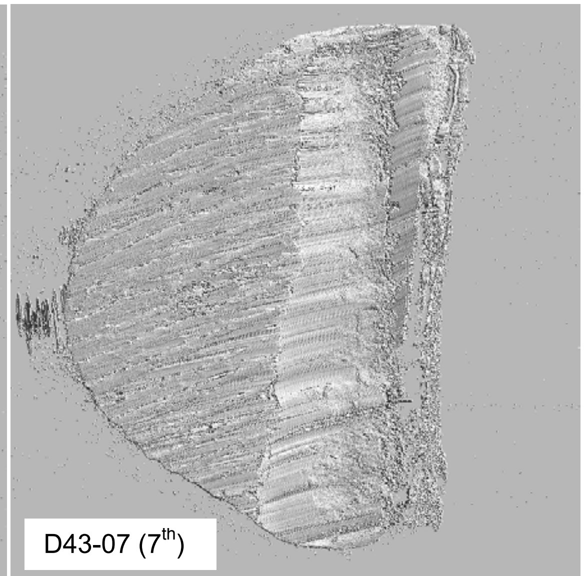
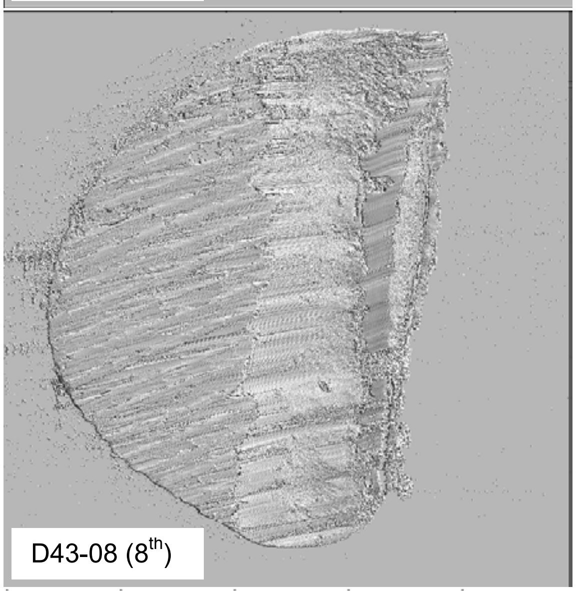


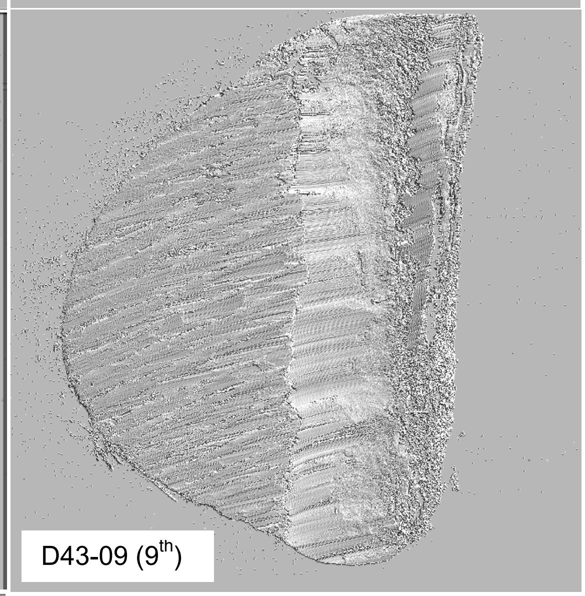
D43-06 (6th)



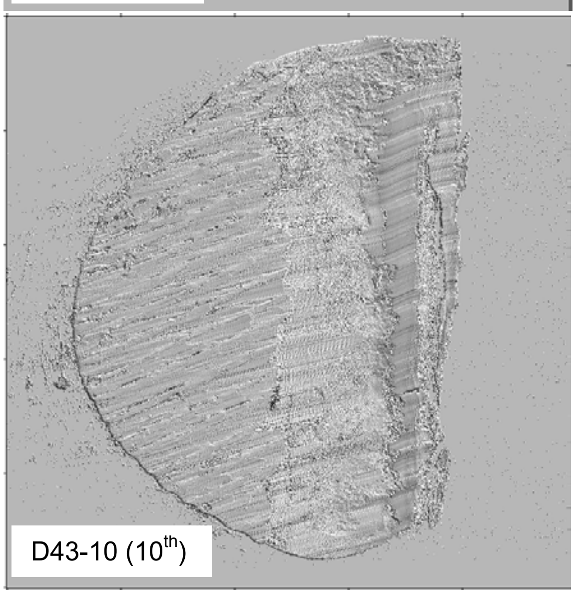
D43-07 (7th)



