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IDENTIFICATIONS OF MACHINED SURFACES USING DIGITAL IMAGE PROCESSING

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ABSTRACT: *The characteristic features produced by machining processes, specifically: shaping, end milling, and horizontal milling, are important parameters for determining salient facts about the processes involved. The need for attaining an optimum balance between the contrasting demands for increased productivity and better product quality, in modern manufacturing, makes the study of such machining information quintessential. The authors of this paper used Digital Image processing method to develop an automated system that was capable of classifying machined plates into one of these three important categories. The outputs of the software were tested rigorously, using known calibrated machined plates of all three types. The software demonstrated an accuracy of 95% and a repeatability of 100%. The authors are of the opinion that their technique is ready for their implementation in the field of advanced materials and manufacturing research. With subsequent modification it the automated classification system could also be used in the industry.*
KEYWORDS: *Edge Detection, Classification, Surface Roughness, Shape Perception, Digital Image Processing*

INTRODUCTION

Machining processes invariably produce unwanted surface features due to tool-work system deflection, chatter, tool wear, built-up edge, chip flow, and the thermal effects of the cutting process [1]. Since, every machining process is different, these features, which are part of the general surface topology, are unique and characteristic to each machining process. These characteristic surface textures can, thus, be used to identify the type of machining process and determine important information such as the machine tool's kinematics, cutting tool geometries, and machining errors [1]. This salient information, about the particular machining process, are vital in meeting the basic goal of any modern manufacturing process, namely, productivity and product quality [2].

Jung et al. [1] developed performed an extensive theoretical analysis for predicting the characteristic lines of the cut remainder in ball-end milling processes. Their model showed greater predictability than the conventional models. Other researchers [3-4] investigated the effects of cutting forces and cutter deflection on machining error. Patwari et al. [5] used coupled Genetic Algorithm (GA) and Response Surface Methodology (RSM) in order to develop a mathematical model relating surface roughness generation to cutting speed, feed, and depth of cut for high speed end milling. They were able to suggest optimum surface roughness attainable within the limits of the machining capacity.

Arif et al. [6] and Patwari et al. [2] used Digital Image Processing (DIP), in MATLAB [7], in order to measure and visualize surface texture in shaped and horizontally milled plates. The authors of this paper used the findings of these seminal works in order to develop an automated system, using DIP in MATLAB, to classify three very important types of machined plates: shaped, end milled, and horizontally milled. For the development of their unique technique, they employed shape perception, investigated by Rosin [8] and wavelength of surface ridges.

TYPES OF MACHINING AND MACHINED SURFACES

A. SHAPING OR PLANNING – Shaper machines are used in high volume production industries to machine straight and flat surfaces, for making keyways, slots, and internal splines. A shaper operates by moving a hardened cutting tool in a linear reciprocating motion across the work-piece's surface [9]. As a result straight and parallel characteristic ridges are produced on the part's surface. Consequently, these ridges appear to have a particular wavelength for a given surface roughness, if machining conditions are kept constant.

B. HORIZONTAL MILLING – Such milling is used widely to machine gear teeth in helical and worm gears, making dovetail recesses and guides, and for machining slabs, profiles and gangs in peripheral milling *operations [9]. The horizontally rotating spiral tool edges remove material by plastic shear, and so, a texture with variable crest sizes and wavelengths is produced.*

C. END MILLING – End milling is used in milling applications such as profile milling, tracer milling, face milling, and plunging [9]. Material removal is obtained when relative motion occurs between the work-piece and the rotating circular cutting tool, usually at right angles to the work-piece's surface. Due to the interaction between the rotation of the cutting edge and the feed-rate, overlaps of the cutting paths are produced, which manifest as converging 'tooth shaped' ridges on the work-piece's surface.

These characteristic features of surface ridges or crests were used along with the surface roughness measurement techniques developed by Arif et al. [6] and Patwari et al [2], to classify and visualize these three categories of machined surfaces.

EQUIPMENTS

A standardized environment was maintained for efficient image acquisition. The equipments used were:

1. *Krüss Optronic (Germany) Model MMB 2300 Metallurgical Microscope as in figure 1.*
2. *Rubert & Co. Ltd. (England) calibrated machined plates (with surface roughness values, 'R_a') for End Milled, Shaped, and Horizontally Milled plates as in figure 2.*

Figure 1. MMB 2300 metallurgical microscope

Figure 2. Calibrated end milled plate from Rubert & Co.

