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Towards part lifetime traceability using machined Quick Response codes

C.E.H. Ventura[a]*, R.V. Aroca[a], A.Í.S. Antonialli[a], A.M. Abrão[b], J.C. Campos Rubio[b], M.A. Câmara[b]

[a]*Department of Mechanical Engineering, Federal University of São Carlos, Rod. Washington Luís km 235, São Carlos, SP, 13565-905, Brazil*
[b]*Department of Mechanical Engineering,Universidade Federal de Minas Gerais, Av. Antônio Carlos 6627, Belo Horizonte, MG, 31270-901, Brazil*

Abstract

In recent years, the manufacturing industry has made several efforts aimed at better monitoring of products life-cycle through special markings added during their manufacturing. Such monitoring is becoming increasingly relevant, especially in order to provide reliable product traceability and other associated services that can be available to the manufacturer, to the retailer and to the end consumer. Thus, low-cost and flexible technologies able to carry data of an individual product during its whole life-cycle currently play an important role. Within this context, the popularity, advantages and facilities of using Quick Response (QR) codes motivate the use of this technology in several applications on the manufacturing industry. Aiming to engrave this kind of code in metallic parts without the need of further laser processing or the use of adhesive labels, this work discusses the machining and reading of QR codes in metallic parts. Challenges in machining codes with different sizes and materials, as well as reading them, are investigated.

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Keywords: Machining; Traceability; QR code

* Corresponding author. Tel.: +55 16 3306-6857; fax: +55 16 3351-9703.
E-mail address: ventura@ufscar.br

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1. Introduction

Production networks have evolved and value added services are becoming increasingly important, as they go beyond production-related stages of the product life-cycle. In such way, these trends may imply more data “traveling with the product” [1], enabling product traceability, which corresponds to the capability to trace the products throughout the supply chain [2]. As an example of possible application, causes of a certain problem can be traced and found by the investigation of the data generated during production. Thus, equipment and part history can be traced back to manufacturing processes and/or raw material used and as the root cause is found, potential problems can be prevented [3].

Information concerning a workpiece is normally stored separately from it, e.g. in databases or on paper and this can lead to loss of data and misleading information. According to Denkena et al. [4], this drawback can be overcome by storing the information during processing directly on the product surface, which enables its use in every stage of the lifecycle. With each component being able to carry information about its design, production, usage or recycling, the required information is always available, allowing production processes to be quickly adapted and thus allowing a complete traceability of products within its lifecycle [5].

In this context, different techniques have been proposed and applied in order to provide easy access to information, such as Radio Frequency Identification (RFID) and adhesive labels, which can be accidentally detached from the piece in subsequent processes, showing the need of a more robust and durable way of storing information about parts. With this purpose, Vedel-Smith and Lenau [6] developed an insert tool for green sand molding, which enabled a Direct Part Marking (DPM) traceability for cast iron castings without process stop. Li et al. [7] applied laser marking to perform DPM, since this method attain permanent and highly contrasted superficial inscriptions on a wide variety of materials. These authors investigated the limits of the process and found out that edge over-burn is a primary cause of DPM code readability loss due to the use of high energy density laser to obtain high contrast modules. Denkena et al. [4] and Denkena et al. [8] applied piezoelectric driven milling and turning tools to machine micro patterns into the component’s surface to store coded information. Signal processing methods are used for data storage with high data density and integrity.

Kemény et al. [1] state that optically readable codes offer the advantage of automatic data acquisition, even when some human assistance may be required for the scanning procedure. In this context, ISO/IEC 18004:2006 defines the Quick Response (QR) codes, which are an interesting solution as they can store dozens of characters, and can handle both alphabetic and numeric characters. Basically, a QR code consists of the combination of white and black modules, which according to their position, encode alphanumeric or numeric information. One important aspect of the QR code specification is that it has an error correction capability, allowing data to be retrieved even if the QR code is partially damaged. When a QR code is generated, it is possible to specify an error correction level from 7% to 30%. This parameter defines the amount of redundant data for correct data retrieval even if up to 30% of the QR code is occluded or damaged.

As for the reading procedure, known patterns at the three corners of the code allow stable high speed reading at any angular position and scale. All these advantages and the disseminated use of smartphones for easy reading such codes motivate its application for storing product information during its life time. QR code reading relies on a high contrast between a background and the code itself. Challenges concerned with reading the code in metallic parts are associated to illumination variation and light reflection on the metallic part, which cannot be guaranteed to be constant depending on the lighting conditions each time a part is scanned and how the part is machined.

