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FILL TUBE BORE INSPECTION WITH MACHINE VISION (U)

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Fill tube bore inspection with machine vision

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ABSTRACT

A semi-automated technique for bore inspection of small diameter tubes is presented. The inspections are performed to insure that the bore surfaces are free of contaminants or defects. The image collection scheme uses a borescope which is stepped along the length of the tube. An image is acquired at each step and portions from each image are combined to yield a planar image. Color analysis classifies the oxidation levels in the bore of the fill tubes. The analysis is performed by taking the image's mean values of the red, green, and blue intensities and computing a figure of merit which is then used to estimate the relative amount of oxidation. This estimation scheme was shown to have a high level of correlation with the tube oxidation levels and the quality of the subsequent welds as determined by metallographic evaluation. Surface imperfections are detected by a series of digital filtering steps followed by a statistical analysis of the resulting binary image. The frequency parameter of the Poisson distribution for the total image and image segments are computed. A statistical significance test is performed by comparing the frequency parameter of each segment to the global statistics of the image. Fine longitudinal scratches were detected with this method.

1. INTRODUCTION

Image processing and analysis algorithms have been developed to inspect the inside surfaces of small diameter tubes called stem tubes. An instrument called the True Color Tube Bore Inspection System (TCTBIS)¹ was used for this work. This instrument was originally intended to improve the imaging for pre-weld inspections of the interior of the stem tubes. These stem tubes are used for high pressure gas transfer systems and visual inspection is required to determine their suitability for welding. At present there is no accepted direct method of nondestructively evaluating these welds². Therefore the assessment of the weld integrity is based on a pre-weld inspection of the tube bore; evaluation of the pinch weld parameters, and periodic destructive evaluation. The TCTBIS was used to develop a semi-automated technique for the tube bore inspection. The inspection is performed to insure that bore surfaces are free of flaws or contaminants (oxides, corrosion products, and foreign matter such as metal chips or lint) that could prevent adequate closure by subsequent pinch welding.

The image collection scheme uses a forward viewing borescope which is stepped along the length of the tube being inspected. An image is acquired at each step and circular portions from each image are combined to yield an "unwrapped" image in which the usual image from the borescope is converted to a planar image which simulates the unwrapping of the tube. The final image contains considerably more information than the image from a single axial location and looks as if the tube were slit along its length and laid flat. This unwrapping enhances visual interpretation of the inside surface of the tube but still results in a very subjective and sometimes erroneous interpretation of the surface conditions. Therefore, subsequent to the acquisition of this image, both color image analysis and gray scale processing and analysis methods are being developed to detect and classify surface defects in the tube bore.

A color analysis technique has been implemented which classifies the oxidation levels in the bore of the fill tubes. The analysis is performed by taking the mean value of the red, green, and blue intensities of the entire image and computing a figure of merit. The value of this figure of merit is then used to estimate the relative amount of oxidation on the inside surface of the tubes. Sensitivity studies have shown that the color analysis is insensitive to the level of illumination from the borescope light source over a large range. This estimation scheme was shown to have very a high degree of correlation with the oxide layer thicknesses. Subsequent metallographic analysis of tube closure welds also showed nearly perfect correlation with the image analysis predictions.

Surface imperfections are detected by a series of digital filtering steps followed by a statistical analysis of the resulting filtered images. A monochrome image is generated from the color image. After filtering the image is converted to a binary image. The subsequent analysis proceeds by first computing the frequency parameter of the Poisson distribution for the total image. The image is then divided into regions and the Poisson frequency is computed for each region. Finally, a statistical significance test is performed on each region to ascertain the likeness of each region with the global statistics. This technique was used to detect fine longitudinal scratches.

2. EXPERIMENTAL SETUP

The main components of the TCTBIS are a small diameter borescope which is interfaced to an RGB camera. This imaging system is interfaced to a microcomputer with three frame grabbers for storage of the red, green, and blue images. The system also contains electro-mechanical positioning equipment for initial alignment and subsequent automatic inspection of the tube bore. Software has been developed in a LOTUS 123 environment to perform subsequent analysis on the stored images. This analysis includes statistical parameters for the three separate color images in the inspected region. One unique feature of the TCTBIS is the way in which it collects the image based on a technique called unwrapping. Several images of the tube bore are collected and portions of each image are combined to yield a rectangular image that appears as if the stem tube were slit along its length and laid out flat. This image contains substantially more detail than a single borescopic image.