METHOD

A. PROCESS FLOW SEQUENCE

The analysis and classification process used a 'fail-safe' method in order to classify the machined plates. This was done, purposively, to ensure a 100% repeatability rate. The authors were satisfied, after extensive review that the following logical sequence of the analysis, as illustrated in figure 3, was reliable.

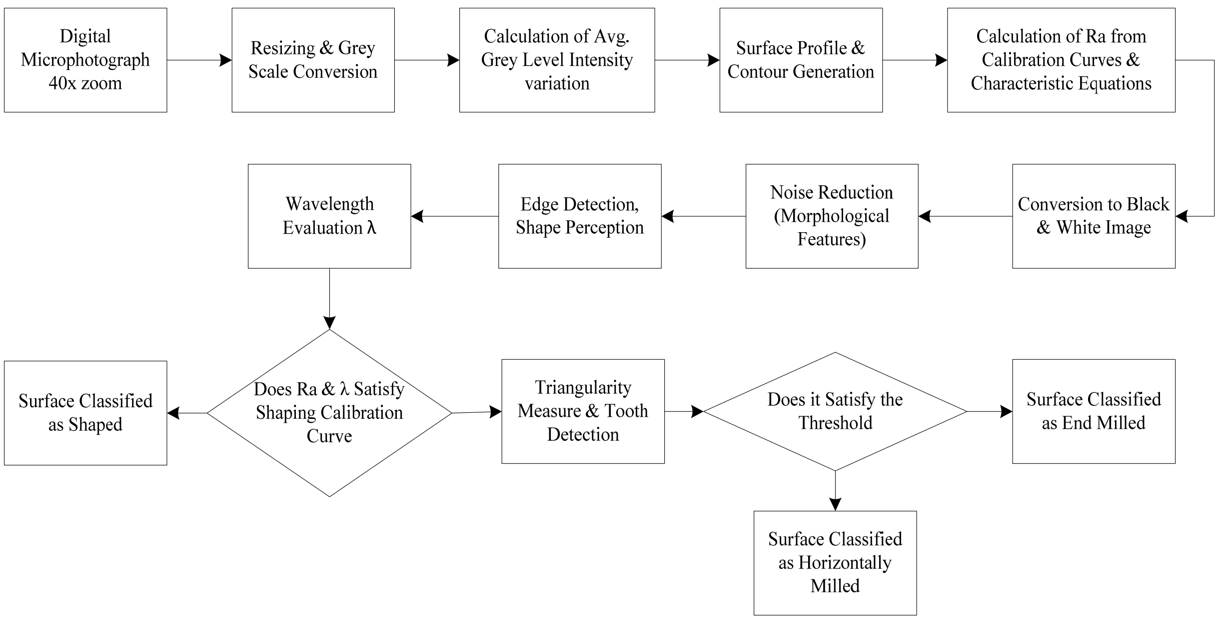

Figure 3. Process sequence flowchart

B. PROCESS FLOW DESCRIPTION

A microphotograph of interest, obtained at 40x zoom, was resized and converted to grayscale. The average grey level (pixel) intensity variation, 'avg' was then evaluated using the algorithm developed by Patwari et al. [2] and the surface topography, in 2-Dand 3-D, were generated.

Next, the average surface roughness values, 'R_a,' was calculated using the average grey level intensity, 'avg,' and the calibration formulae for shaping, end milling, and horizontal milling as represented by equations 2-4 in the next section [2]. Thus, there are three possible R_a values depending upon the probable type of machining involved and further analysis was needed to classify the work-piece surface with 100% certainty.

The resized grayscale image was then converted into black and white format for edge detection and wavelength, 'λ,' calculation. λ was defined, by the authors, as the distance, in millimeters, between consecutive roughness crests (ridges) as manifested by bright areas in the microphotograph and detected by edge detection. It was observed that any particular shaped plate, generally, had a near-constant λ, as expected and discussed above. While the λ of any particular end milled plate varied. The variance, in λ was the largest for horizontally milled plates.

A subroutine, composed of 'If-else' logical blocks, was used in the software to decide whether the microphotograph was that of a shaped plate. If the calculated Ra_s from equation 2 (below) and λ satisfied equation 5, the photograph was identified as a shaped plate.

If equation 5 (below) was unsatisfied, the software subsequently evaluated the triangularity measure of the edges detected and passed the results to another decision subroutine. This second subroutine used a shape threshold measurement to determine whether the edges of asperities, detected, were triangular enough to be considered the characteristic teeth present in end milled plates. The upper limit for this was set at 0.09. If the shapes, detected, evaluated to a value equal or less than this threshold, it was categorized as an end milled plate and the corresponding Ra_e, calculated from equation 3 (below), was output.

