MEASUREMENT OF THE THICKNESS DISTRIBUTION BY DIGITAL IMAGE PROCESSING TECHNIQUES

Edmundo R. Sérgio [1], João R. Barros[2], Diogo M. Neto[1], Marta C. Oliveira[1], Rui M. Leal[1,3], José L. Alves[2] and Luís F. Menezes[1]

1: Centre for Mechanical Engineering, Materials and Processes (CEMMPRE)
Department of Mechanical Engineering, University of Coimbra
Polo II, Pinhal de Marrocos, 3030-788 Coimbra, Portugal
e-mail: {diogo.neto, marta.oliveira, luis.menezes}@dem.uc.pt

2: Microelectromechanical Systems Research Unit (CMEMS)
Department of Mechanical Engineering, University of Minho
Campus de Azurém, 4800-058 Guimarães, Portugal
e-mail: jlalves@dem.uminho.pt

3: ESAD.CR, Polytechnic Institute of Leiria,
Rua Isidoro Inácio Alves de Carvalho, 2500-321 Caldas da Rainha, Portugal
e-mail: rui.leal@ipleiria.pt

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Abstract *The thickness measurement of thin metallic sheets is of great interest in several areas of engineering. This study presents an algorithm to evaluate the thickness distribution in thin metallic sheets by digital image processing techniques. The basis is a high definition picture containing the cross-section of the component under analysis, obtained using an optical microscope, after the part is cured on resin, cut and polished. The digital image is converted into a matrix of pixels containing the RGB colour code. Since the colour of the metallic sheet is significantly different from the colour of the resin, the borders of the cross-section part are identified based on sudden changes in RGB values. The number of pixels between the previously identified borders are converted into a physical dimension, taking into account inclination of the sheet in the image. The thickness distributions obtained with the proposed algorithm are compared with the ones acquired using a manual approach, to show its applicability.*

1. INTRODUCTION

Sheet metal forming is one of the most important key technologies in the automotive industry. In order to fulfil the greenhouse gas emission standards, vehicles must be lighter to reduce the fuel consumption. On the other hand, vehicles safety is a key issue, which can be improved by increasing the strength of the component. But, to attain both goals, the strength increase must be accomplished with weight reduction. Therefore, new materials with high strength/weight ratio as well as thin metal sheets have been used in the automotive industry in metal forming operations [1] [2]. The success or failure of the sheet metal forming process design is strongly related to the failure modes, among which springback, wrinkling and fracture (or necking) are the most important. The localized thickness strain in the component is one of the main defects arising during the process design. Thus, the evaluation of the thickness distribution in critical zones of the final part is indispensable to access the robustness of the forming process. On the other hand, the thickness distribution is commonly used in the validation of numerical models by comparing numerical with experimental results.

Several procedures have been developed to measure the thickness of thin metal sheets, which can be divided in two groups: (i) contact-based and (ii) contact-free methods. Regarding the contact-based methods, callipers are the simplest, where the thickness is measured manually by physical contact with the sample. This process is non-destructive, but the accuracy is limited and highly affected by the skill of the operator. On the other hand, when using a coordinate measuring machine, the process can be automatized [3]. A cloud of points can be generated by sensing discrete points on the object surface, which characterizes its geometry. The contact-based techniques present some drawbacks, namely the requirement for jigs to control the location and/or motion of parts. Besides, they are not adequate for extremely delicate or yielding materials.

Concerning the contact-free methods, they can be divided in the optical based and ultrasound-based techniques. The optical based techniques detect the object surfaces using light reflection properties, as presented in [4] and [5]. Thus, the measurement can be carried out in hot components or in motion. Nevertheless, surface contaminations, low contrast and brightness or an inappropriate acquisition strategy can influence the measurement results. Ultrasound based devices allow to measure thin thickness values using specific wave propagation properties. The advantages and drawbacks are mostly the same as the ones of optical based methods [6].

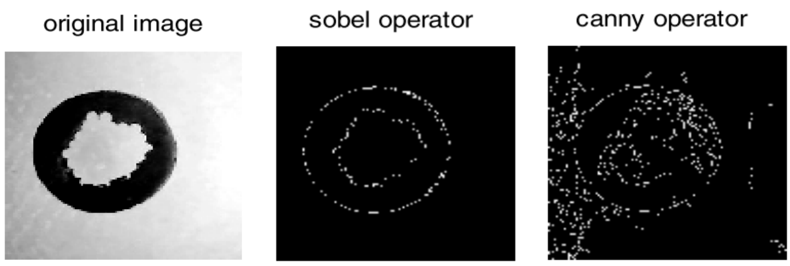


Figure 1. Comparison between the application of Sobel and Canny edge detection methods [10].