In order to avoid changes in product characteristics, QR codes should be produced as small as possible. Thus, engraving these codes in metallic parts demands the application of micro machining technology. Therefore, the size of a machined QR code is based on the combination of tool diameter and information quantity, while black and white features are represented by different cut depths. Moreover, there are certain concerns that must be observed: problems regarding the usage of micro machining technology are mainly related to low uncut chip thickness to edge radius ratio, which leads to the predominance of ploughing over shearing. According to Bissaco et al. [9], this results in a relatively large fraction of the material bulging aside and in front of the cutting edge, remaining attached to the milled surface. As a consequence, surface roughness is increased and top burrs are formed. Such aspects of micro machining must be considered when producing small QR codes, as burr formation or increased surface roughness can impair its reading.

Results from different researchers indicate that these issues are recurrent in different kinds of materials. When micro end milling austenitic stainless steel, Biermann and Steiner [10] observed that burr height on the up-milling side is drastically reduced in comparison to the down-milling side due to the smaller supporting effect of the non cut material on this latter side of the micro channel. In agreement with that, Kiswanto et al. [11] also observed fewer burrs on the up-milling side of the channel after micro end milling an aluminum alloy. They noticed that burr on the down-milling side occurred as the tool began to wear and became larger than the burr on the up-milling side as the tool wear increased or the tool fractured. Thereby, they concluded that tool wear is the most influential factor on burr formation. Aramcharoen and Mativenga [12] report that the selection of optimum micro milling variables involves a compromise between best surface finish and burr size. Their investigations revealed that the best surface finish in micro machining of tool steel is obtained when the undeformed chip thickness has the same magnitude of tool edge radius. They also observed that the increase of the ratio of undeformed chip thickness to cutting edge radius causes a reduction of burr size, as ploughing becomes less dominant.

Another concern related to micro machining technology could be the need of a special machine due to the small tool diameter, which demands high spindle speeds. Nevertheless, micro milling QR codes does not necessarily means the acquisition of dedicated equipment, since under many circumstances a conventional machine tool can be used attaching a high speed turbine to the main spindle.

Considering the challenges discussed and with the goal of engraving QR codes in metallic parts by micro milling, this paper presents an investigation on the production of the codes as well as a novel methodology for reading machined QR codes. In order to accomplish that, a computer vision algorithm is proposed to allow successful reading of machined QR codes.

2. Machining of QR codes

In order to carry out the proposed investigation, a worst case correction level was chosen (7%). Then, a QR code (Fig. 1a) was generated using the standard ISO/IEC 18004:2006 to store the following address: *www.ufscar.br*. Codes were then machined in aluminum and brass specimens using a high speed turbine (40.000 rpm) from Air Turbine Tools model 650BT40 attached to a machining center, see Fig. 1b. The QR codes were generated in two different sizes (12.5 x 12.5 mm and 25 x 25 mm) using CAD/CAM software. TiAlN coated tungsten carbide end mills with two flutes and 500 µm diameter were used as cutting tools. Constant cutting speed of 62.8 m/min and feed rate of 1 µm/tooth were employed. The axial depth of cut was 0.1 mm for the larger specimens and 0.05 mm for the smaller specimens. Fig. 2 shows the QR codes machined in different materials and sizes: (a) brass 12.5 x 12.5 mm, (b) brass 25 x 25 mm, (c) aluminum 12.5 x 12.5 mm and (d) aluminum 25 x 25 mm.

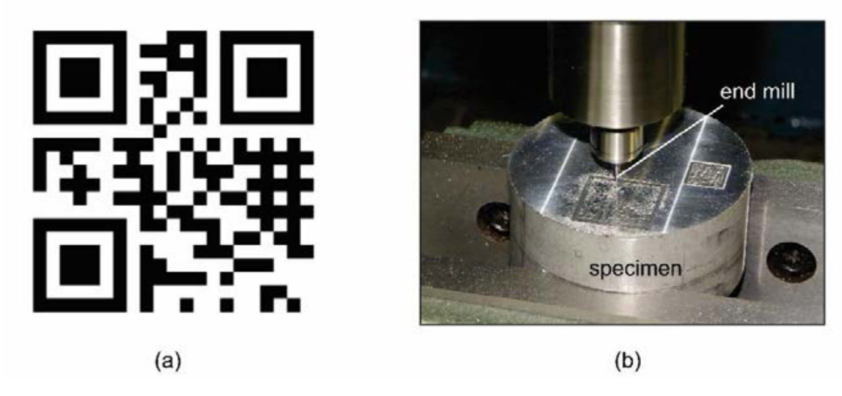

Fig. 1. (a) QR code (*www.ufscar.br*) with 7% error correction level and (b) Micro end milling QR codes