A schematic of the TCTBIS can be seen in Figure 1. The tube bore is imaged with an Instrument Technology, Inc. (ITI), Model 124300-5-F forward viewing microborescope. Typical bore diameters are 1 to 2 mm. Illumination is provided by an ITI Model 12520 illuminator through an ITI Model 125500 fiber optic cable and optical fibers in the microborescope. The microborescope eyepiece is interfaced with a Pulnix Model TMC 54R/56R RGB video camera. The red, green, and blue images from the camera are acquired by three Datacube, Inc. Model IVG-120 video cards mounted in an IBM AT microcomputer. The RGB camera is held in a fixed position and the stem tube is moved along the borescope axis with a Unislide Model M092-FD08 stepping motor driving a Model B4009BJ positioner. The motion is controlled by the computer which steps the tube and acquires an image at each step. The total length inspected is one fourth of an inch. At each step the picture elements on a predetermined circle are stored in memory for later display as one column in the unwrapped image. The inspection takes about 4 minutes to complete and contains about 240,000 data points.

3. RESULTS AND DISCUSSION

The first series of test to be discussed were performed to demonstrate the feasibility of performing an automated computer sort of the oxidized stems by color detection. These tests were followed by tests to demonstrate the robustness of the sorting technique by checking its sensitivity to variations in signal level. The second series of tests for the detection of surface flaws on the inside of the stem tubes will follow.

3.1 Stem tube oxidation levels

Eighteen 304 Stainless Steel stem tubes were selected for these experiments. Fifteen of the tubes were oxidized by heating them in air. They were heated in groups of three at successively higher temperatures for a period of approximately 30 minutes. The three remaining tubes were left unheated. Table 1 gives the nominal oxidation temperatures with the specific identifying stem numbers. These stem numbers are stamped into the side of the stems so that there was very little chance for handling errors. The approximate thickness of the oxide film of each group is also included in Table 1. This thickness is based on Auger Electron Spectroscopy (AES) measurements of one sample from each group.

A photograph showing a set of six of the stems with increasing oxidation levels running left to right is shown in Figure 2. With no oxidation the stems have the usual silver metallic lustre. As the oxidation level increases the stems take on a straw-like color and appear to reflect less light. This decrease in total reflectivity was only partially borne out quantitatively by the subsequent analysis of the measurements. Sorting the stems by looking at their exteriors is much easier than trying to do the sort by looking at the borescope images. This is in part due to the variations in surface reflectivity and also the lack of the surroundings as a basis for reference.

Table 1 Stem Tubes Oxidation Levels

Level No.	Temperature	Stem Number	Approximate Oxide Film Thickness (Å)
0	Unaltered	R-745, R-765, R-770	126
1	550F(288C)	R-781, R-816, R-852	140
2	700F(371C)	R-755, R-786, R-821	350
3	850F(449C)	R-738, R-783, R-835	840
4	1000F(533C)	R-751, R-810, R-841	910
5	1150F(616C)	R-787, R-791, R-812	1722

Lack of spatial resolution in the images also seems to play a part in increasing this difficulty. The sorting technique was based on elementary color theory in which the levels of the red, green, and blue outputs were compared in a simple way to assess the color of the inside of the stem tubes. It is reiterated that the unwrapped images themselves were not used but only the numerical data obtained from those images. The actual oxidation levels of the stems were not known by the analyst until after the analysis was performed and the stems were sorted by the computer program. Only then was a comparison done with the actual oxidation level data.