If, however, the shape metric was greater than the threshold, the surface was identified as a horizontally milled plate. Its specific Ra_h, calculated from equation 4 (below), was output.

C. Governing Equations

The mathematical definition of the average surface roughness, R_a, was utilized. R_a is equivalent to half of the mean difference in heights between the asperities and troughs of a rough surface. The equation is as follows:

$$R_2 = \frac{1}{n}\sum_{i=1}^{n} y_1 = \frac{1}{n}\int_1^n y(x)dx \qquad (1)$$

The equations obtained from the calibration curves for shaping, end milling, and horizontal milling are as follows [2]:

- $Ra_s = 2E\text{-}12 avg^{8.3491}$ *(Shaped Plates) (2)*
- $Ra_e = 1925.5e^{-0.11avg}$ *(End Milled Plates) (3)*
- $Ra_h = 4E{+}15 avg^{-8.753}$ *(Horizontally Milled Plates) (4)*

The equation relating average surface roughness and wavelength in shaping processes is as follows:

- $Ra_s = 2.8689\lambda^{1.5984}$ *(5)*

RESULTS AND DISCUSSIONS

The results of digital image processing (DIP) and edge detection, for the images of the three types of machined plates, are shown in figures 4-6. The results of the evaluation of the method are displayed in table I.

Table I. Accuracy and repeatability of the automated classification method

No.	Actual Ra	Calculated Ra	Error %	Actual Process	Classification	Repeatability %
1	3.2	3	-6.25	Shaping	Shaping	100
2	0.8	0.83	3.75	Shaping	Shaping	100
3	6.3	6	-4.76	End Milling	End Milling	100
4	12.5	13	4.00	End Milling	End Milling	100
5	0.8	0.849	6.12	Horizontal Mill	Horizontal Mill	100
6	3.2	3.05	-4.69	Horizontal Mill	Horizontal Mill	100
Avg. Error % =			4.93	Avg. Repeatability % =		100

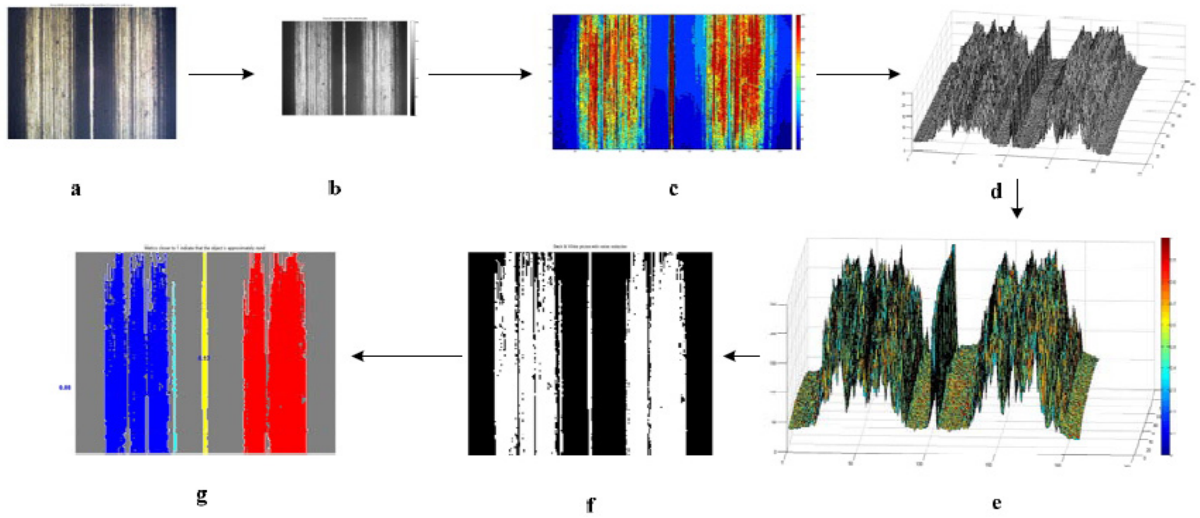

Figure 4. DIP results (shaped plates): (a) 40x zoom RGB micrograph, (b) grayscale, (c) 2-D contour plot, (d) 3-D contour plot, (e) 3-D colored contour plot, (f) black & white image, (g) edge detection

