

REAL-TIME SURFACE DEFECT DETECTION AND TRACEABLE MEASUREMENT OF DEFECT IN 3D

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Abstract:

In recent years, there has been an increased emphasis for quality control in the manufacturing sector. Many manufacturing processes have become fully automated resulting in high production volumes. However, this is not necessarily the case for inspection of aerospace surface defects. Volume measurement of defects is one of the key elements in quality assurance in order to determine the pass or failure of certain manufactured parts within this industrial sector. Existing human visual analysis of surface defects is qualitative and subject to varying interpretation. Non-contact 3D measurement should provide a robust and systematic quantitative approach for surface defect analysis. Instrument native software processing of 3D data is often subject to issues of repeatability and may be non-traceable in nature, leading to significant uncertainty about data quantisation and representation. This is compounded by a lack of traceable surface defect standards and softgauges with which to test the instruments and software respectively.

This research is concerned with the development of novel traceable sub-millimetric surface defects produced using a Rockwell hardness test instrument on flat, single curvature (SC), and double curvature (DC) metal plates, and the development of a novel robust, repeatable, mathematical solution for automatic defect detection and characterization. This is then extended to a surface defect on an aerofoil that is measured in real-time and characterized using the novel algorithm. The results show that the new surface defect detection and quantification is more robust, efficient, and repeatable than existing solutions.

Keywords: Surface defect, Detection, Volume measurement

1. INTRODUCTION

In industry, surface topography may be one of the significant factors (and indicators) in performance of high precision components. Surface topography is normally recognized as comprising of different surface components, i.e. roughness, waviness, form, and surface defects. Whilst separation of roughness, waviness and form components is usually conducted by the mean-line based filters [1], discrete detection of surface defects is also crucial because they may play very important roles in functional performance. Inspection of surface defects is a crucial task for aerospace industries, in terms of product quality, production efficiency, and performance efficiency. Any defect requires assessment in terms of a pass / fail criterion.

Automatic detection of process-induced defects (e.g. indentations and scratches), is an important issue in machine

vision. Detection of surface defects in 2D and 3D has been reported for various applications in different industries. Examples include; the real-time detection of defects on highly reflected curve surfaces [2], the robust and automated detection of tooling defects for polished stone [3], along with a computer-aided visual inspection system for surface defect detection in ceramic capacitor chips [4]. Once defects have been identified, it is important to accurately extract the defect from the surface. Several algorithms have been developed and published for defect detection in images [5-7] as well as different filtration techniques set out in the ISO 16610 series of standards [8] to aid the characterization of surface features [1][9]. This can also be adopted to detect surface defects. Once a defect is detected and ideally isolated, it then becomes important to quantify the defect geometry (such as volume). Although significant work has been reported in detecting surface defects using various optical methods, robust, traceable and importantly, automatic methods for volume measurement in 3D, is less well explored.

ISO 8785 [10] gives the definition of types of surface defects but currently standards are not available to quantify defects. Currently ISO 25178-2 [11] is available to quantify aspects of surface volume of materials, which can and has been adopted to measure the volume of defects. Commercial analysis software are also available that allow a user to delimit a defect manually and consequently calculate the volume. However visually driven manual delimiting of a defect is always subjective and qualitative, leading to repeatability/reproducibility issues and errors of volume measurement. Moreover, there is an issue of reliability of data representation due to the lack of traceable surface defect comparators and defect softgauges.

In this research, standard, repeatable and traceable defect artefacts have been generated and a novel algorithm has been developed to measure the volume of defects automatically and rapidly.

2. ARTEFACT

2.1 Artefact Generation

There is no significant evidence of standard surface defect comparators commercially available and hence there is a need to generate standard and traceable surface defect artefacts. In this work, artefacts have been generated using repeatable Rockwell hardness test equipment, typically used to determine the hardness of substrates. Indentations are made using a known conical indenter that creates a dent on the metal surface. Irrespective of the material hardness, this

indentation has a very unique shape and geometry that can be used as a standard defect to develop a robust method to measure the volume of the defect. In this context, the term traceable means that the geometric parameters (depth for instance) of a standard defect are directly traced to the SI definition of the metre.

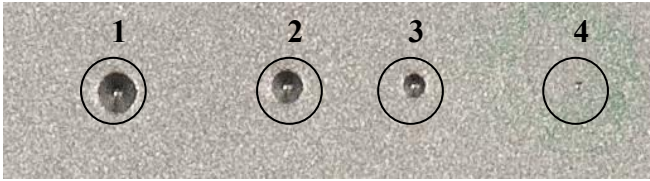


Fig. 1: Different sizes of Rockwell indentation

Four different sizes of indentation have been generated on flat standard stainless steel following the specification set out in ISO 6508-1 [12]. These are nominally 300 μm , 250 μm , 180 μm and 40 μm in depth. Similar sets of indentations have been produced on a concave side of a SC plate and convex side of a DC plate. Fig 1 shows the four different sizes of Rockwell indentations on a flat plate.