The analysis is based on the assumption that color matching can be performed with the camera's three color bands and that the camera has a linear response in the light level range of interest. A further assumption is that the color is fairly uniform over the entire inspection field. This uniformity is only necessary to the extent that the statistical quantities computed by the system are relevant. Thus glints and light dispersion can occur so long as these effects represent only a small fraction of the image area. In this case one can then speak about an average brightness of the image both in total and in each spectral band. The TCTBIS stores three 8-bit color level values for each pixel in the unwrapped image so the dynamic range is a value from zero to 255 for each color band. The actual light level is unknown but it can be varied by increasing or decreasing the illumination level. Even with this capability some signals are too weak and some stem tubes could not be analyzed with the current illumination source, optical arrangement, or camera. This is clearly an area for improvement. For the purposes of these experiments the un-oxidized stems were selected so that this would not become a limiting factor. If the response of the camera is linear then the color can be expressed as a coordinate pair of the ratio of any two colors to the third. Thus the color integrated over the entire image can be written as:

$$C = C(r/b, g/b) \quad (1)$$

Where r , g , and b are the averages of the red, green, and blue responses, respectively. Naturally there are numerous complicating factors must be taken into account for a general spectrophotometric measurement of this type. On the other hand, when only comparative measurements of different samples are desired and the same light source, detectors, and other optical equipment are used, these measurements can be performed rather easily. This implies that for a practical inspection system, standards will be required for each type of stem tube. For example, different machining or drawing processes can have a large effect on the reflective properties of the stems. Therefore, a standard set of values for a particular type of stem tube obtained with the actual measuring instrument would have to be used as the basis for comparison. Maintaining such standards would also be used to compensate for long-term drift in the illumination and imaging systems.

The bar chart in Figure 3 shows the results of the automated sorting process which was performed. This bar chart has as its abscissa the stem numbers as given in Table 1. There are two parameters plotted with the ordinate giving the numerical value for both of them. One is the product of the ratios red to blue and green to blue resulting in the sorting parameter, S given by:

$$S = (r/b) * (g/b) = r * g / b^2 \quad (2)$$

The other is the root mean square average, A_{RMS} of the red, green, and blue values, given by:

$$A_{RMS} = [(r^2 + g^2 + b^2)/3]^{1/2} \quad (3)$$

S and A_{RMS} are based on the RGB cube model³ which treats the three colors as orthogonal vectors. Therefore A_{RMS} is proportional to the magnitude of the three dimensional color vector formed by the red, green, and blue vectors and hence the image brightness. The definition of S is not unique. It was chosen by noticing that as stainless steel becomes oxidized, the amount of blue becomes less in comparison to the red and green content as can be seen from a chromaticity diagram. Other combinations can result in a successful sort but not all combinations will.

Figure 3 (in comparison with Table 1) shows that the oxidation level was perfectly sorted based on S . The first three stems correspond to the zero oxidation level in Table 1 the second three correspond to level 1 and so on. Notice that only levels 0 through 3 are shown although the sort was perfect for the entire set of 18 stems. While one may see a general reduction of A_{RMS} with oxidation level, a sort based on this parameter alone would have failed as mentioned previously. The automatic sorting was performed by a spread sheet code called AS-EASY-AS⁴. Analysis of all of the data showed that the sort would not have been successful had it been based on any of the individual colors. The primary reason for this is that the light level of the total image was not constant and it did not correlate with the oxidation level. The individual colors were also normalized to A_{RMS} and used as a sort parameter. The normalized

values of red and green were also unsuccessful but only between oxidation levels 0 and 1. This is consistent with the difficulty that was encountered when the stems were visually inspected. The stems would have been successfully sorted by looking at the normalized value of blue; but only barely so. Not every combination of the three colors worked. For instance r^*g/A_{RMS} missed the most important distinction which is between the un-oxidized stems and the first level of oxidation. These results clearly demonstrate the potential of the TCTBIS to discriminate between different oxidation levels.

All of the measurements discussed so far were performed with the illumination light level set at a single value. Since this is such an obviously important parameter, a sensitivity study was performed to determine the effect of variations in the illumination level. In a practical system, the illumination level could vary both intentionally and by uncontrolled factors. The uncontrolled factors could be such things as lamp life or line voltage fluctuations. Factors that can affect the illumination that are controllable but still subject to error are: the exact location of the inspected area; the equipment warm up time; room temperature; and level setting. The sensitivity studies were performed both on oxidized and un-oxidized stems. These results are discussed in the following paragraphs.