This study proposes an image processing approach to evaluate the thickness distribution in specific cross sections of sheet metal forming components. Since the proposed method requires an image of the cross section containing the component profile, it is categorized as a destructive method. The main idea behind the proposed algorithm is the identification of the sheet boundaries in order to evaluate the thickness. Among the methods developed for edge detection [7], the Sobel and Canny methods are usually mentioned. The Sobel edge detection [8] uses a discrete differential operator to compute an approximation for the gradient of the image intensity function at the proximity of each image point. In case of Canny edge detector [9], an edge is identified through the magnitude of the Sobel gradient, i.e. a sudden colour change defines an edge. Besides, the direction of the gradient shows the edge orientation. Figure 1 shows a comparison between Sobel and Canny edge detection methods. Nevertheless, these algorithms were aimed to analyse complex images, such as face detection and medical images, making their implementation very complex. This work describes a simple and cost-effective algorithm to evaluate the thickness distribution in metallic components, based on a high definition picture containing the cross-section of the component under analysis. The images analysed were obtained with an optical microscope, after the part was cured on resin, cut and polished. The procedure is intrusive, as the part needs to be cured in resin, cut and then photographed in an optical microscope.

2. IMAGE PROCESSING ALGORITHM

The algorithm developed to distinguish the metallic sheet from the surrounding fixing resin, in a specific cross section of a component, is presented in this section. The image processing algorithm comprises several operations, as shown in Figure 2. The first step consists in the assignment of a proper 2D space system to the image, where each pixel assumes a position in the space. The colour of each pixel will be used to identify the edges of the sheet. The second step corresponds to the image pre-processing, which is performed to avoid errors during the localization of the metal sheet edges. The third step comprises the localization, where each pixel over the borders of the sheet is identified and painted (red). This is a recursive algorithm allowing an easy interpretation of the process to the user. The last step is the measurement of the amount of pixels (distance) between two consecutive red pixels in the same line (oriented normal to the red line). These algorithms were developed trying to reduce both computational time and memory. Their detailed description is presented in the following subsections.

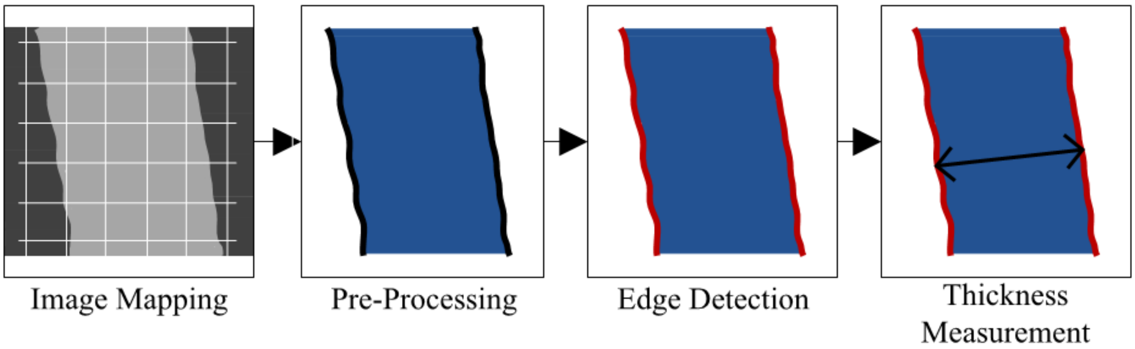


Figure 2. Sequence by which main algorithms are applied in the overall image processing algorithm.

2.1. Image Mapping

The RGB colour space has been chosen in this study due to the similarity with the human visual system, simple understanding and ease of implementation on computer algorithms. This colour space is defined by the chromaticity of **R**ed, **G**reen and **B**lue addictive primaries. More information on the RGB model and colour spaces may be found in [11], [12].

The colour information of each pixel is obtained through an intrinsic function of C# (`bitmap.GetPixel(,)`), which devolves a String with the RGB values in a predefined position. Accordingly, the image is interpreted as a matrix, where each pixel location is identified by a set of coordinates (*i*,*j*) with origin in the top-left corner of the image (see Figure 3). The numeric RGB information is saved in a single dual indexed integer variable, whose indices refer to the space coordinates of the corresponding pixel. A different magnitude is assigned to R, G and B values. In order to scan the entire image, the code will always run line by line.