2.2 Artefact measurement

Artefacts have been measured in 3D using a parallel optical coherence tomography (pOCT) instrument. The 3D optical sensor is capable of measuring different surface types, including ground and polished surfaces, steps and films. The instrument produces 3D datasets with a field of view of approximately 2.4 mm x 2.4 mm with a lateral resolution of approximately 8 μm .

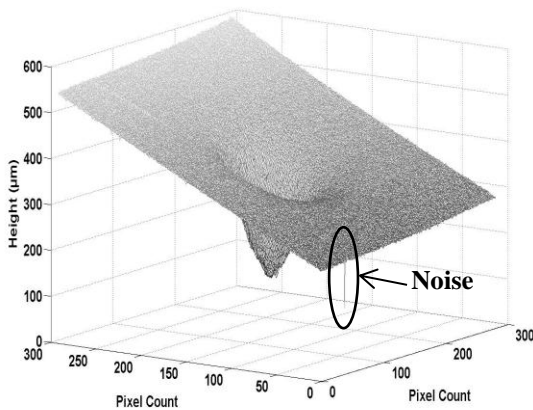


Fig. 2: Raw data derived from a Rockwell indentation

3. NOVEL ALGORITHM

The novel algorithm to measure the volume automatically has been developed using MATLAB R2011b and is briefly illustrated in Fig. 3. The 3D measuring instrument provides point cloud data as the output of the measured surface. Fig. 2 illustrates 3D data of the measured surface that contains conical defect 2 (Fig. 1). Note that due to constraints of the MATLAB data processing and the aspect ratio of the defect, the height data is given in

micrometres, but the X and Y ordinates are provided as a pixel count.

Noise, for instance spurious peaks, is always present in acquired data from any 3D optical instruments and it is important to remove the noise for better assessment otherwise it could lead to incorrect measurement. A smoothing Gaussian filter is implemented to remove such noise. Moreover, 3D datasets also contain geometric form that needs to be removed for better assessment of the defect. If this is not completed, large scale form would mask smaller scale defect detail. By generating the mean surface using advanced Gaussian filtration techniques, form can be removed and the residual surface can be obtained. After the filtration process, it is important to separate the defect from the residual surface. The purpose of this process is to outline the defect region and 3D data portions for later volume measurement. For defect isolation, edge detection of the defect is essential. An edge of the defect is defined as an abrupt change in surface height on the 3D data. There are various image processing techniques available for edge detection, such as gradient operators and thresholding. Due to embedded surface roughness, gradient operators for edge detection were found too complex and hence local thresholding methods were adopted to isolate the defect.

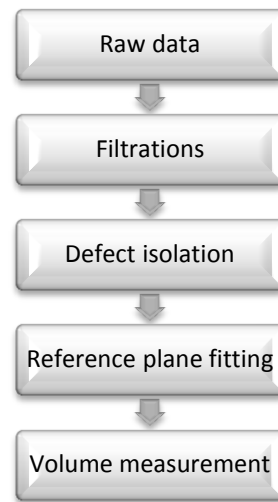


Fig. 3: Flow chart of the novel algorithm

Once a defect is isolated, it is relatively straight forward to derive the boundary of the defect in 3D that can be clearly seen in Fig. 4 as a black circumferential line outlining the throat of the defect region. A reference plane is generated using the least square method to fit into the defect boundary data points. In a given field of view, the algorithm tries to find the perpendicular distance from each measurement point (pixel) to the generated reference plane. Considering an area of a pixel, the sum of all perpendicular distance from each pixel to the reference plane is ultimately the volume of the defect. The area of a pixel is defined by the lateral resolution of the measuring instrument.

This process is applied to various defect artefacts of different sizes and in different substrates, as explained in section 2.1, and the results are discussed as follows.