The tests on the **un-oxidized stems** consisted of inspecting each of five un-oxidized stems at four different intensity levels. Two of the stems (R-765 and R-770) were the same as the un-oxidized stems inspected in the previous set of data. The remaining were additional un-oxidized stems. Figure 4 shows the results of these measurements. The bar chart in Figure 4 has the sorting parameter S , and the RMS intensity as before. The abscissa is the illumination level setting. In this chart each bar represents the average of the five stems measured at the four distinct illumination level settings as set by the dial on the illumination source. The RMS intensity increases monotonically through level 9 and then flattens out between levels 9 and 10. There doesn't appear to be any correlation between the intensity level and the sorting parameter. Furthermore, all of the values of S fall well below the values of the level one oxidized stems that were shown in Figure 3. For the stems that were common to both sets of experiments, the measured values of the sorting parameter are different. These differences did not effect the outcome of the sort but only emphasize how unanticipated variability can enter into the data. All of the average values of S given in Figure 4 are well below the values of S for the level one oxidation. In fact, only one reading out of the 20 taken exceeded the lowest value of S from level 1 oxidation results. The fact that the readings on the same stems is slightly different emphasize how the variability can effect the individual readings but not the final result.

The second set of illumination sensitivity studies were done on the **oxidized stems**. These results are shown in Figure 5. In these experiments, pairs of stems were oxidized to levels one, two, and three. These pairs were then inspected at intensity settings of 7, 8, 9, and 10. The results are plotted in three groups in Figure 5. The ordinate is the sorting parameter S , and each group consists of the two stems at each oxidation level. So, for example, the two left-most points in each grouping are for an intensity level setting of 7 for the stems numbered R-852 and R-781, respectively. The next two points are for the same stems with the intensity level of 8 and so on. This is repeated for an oxidation level of 2 in the center group and for an oxidation level of 3 in the third group. Two things are immediately apparent from the figure. Firstly, there is very little overlapping in the sorting parameter values from one oxidation level to the next. In fact there is none between levels 1 and 2. Secondly, the higher the oxidation level the more scatter there is in S . This second effect arises because the reflected light signal decreases and hence increases the number of pixels in which the light level is too low to give a good reading. This nonlinearity has the effect of putting noise into the data set which results in the observed scatter.

The above discussion clearly shows the potential for the TCTBIS to distinguish between stems that have undergone various levels of oxidation. The effect of oxidation level on pinch welds was also studied metallographically. It was found that there was a clear correlation between the quality of the pinch welds and the oxidation level. In an electric resistance weld, one expects to find little evidence of the contact surface between the welded pieces. If a pronounced surface is seen, it implies a low quality weld. It was found from these metallographic studies the weld surface became significantly more pronounced as the oxidation levels were increased.

In summary, the TCTBIS was demonstrated to have the ability to distinguish between oxidized and un-oxidized stem tubes and to rank them as to their relative amounts of oxidation. Furthermore, the oxidation levels were demonstrated to have a significant effect on weld quality. These two results when taken together clearly imply that the TCTBIS has the capability to automatically predict weld quality based on oxidation level in the weld zone of reservoir stem tubes. The detection of surface flaws as scratches are discussed next.

3.2 Surface imperfections

Surface imperfections have the potential to lead to poor quality welds in several different ways. For example, foreign matter trapped in the weld region could lead to excessive porosity in the weld microstructure or deep scratches could lead to incomplete tube closure. It should be noted that the bore surfaces have machining marks that consist mostly of circumferential lines due to drilling. During the pinch welding process, there is generally enough plastic flow to overcome these typical surface nonuniformities. In these experiments longitudinal scratches were detected since they are not normally encountered and could lead to a rejection of the piece if they were.

The analysis method (as in the color analysis) is based on quantitative analysis of the image rather than visual interpretation. As one might expect, detecting features was more complicated in certain ways than computing averages as was done for the color analysis. The approach was to do an autocorrelation in which regions of the total image were compared with the entire image. Prior to doing the autocorrelation, the image was low-passed filtered to remove noise introduced by the machining marks and other high frequency surface variations. The filtered image was then converted to a binary image and the binary noise was reduced by converting stand alone pixels to the surrounding pixel value. In general, surface imperfections of such a small scale would not effect the weld quality or never would have been detected by a human inspector in any event.