D43-08 (8th)



D43-09 (9th)



D43-10 (10th)

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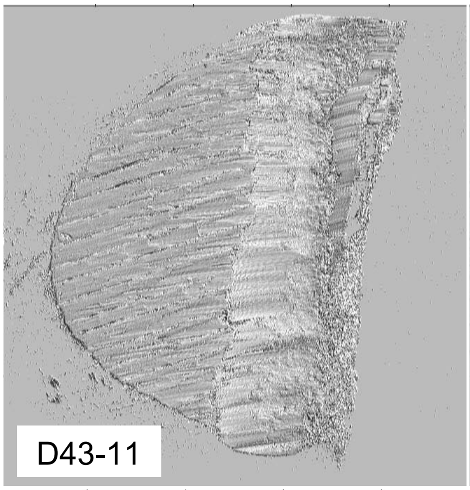
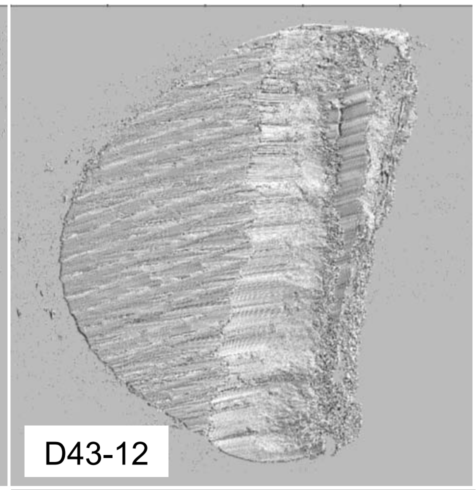
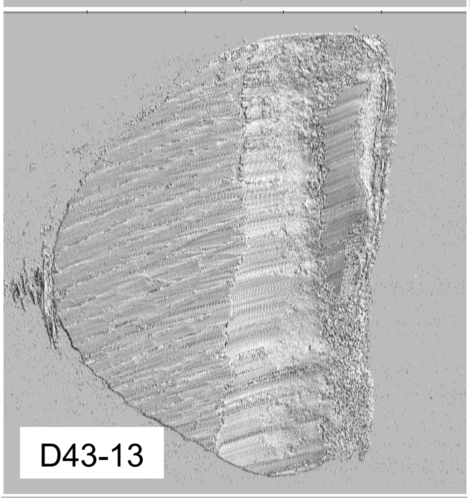
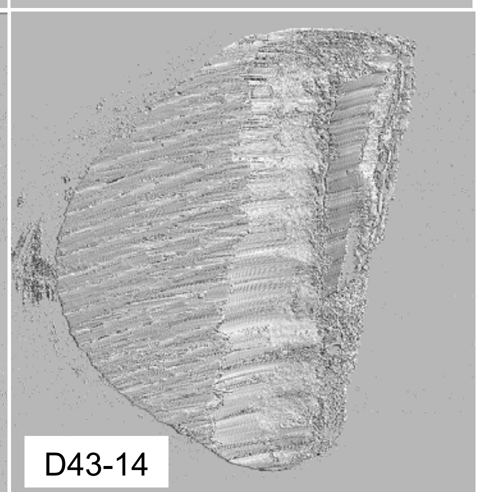
10. Appendix E: Images of tool Marks from the tool exposure experiment

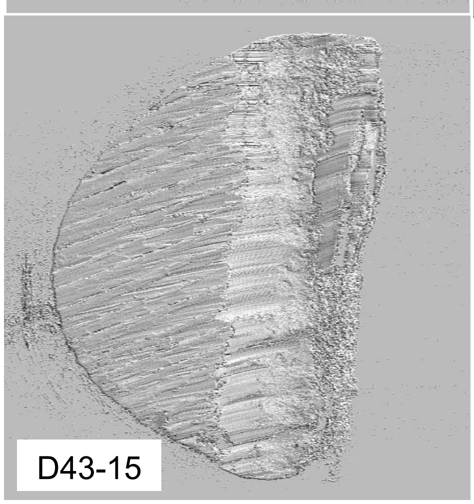
10.1 Appendix E.1: Images of Tool Marks from D43 with 1.75% exposure