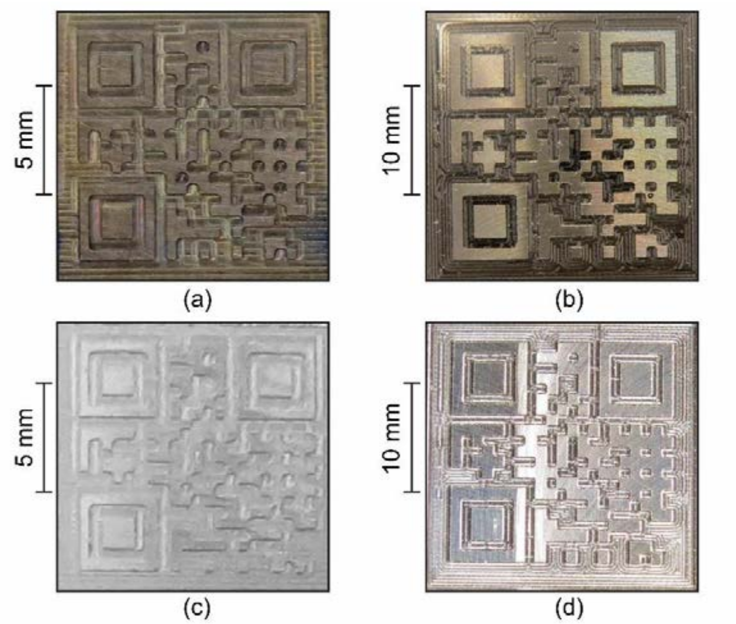

Fig. 2. (a) Machined samples: (a) brass 12.5 x 12.5 mm, (b) brass 25 x 25 mm, (c) aluminum 12.5 x 12.5 mm and (d) aluminum 25 x 25 mm

It can be noticed that, in general, better surface quality is obtained after micro machining brass (Fig. 2a and 2b), probably due to the more fragile nature of this material in comparison with the aluminum alloy (Fig. 2c and 2d), which leads to the formation of burrs with much smaller dimensions on the surface of the former material. In addition to that, more accurate geometry is achieved after generating QR codes of larger dimensions (Fig. 2b and 2d). This can be explained by the fact that interpolation is not attainable for an end mill with 500 µm diameter micro milling QR codes with 12.5 x 12.5 mm and the smaller feature (square) is generated using the end mill as a drill, i.e., without movement in the X and Y directions. Another aspect to be observed corresponds to the tool tracks associated with the radial depth of cut. As slot milling is performed, these tracks are related to the tool diameter and cannot be neglected. Regardless of the machined material, marks stand out in the codes with larger dimensions (Fig. 2b and 2d).

3. Reading of QR codes

Ideally, the machined QR code should be read by any standard QR code reader device or software, allowing pervasive integration and usage of the DPM concept using the QR code technology. However, in several experiments made with the official Google Android and other QR code readers, it was not possible to successfully read the code in any case. The ZBar [13] library was also tested with no successful readings. One possible solution for the QR code decoding may be based on the use of a depth camera or other 3D scanning devices. Such solution would provide an interesting and robust recognition method for machined QR codes, as the depth information would enable directed separation of milled and not milled regions, which correspond to the QR code black/white regions. However, in our proposal, the machined QR code depth is only 0.1 mm, which may not be detected by low cost 3D scanning devices or depth cameras. Moreover, it is desirable to provide a method that allows machined QR code decoding with standard cameras, enabling broader and lower cost application of QR code decoding with smartphone and other devices that already have a standard monocular camera. In that way, the development of a computer vision algorithm to allow preprocessing of the machined QR code was needed to enable successful reading.

The main idea behind the proposed algorithm is to analyze the machined QR code image (Fig. 3a) captured by a camera and use it to reconstruct a new QR code by synthesizing it to provide the information of the captured image. First the algorithm builds a grid of QR code modules and merges it to the captured QR code image, as shown in Fig.

3b. For this merge, three parameters are important: the scale of the original image (*S*) and the X and Y translations (*Tx* and *Ty*) of the original image with respect to the grid. These parameters ease the alignment of the modules to be synthesized with machined QR code modules.