Five stems were analyzed with two of the stems being purposely scratched with a jewelers file. A monochrome image was generated from the color image by directly reading the color image into a different system. This was done because at the time these tests were performed the TCTBIS did not have the capability of gray-scale processing. Since then an image processing card has been added. CUE-2 image processing software⁵ by Olympus was used to process and analyze the images. A number of different procedures were tried insofar as filtering steps. The best one tried involved performing ten smoothing steps prior to binarization. Prior to performing the smoothing a stretch operation was performed to make use of the full dynamic range of the image processor. The threshold level for binarization was chosen so that the ratio of dark pixels to the total number of pixels in the image was about 10%. The subsequent analysis proceeds by first computing the frequency parameter of the Poisson distribution for the total image. Where:

$$P(N) = e^{-\lambda} \lambda^N / N! \quad (4)$$

where λ is the sample mean and can be expressed as the frequency of dark pixels and $P(N)$ is the probability of obtaining a representative sample with a frequency of N dark pixels. The standard deviation, σ for a Poisson distribution is simply the square root of λ . The threshold level was chosen to give a value of λ of about 10% so that the image's binary distribution could be modelled as a Poisson distribution. The image was then divided into 225 rectangular regions of 28 by 26 pixels each. The Poisson frequency, N was computed for each region. Finally, a statistical significance test is performed on each region to ascertain the likeness of each region with the global statistics. In this case any region that had a frequency parameter, N exceeding the image population mean by 2σ limit was considered suspect.

The results for two of the stems are shown in Figures 6 and 7. Each figure contains a copy of the original image, a binary image, and an array containing the numerical data. Note that the binary images were negated before they were analyzed. This is an artifact of the image processing software used and is not in general a necessary step. The numerical data for each region is given in light pixels per hundred so that they must be multiplied by 100 to be expressed as a percentage to be compared directly with the population mean.

Figure 7 is for one of the stems that was intentionally scratched. The scratch is located mostly in the lower portion of the image. Since the image wraps around, part of the scratch is at the top of the image. It is clear that the filtered and binarized image greatly enhances the scratch. The object of this work was however to get a numerical representation. This quantitative evaluation can be seen in the numerical data. The regions that are shaded are those in which N is in excess of two sigma from the mean. It would be a straight forward matter at this point to have the computer highlight these regions on the original image to gain an inspector's attention.

A stem which was not intentionally scratched can be seen in Figure 8. In this image there is much less connectivity between the regions that exceeded two standard deviations than in Figure 7. The final call however is still somewhat subjective. One of the reasons is probably the filtering method. Since the smoothing was performed by neighborhood averaging, there was no discrimination between circumferential lines that appear as edges parallel to the vertical axis in the images and the scratches which appear as horizontal lines.

As alluded to earlier, circumferential marks are not considered faults. Therefore, a filtering method which works on a given spatial frequency in the horizontal direction while preserving more of the variations in the vertical direction is probably more appropriate for this application. The software used for this analysis did not have these capabilities. The new image processing hardware mentioned earlier has capabilities to do FFT so the bandpass filtering operations can be done in the future. This is primarily because the flaw sizes have not been related to weld quality as they were for the oxidation levels in the color analysis results described above.

CONCLUSIONS

The work discussed in this paper has demonstrated the feasibility of using color analysis to detect generalized oxidation in the bore of the stem tubes. While not explicitly shown in this paper due to space limitations, it was also clearly demonstrated that the oxidation could be directly related to the quality of the subsequent closure weld. Thus, this method of image analysis appears to be an effective inspection tool for predicting product quality.

The potential for detecting flaws on the bore surfaces by statistical analysis of the unwrapped images was also demonstrated. In this second case, however, more work is needed on filtering and analysis before feasibility can be said to have been demonstrated. Furthermore, numerous other features must still be included such as localized corrosion and foreign matter. In addition, one must be able to distinguish between the various types of localized flaws. We are currently implementing additional hardware and software to do this. More effective filtering and analysis procedures are being investigated on monochrome images. Once this has been completed, these methods may be applied sequentially to the red, green, and blue images. This should allow one to determine for instance whether a surface feature is a mechanical flaw such as a scratch or a solid particle versus local chemical attack or liquid films such as oil.

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Figure 1. Schematic of the True Color Tube Bore Inspection System (TCTBIS) The system collects a set of pixels corresponding to a user defined circle overlaid on the image of the tube bore.