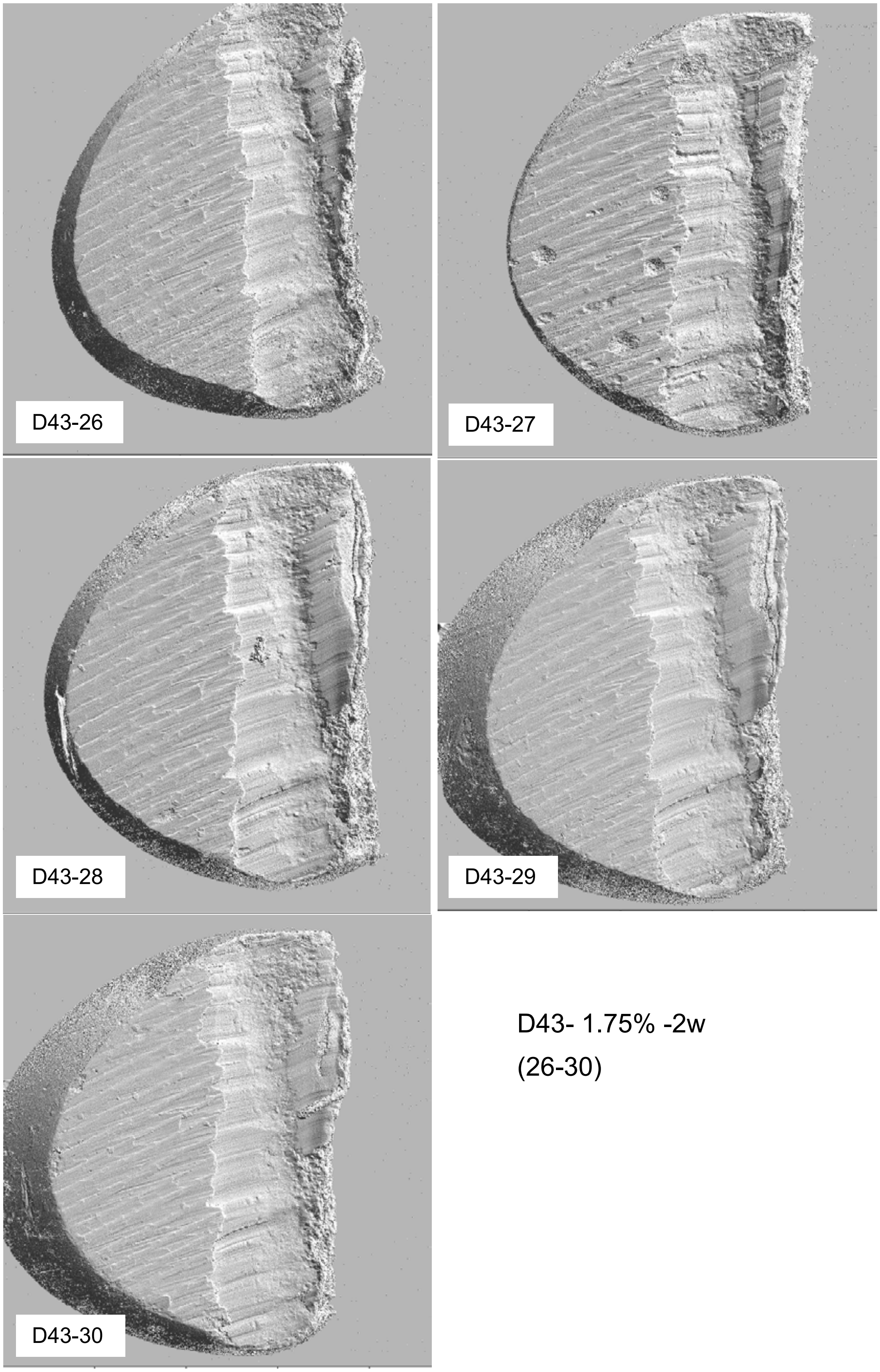






D43- 1.75% -0w

(11-15)



D43- 1.75% -2w
(26-30)