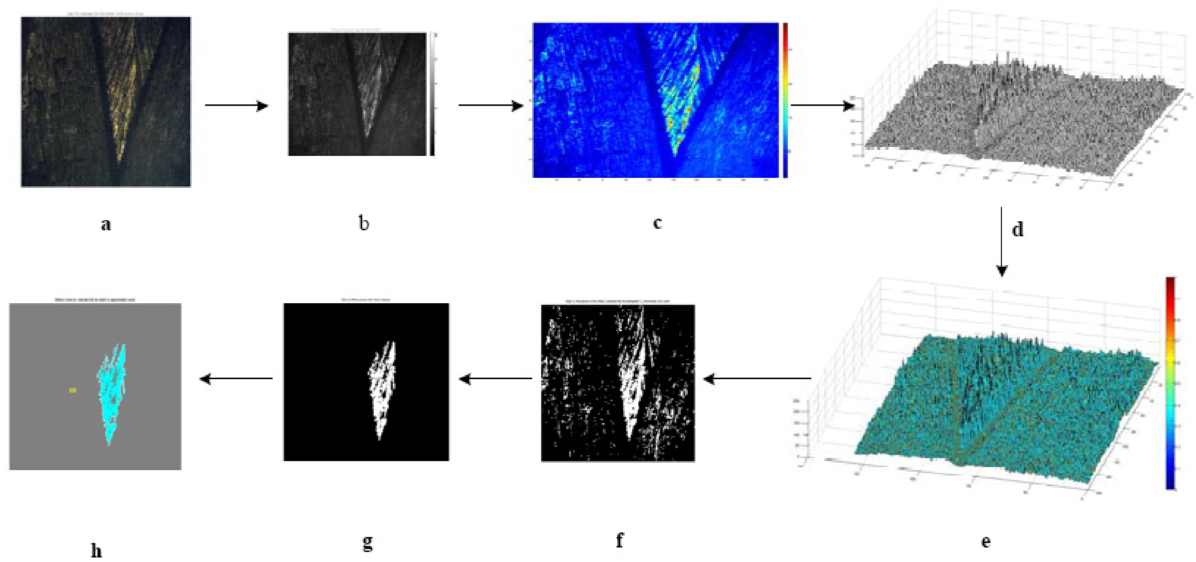

Figure 5. DIP results (end milled plates): (a) 40x zoom RGB micrograph, (b) grayscale, (c) 2-D contour plot, (d) 3-D contour plot, (e) 3-D colored contour plot, (f) black & white image, (g)noise reduction, (h) edge detection

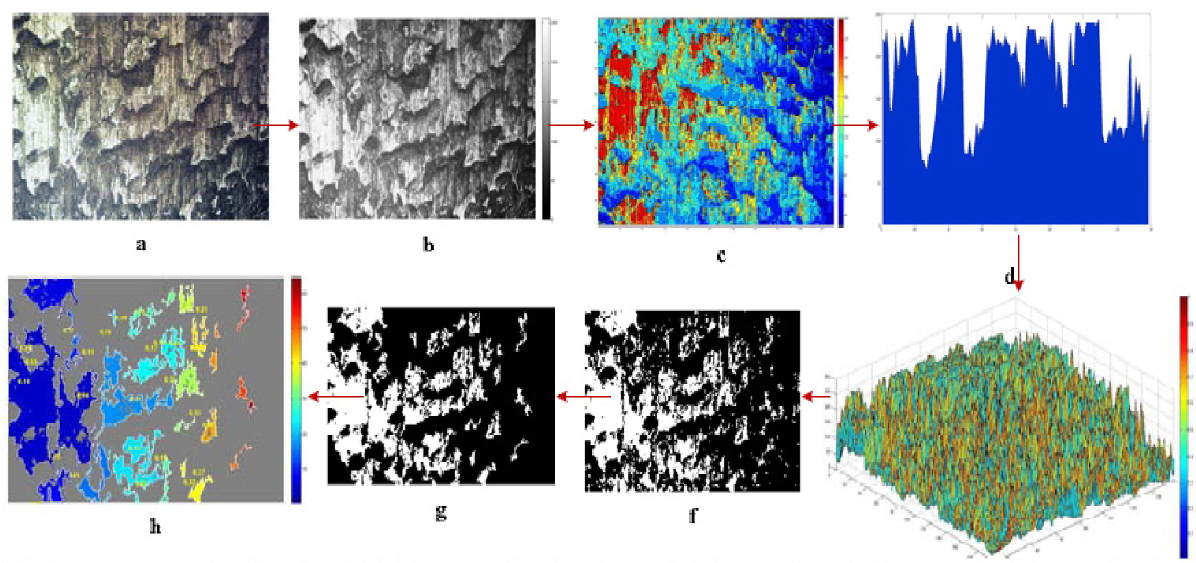

Figure 6. DIP results (horizontal milled plates): (a) 40x zoom RGB micrograph, (b) grayscale, (c) 2-D contour plot, (d) 3-D contour plot, (e) 3-D colored contour plot, (f) black & white image, (g)noise reduction, (h) edge detection