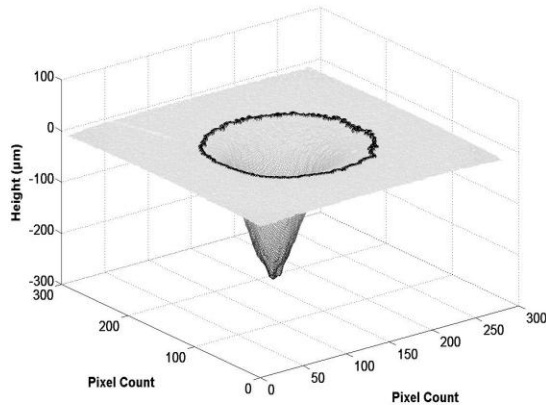


Fig. 4: Residual surface with isolated conical defect

4. ARTEFACT ANALYSIS

Automatic volume measurement of the different sizes of defect artefacts using the novel algorithm is shown in Table 1. In this example, artefacts shown in Fig. 1 are measured five times repetitively. Defect depth, is the perpendicular distance from the lowest point in the measured field of view to the generated reference plane, as explained in earlier work [13].

Table 1: Depth and volume measurement of different size defects

Defect	Depth (µm)	Volume (µm) ³	% Standard deviation
1	304	87888000	0.11
2	252	57007400	0.22
3	177	24837400	0.19
4	38	431164	2.71

It can be seen that the standard deviation in each defect's volume measurement is approximately 0.1 % to 0.3 % for defect depth above 170 µm, whilst the standard deviation of the shallowest defect is 2.7%. Fig. 5 is a graphical representation of the geometric parameters of the four different size defects.

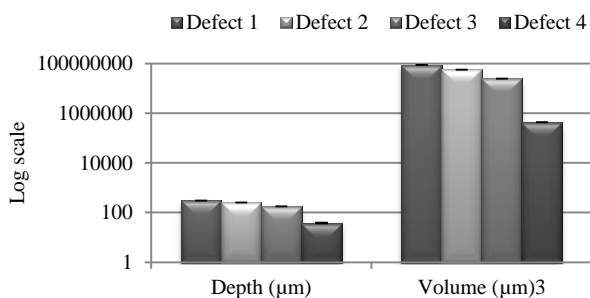


Fig. 5: Depth and volume measurement

A key element of this work is to able to identify how effective the developed automated process is when dealing

with defects embedded in substrates of various shapes. Table 2 shows a comparison of a volume measurement of a defect (depth of 250 µm) embedded in a flat plate, a SC plate and a DC plate. It can be seen that the algorithm copes well with all three substrates in finding the volume measurement of the defects, the standard deviation in volume measurement is less than 1% in all cases. To show this more effectively, depth and volume of defects are graphically shown in Fig. 6.

Table 2: Depth and volume measurement of defect 2 in different substrates

Substrate	Depth (µm)	Volume (µm) ³	% Standard deviation
Flat plate	252	57007400	0.22
SC plate	250	48358600	0.17
DC plate	249	54019600	0.91

The results presented in Table 1 illustrates that the novel algorithm is very repeatable and effective for quantifying defect artefacts of different sizes. Likewise the results presented in Table 2 shows the performance capability of the novel algorithm to detect the defect artefacts in different shapes of substrates and to measure the volume automatically, is again very repeatable. However, whilst the novel algorithm is effective on artefacts which are of known size and controlled geometry it is very important to identify the effectiveness of the algorithm on real defects which are embedded in free form surfaces.

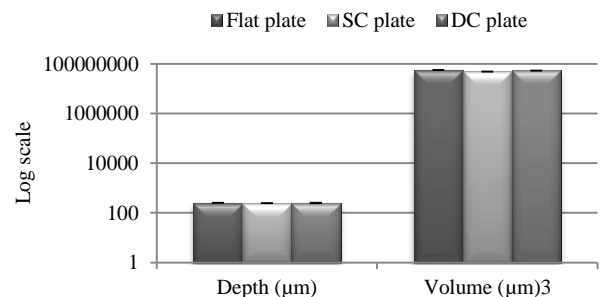


Fig. 6: Depth and volume measurement

5. REAL DEFECT MEASUREMENT

The aerospace industry may reject parts with defects in the manufacturing process, because even a minor defect in a manufactured part may result in a functional failure at a later in-service stage. Thus it is very important to detect, classify and quantify defects at an early stage, and (as in this case) to measure the volume of the defect because it is often a key parameter in quality assurance in order to determine pass/failure of the manufactured part.

Fig. 7 shows the 3D data of an indentation on an aerofoil. It can be seen that the defect is masked by the large scale of geometric form, with the suspicious defect region highlighted in Fig. 7. It thus follows that the precise detection of the defect, isolation from the surrounding substrate, and its quantification, is very critical.

Measured 3D data of an indentation on an aerofoil is processed using the novel algorithm explained in Section 3. Fig. 8 illustrates the noise-free and form-free residual surface with the highlighted defect region. The novel algorithm computes the maximum depth as being 20 μm and measures the volume as being 5087080 μm^3 with a standard deviation of 1.4 %.