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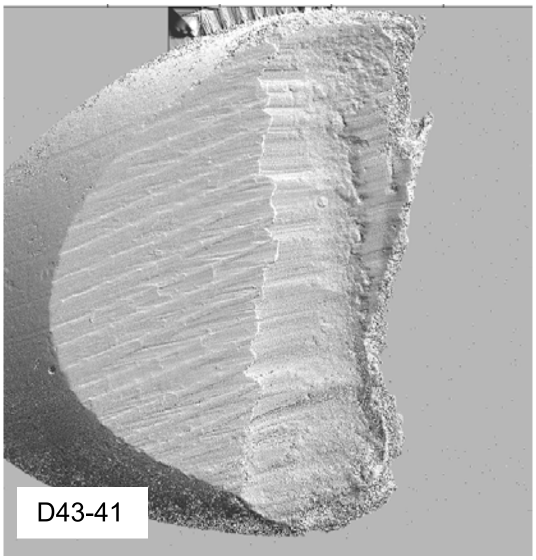

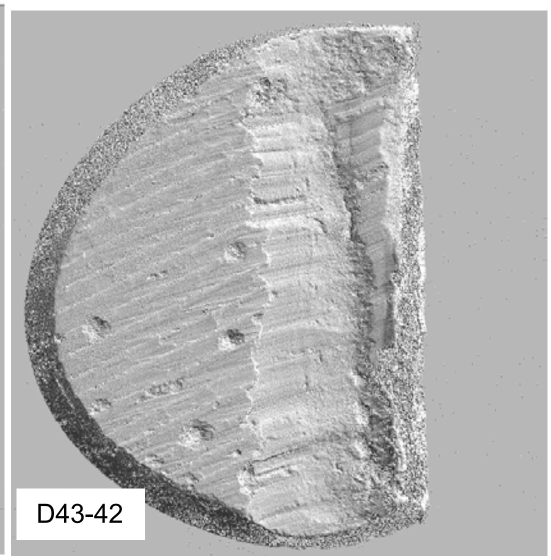

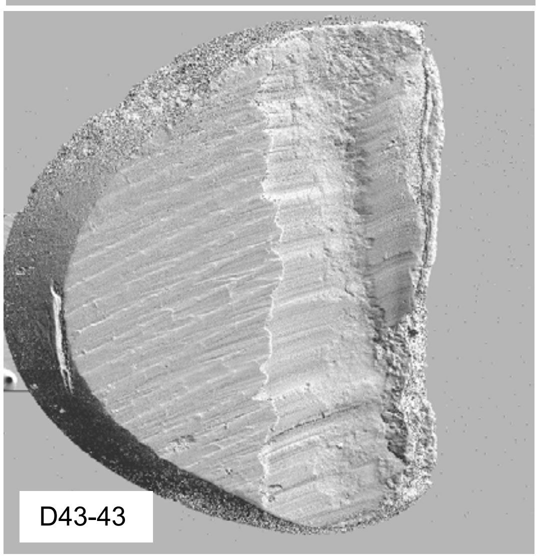

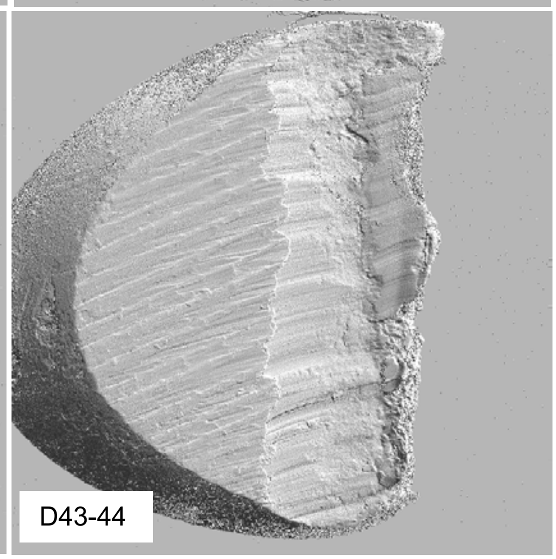

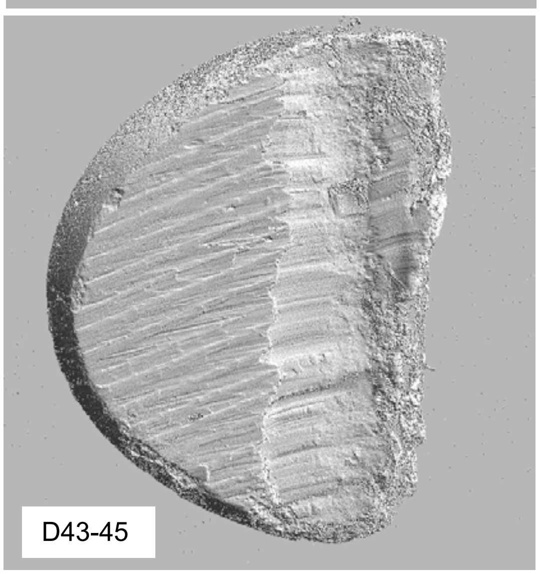

D43- 1.75% -4w
(41-45)