Figure 2. Photograph of stem tubes inspected by the TCTBIS. In addition to an apparent decrease in reflectivity the color of the stems shifted from silver to yellow and then brown as the oxidation level increased.

Figure 3. Computer sort of the oxidized stems. The short bars are the value of the sorting parameter, S and the tall bars are the RMS average, A_{RMS} . This figure demonstrates that the sort based on the color is successful but a sort based on the brightness of the image would have failed.

Figure 4. Sensitivity of Sorting Parameter to illumination level for un-oxidized stems. The value of the sorting parameter S for un-oxidized stems is insensitive to the illumination level. The illumination level increases with the setting on the instrument and then flattens out.

Figure 5. Effect of Illumination Level on Oxidized Stems. The negligible amount of overlap in the value of the sorting parameter demonstrates the ability of the TCTBIS to sort oxidized stems over a wide range of illumination levels.

0.00137	0	0	0	0	0	0.01994	0.00285	0.03556	0.20655	0.40313	0.82051	0.21937	0.11111	0.23449
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00645
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0129
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.03549
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.19462
0.01571	0	0	0	0	0	0	0	0	0	0	0	0	0	0.22351
0.00714	0	0	0	0	0	0	0.01482	0.00296	0.2162	0.04	0	0	0.00889	0.21934
0.01857	0	0	0	0	0	0.06074	0.14519	0.0563	0.25926	0.14222	0.10069	0	0.06963	0.20546
0	0	0	0	0	0	0	0	0	0.03111	0	0.32769	0	0	0.05161
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.06839
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.04563
0	0	0	0	0	0	0	0	0	0	0.00148	0.18519	0.0237	0.0237	0.37032
0	0	0	0	0	0	0.08333	0.305	0.37351	0.69907	0.84877	0.84877	0.84877	0.84877	0.85753
0.01736	0.01923	0.01113	0.02469	0.05926	0.03951	0.30036	0.62184	0.69167	0.8642	0.8642	0.8642	0.86527	0.9642	0.87312

Figure 6. Analysis of scratched stem tube. The upper figure is a copy of the original “unwrapped” image. The center shows this image after ten smoothing operations and segmentation by thresholding. The table on the bottom highlights the potentially defective part of the surface.

0.00824	0.00444	0.00427	0.05128	0	0.02992	0.00142	0.05556	0.00285	0	0	0	0	0	0.01282
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.07057
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.12933
0	0	0	0.03259	0	0	0	0	0	0	0	0	0	0	0.07333
0	0.03407	0.08889	0	0.1037	0.46462	0	0.01037	0.01333	0	0	0	0	0	0.04
0	0.03561	0.17185	0	0.09482	0.28286	0.03846	0.02534	0.0237	0	0.02963	0	0	0	0.024
0	0.51852	0.75776	0.00296	0	0.12296	0.07852	0.0237	0	0	0	0	0	0	0.06621
0.12251	0.6887	0.52932	0.18976	0.00462	0.06154	0.15111	0.50074	0.02074	0.05037	0	0.12296	0.03407	0.01333	0.08267
0.5303	0.7	0.43704	0.11704	0.22815	0.15704	0.35556	0.38815	0.23111	0.30074	0.05037	0.50519	0.01482	0.20741	0.41733
0.42143	0.4559	0.21926	0.02541	0	0	0	0	0	0.0563	0.04296	0	0	0.21397	0.236
0.16857	0.22815	0.00741	0.0163	0	0	0	0	0	0	0	0	0	0	0.068
0.26286	0	0.0237	0.36148	0.04	0	0	0	0	0	0	0	0	0	0.06133
0.03429	0	0	0.08012	0	0	0	0	0	0	0	0	0	0	0.05867
0.69143	0.12148	0.48148	0.10815	0.02519	0.45185	0.60889	0.39407	0.12184	0.12593	0	0	0	0.0163	0.05867
0.40306	0.27249	0.10318	0.13757	0.06614	0.23016	0.209	0.25363	0.27852	0.05556	0.08069	0.0527	0.05423	0.03042	0.04524

Figure 7. Analysis of unaltered stem tube. The upper figure is a copy of the original "unwrapped" image. The center shows this image after ten smoothing operations followed by segmentation by thresholding. The table on the bottom highlights the potentially defective part of the surface.

END

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