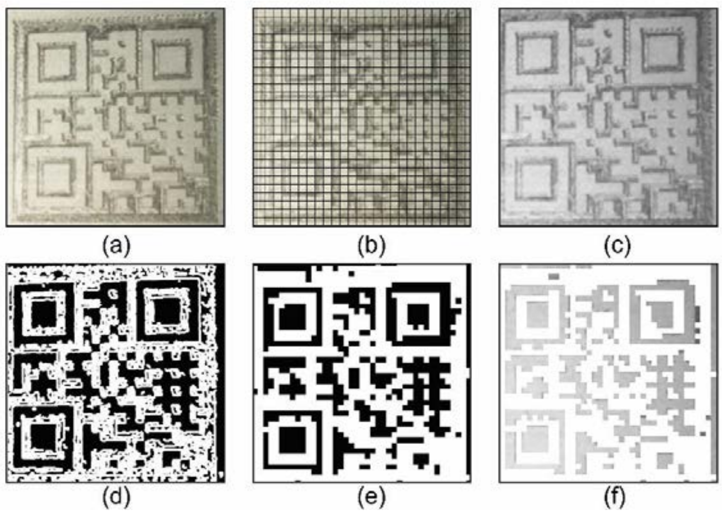

Fig. 3. (a) Machined QR code, (b) Machined QR code image merged to a computer generated grid, (c) grayscale image, (d) detected edges and blurring, (e) synthetized QR code, (f) captured image with the obtained QR code merged to it

Next, a Gaussian blur filter [14] is applied to the QR code captured image and the resulting image is converted to gray scale (Fig. 3c). A Gaussian blur filter is applied in order to smooth the QR-Code captured original image. The smoothing filter has the advantage of averaging regions, thus smoothing noise present in the image generated by the tool path, which is perceptible. However, an adequate value for the smoothing filter must be chosen. If its window, or kernel, is too large, the smoothing will be intense, and imparted edges that characterize the QR-Code of interest itself will be lost by the smoothing process. However, if the filter is modest, the tool track pattern is not removed and confuses the edge detecting algorithm, generating noise and edge detection unwanted for the proposed system. The algorithm, then, applies the Canny [15] edge detector with parameter *pC* and in the sequence applies a normalized box filter with kernel size *pB* x *pB* [14] to blur the resulting edges, enhancing their width. Next, a threshold filter [14] is applied to reduce edge fragments to a minimum level with parameters *Tmax* and *Tmin* (Fig. 3d). Finally, the resulting binary image is analyzed according to each module shown on Fig. 3a. The mean value of all pixels on a given module region is taken, and compared to threshold values (*t*), which will define if one entire module of the newly synthesized image (Fig. 3e) is completely black or completely white. Fig. 3f shows the captured image with the obtained QR code merged to it.

After the synthesized QR code is obtained, its image is sent to the open source Zbar [13] library for de-codification and information retrieval. The library error checking system will provide information if the QR code is valid. If it is not valid, the parameters *S, Tx, Ty, pC, pB, Tmax, Tmin* and *t* must be modified in a given range until the reading successfully occur. These parameters can be manually controlled, or dynamically adjusted until a valid QR code is detected and decoded.

Preliminary tests demonstrated that issues related to image size and inaccurate geometry of the smaller code did not affect the reading. In the QR code reading algorithm, a square grid is generated with the module dimensions of the original code. This guarantees that final QR code generated will have the modules format according to the QR code specification and nothing different from these modules will appear in the final image. The grid is superimposed over the detected edges, and the average number of pixels in each area of the edges image corresponding to the module is analyzed. If it is bigger than a threshold, then a black module is generated. Otherwise, a white module is generated. Due to this, inaccurate geometries derived from the ratio tool diameter / smallest module can be overcome.

However, difficulties were found in order to properly filter the original image and detect the edges of the QR code, as tool track patterns on the machined surface are evident (Fig. 4a), confusing the edge detecting algorithm. Moreover, brightness variation in the QR code makes it harder to find the right parameters, since optimal parameters vary for different parts of the code. Fig. 4b points out the differences between the reference code and the reconstructed code. Divergences are mainly noted on the left side, which is more affected by the light, according to the photograph of the machined code. According to Brown et al. [16], the success of a machine vision system largely depends on the lighting system, more than on a sophisticated image analysis. In that way, the lighting conditions of the system have major influence on the system performance [17], playing a key role in the machine vision process [18].