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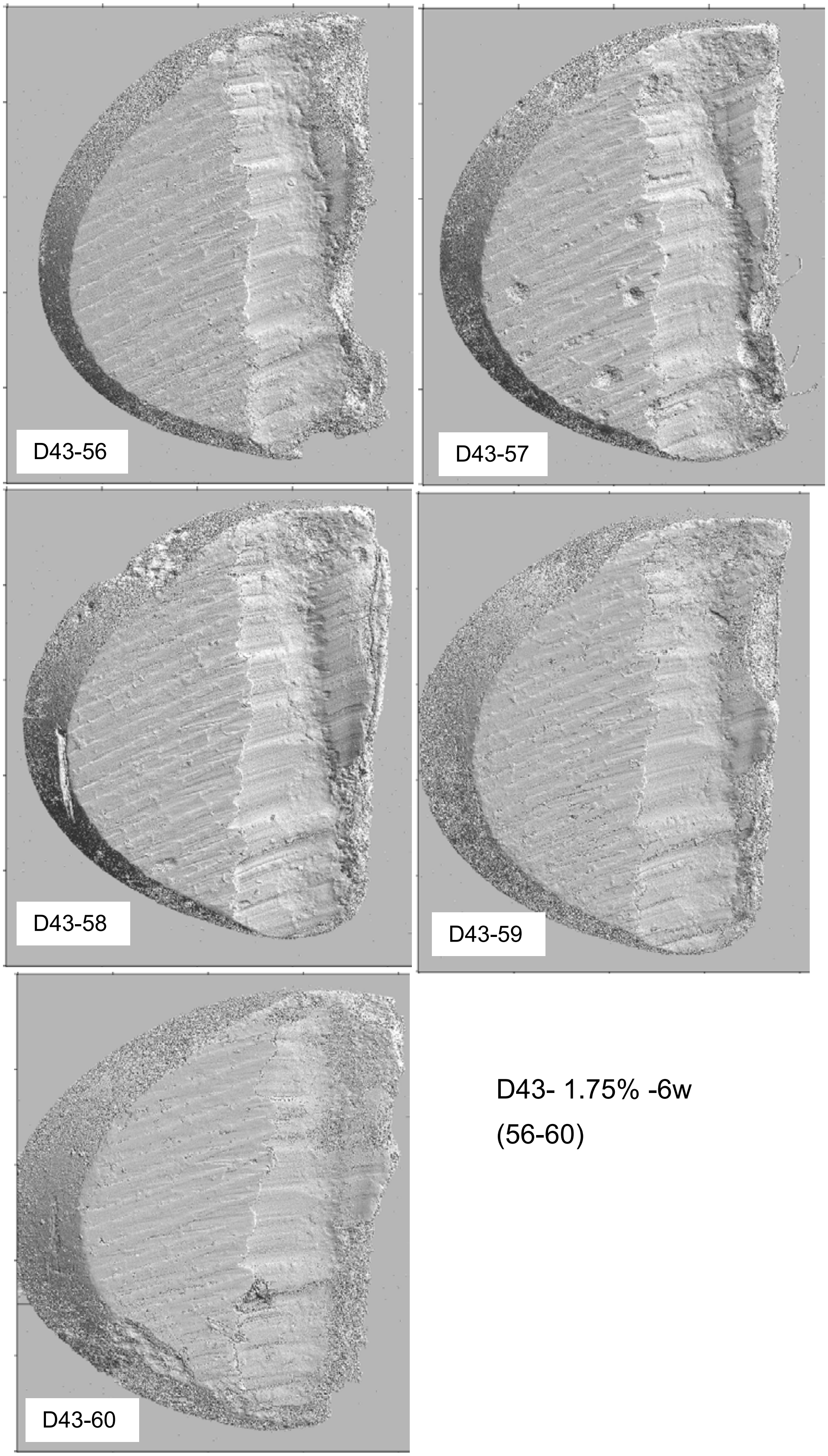

D43- 1.75% -6w
(56-60)