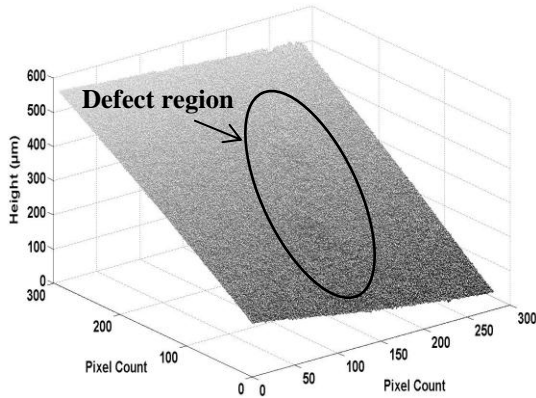


Fig. 7: Raw data of a defect on an aerofoil

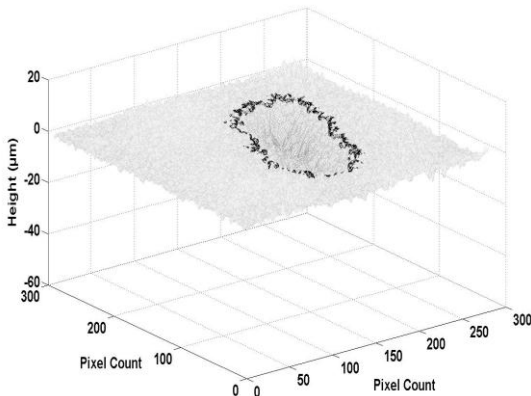


Fig. 8: Residual surface of an aerofoil with an isolated real defect

6. CONCLUSION

The current research has identified the need for enhancing the functional capabilities and efficiency of 3D surface defect detection and quantification. To date, this research has developed and successfully demonstrated;

- (1) Traceable and repeatable defect artefacts with different shapes and sizes, in a range of substrates.
- (2) Robust, rapid, automated measurement of defects using new MATLAB based algorithms, with high level of repeatability on the defect volume measurement.

Further work is currently involved with refining algorithm capability and speed, and exploring the applicability of this process to a broader group of real defects on a range of different operational surfaces.

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REFERENCES

- [1] Lou S, Jiang X, Scott P, Application of the morphological alpha shape method to the extraction of topographical features from engineering surfaces, *Measurement*, 46(2), 1002-1008, 2013.
- [2] Rosati G, Boschetti G, Biondi A, Rossi A, Real-time defect detection on highly reflective curved surfaces, *Opt.Las.Eng.*, 47(3), 379-384, 2009.
- [3] Lee J, Smith M, Smith L, Midha P, Robust and efficient automated detection of tooling defects in polished stone, *Comput.Ind.*, 56(8), 787-801, 2005.
- [4] Lin H, Computer-aided visual inspection of surface defects in ceramic capacitors chips, *J. Mater. Process Technol.*, 189(1), 19-25, 2007.
- [5] Tsai D, Huang T, Automated surface inspection for statistical textures, *Image Vision Comput.*, 21(4), 307-323, 2003.
- [6] Tsai D, Lai S, Defect detection in periodically patterned surfaces using independent component analysis, *Pattern Recognit.*, 41(9), 2812-2832, 2008
- [7] Li W, Tsai D, Automatic saw-mark detection in multicrystalline solar wafer images, *Solar Energy Mater. Solar Cells*, 95(8), 2206-2220, 2011.
- [8] ISO 16610 series. Geometrical Product Specifications (GPS) – Filtration. 2010.
- [9] Lou S, Zeng W, Jiang X, Scott PJ. Robust filtration techniques in geometrical metrology and their comparison, *International Journal of Auto. Comput.*, 10(1), 1-8, 2013.
- [10] ISO 8785. Geometrical Product Specifications (GPS) – Surface imperfection. Terms, definitions and parameters, 1999.
- [11] ISO 25178-2. Geometrical Product Specifications (GPS) – Surface texture: areal. Part 2. Terms, definitions and surface texture parameters, 2010.
- [12] ISO 6508-1. Metallic material. Rockwell hardness test. Test method, 2006.
- [13] Tailor M, Phaithoonbuathong P, Petzing J, Jackson M, Parkin R, Real-time surface defect detection and the traceable measurement of defect depth in 3D, 10th Int. Conf. on Laser Metrology, Machine Tool, CMM & Robotic Performance, Proceedings of Lamdamap 2013, 171-180, Kavli Royal Society International Centre, UK.