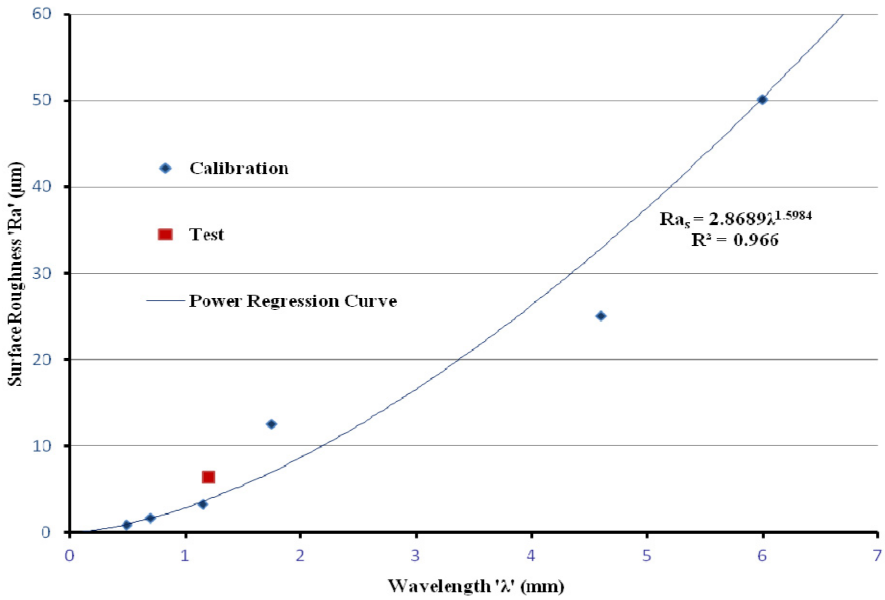

Figure 7. Calibration curve of average surface roughness vs. wavelength of roughness crests for shaped plates

The curve relating surface roughness with wavelength, in Shaping, is illustrated in figure 7. A power regression, with $Ra_s = 2.8689\lambda^{1.5984}$ and correlation coefficient $R^2 = 0.966$, was determined to be the best fit model relating average surface roughness to wavelength of consecutive roughness peaks (figure 7) for shaped plates. The curve clearly demonstrated that λ increased with increasing surface roughness as was seen in the microphotographs of shaped plates. No such apparent relationship, between Ra and λ, was obtained for end or horizontally milled plates; in both these cases λ was not constant and well defined.

The nature of λ was also apparent from the picture sequences illustrated by figures 4-6. The roughness peaks of shaped plates are usually parallel and well defined. End milled plates showed almost parallel but overlapped roughness peaks along with the existence of 'teeth' where the ridge boundaries overlapped. Horizontally milled plates demonstrated no consistent repetitive pattern of roughness crests and thus, no constant λ. These characteristic features of the three types of plates were used in the automated DIP classification process, as described in the previous section.

The accuracy of the method was tested with 6 calibrated machined plates; 2 plates for each type of machining process. The average accuracy of the method, after error compensation, was 95%. Also, the repeatability of the method was tested by evaluating 3 different images for each of the six plates. The repeatability was found to be 100%, showing that the method consistently categorized each machined plate into the right class.

CONCLUSIONS

The characteristic feature and textural patterns on the surface of machined plates result because of particular conditions existent during a particular machining process. Consequently, various vital information can be determined from the study of surface topology. Thus, the authors believe that their classification software will aid researchers and industry professionals acquire relevant information about shaping, end milling, and horizontal milling in an expedient manner.

The process developed demonstrated accuracy and consistency within the desired range for most modern industry requirements. It is also a very economical and simple technique and requires access to a metallurgical microscope of reasonable magnification and decent computing facilities to complete the analysis.

The major shortcoming of the automated technique was that it could only analyze three types of machined surfaces, namely: shaped, end milled, and horizontally milled. This was because the software was calibrated using only these three types of plates.

The authors are currently engaged in developing and calibrating an universal software which will be able to classify in a wider range of machining processes. A Graphical User Interface (GUI) version of the software, using MATLAB, is currently in the process of development, which will further simplify the technique.

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