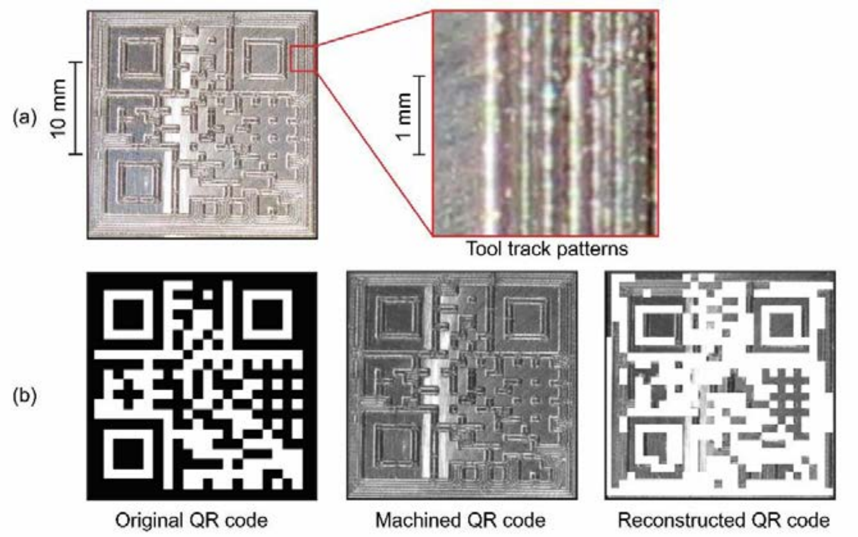

Fig. 4. (a) Tool track patterns in a QR code machined in an aluminum alloy, (b) Original, machined and reconstructed code

Considering this, in order to evaluate the proposed system and in an attempt to avoid tool tracks on the surface, an extra QR code with 25 x 25 mm size and 0.1 mm depth, having 21 x 21 modules was machined in an aluminum alloy part using a Roland MDX -20 desktop engraving machine and a high speed steel ball end mill with 1 mm diameter. Then, a standard smartphone with an 8 MegaPixel camera was used to take a photo of the part at a distance of 100 mm on homogeneous daylight. The camera parameters were: aperture f/2.4; exposure time: 1/30 s; focal length 3.4 mm; ISO 1000; no flash was used. This image was then loaded on a test program developed using the OpenCV computer vision library [14]. Successful data retrieval was obtained in all cases when the parameters were set as described in Table 1. The values mentioned refer to the results already shown in Fig. 3.

Table 1. Parameters used for successful QR code information decodification of the machined part.

Parameter	Description	Value	Working range
S	Scale factor of the original image	0.96	0.95 – 1.10
Tx	Offset X	-58	(-59) – (-55)
Ty	Offset Y	-59	(-61) – (-58)
pC	Canny threshold	17	13 – 19
pB	Gaussian blur	7	6 – 9
Tmax	Threshold maximum	255	246 – 255
Tmin	Threshold minimum	12	0 – 32
T	Pixels mean value threshold to detect as module	122	89 – 128

Conclusion

In the modern supply chains, where companies are more and more engaged to parts life cycle, being able to identify and retrieve information of a given part at any situation becomes a key issue. Standard methods such as the use of bar code labels and RFID tags are widespread, however, such methods are not guaranteed to always identify a part, as the labels might someday detach from the part, and be even replaced mistakenly. Moreover, it is known that RFID technology does not work well on metal parts. A suitable solution for such problems is the use of Direct Part Marking (DPM), however, this approach requires new processes to be added to the part manufacturing processes, requiring new equipment, personal and planning, increasing costs and production time. As a solution to the mentioned problems, this article proposes the possibility of directly machining QR codes on CNC machines, allowing companies to directly mark their parts using already installed machines. Moreover, the marking process can be programmed within other machining operations.

An algorithm is proposed for preprocessing photos of machined QR code, which makes it detectable and decodable by QR code decoding algorithms. The algorithm relies in synthesized QR code grid, which has its modules set to black or white according to the analysis of the mean pixel intensity value of the original image edges. The system has been assessed by machined QR codes in aluminum alloy with 25 x 25 mm and capturing their images at a distance of 100 mm. When adequate parameters are selected, the algorithm is able to reconstruct a QR code similar to the original. These parameters can be dynamically adjusted and when the adequate parameters are selected, decoding success rate is of 100%. The proposed system would possibly allow better part traceability during its life cycle, and even provide product history information to investigators, retailers, and end consumers.

As far as the machining of the QR codes is concerned, the major challenge refers to the production of burr free surfaces employing micro milling. Moreover, tool track patterns should be avoided in order to prevent edge detection problems in the code reading algorithm. Although these goals can be easily achieved for some materials (brass, for instance), code dimensions using conventional machine tools and tool path strategies, under less favourable circumstances decoding QR codes may become impracticable due to the additional time and computer effort required.

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