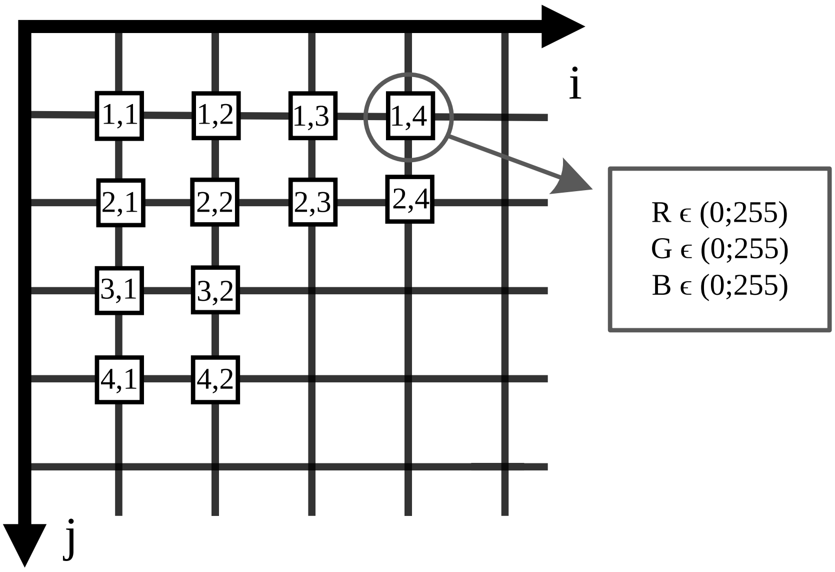


Figure 3. Coordinate system and pixel identification mode.

2.2. Pre-processing

In a digital picture, edges represent locations characterized by discontinuities in brightness [13], intensity [14] or colour [15]. The procedure under analysis was developed for thin metal sheets, which are more difficult to analyse with contact-based systems. This means that it is assumed that the thickness is always lower than 1 mm and, consequently, the microscope image can present enlargements up to 200x. Thus, the metal sheet is roughly monochromatic in the image, while the edges can be identified through the abrupt variation of colour on the transition from the sample resin to the metal. The monochromatic tones are typically in the grey scale, with similar values for R, G and B. In fact, in the images analysed, the difference between consecutive pixels occurs for just one of the colours. This allows to detach the influence of different orders of magnitude in the R, G and B values. However, several discontinuities may be found within the metal and the resin, mostly due to polishing anomalies. This type of discontinuities is shown in Figure 4 (left).

The pre-processing step attempts to prevent the detection of artificial edges by performing an initial edge detection procedure. In this procedure, the picture is scanned line by line to compare the colour of two consecutive pixels. If the colour gap surpasses a threshold value (λ), the pixel under analysis is painted with pure blue. However, in the following comparison the reference to estimate the colour gap is the original image. The flowchart of the algorithm is presented in Figure 5. The proper selection of the threshold value allows the identification of discontinuities, which by this procedure are also marked with pure blue (see Figure 4 (right)). Once the procedure is completed, the modified image is saved to be used as reference for the next step. Although the pre-processing step can guarantee that colour discontinuities in the resin harshly affect the procedure, they can be strongly reduced by adjusting the exposure, contrast and other parameters in the microscope.

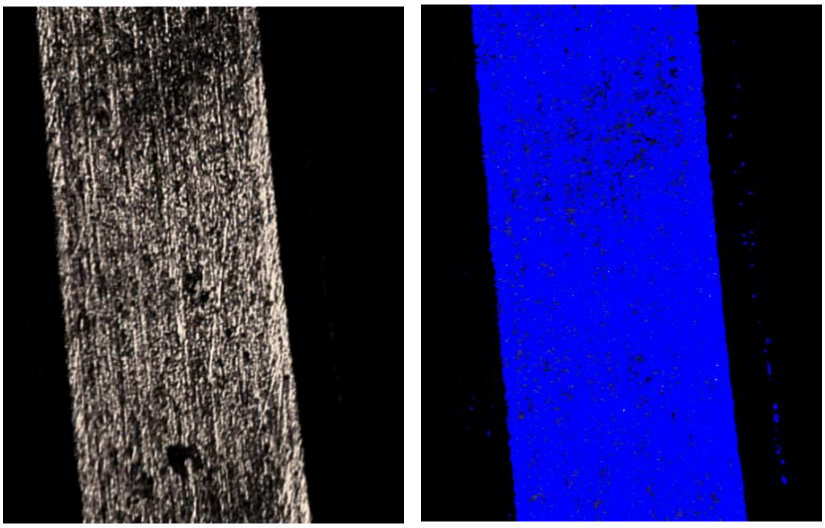


Figure 4. Sheet cross section before (left) and after (right) applying the Pre- processing procedure. Several undesired colour discontinuities were identified in a harshly polished sample.

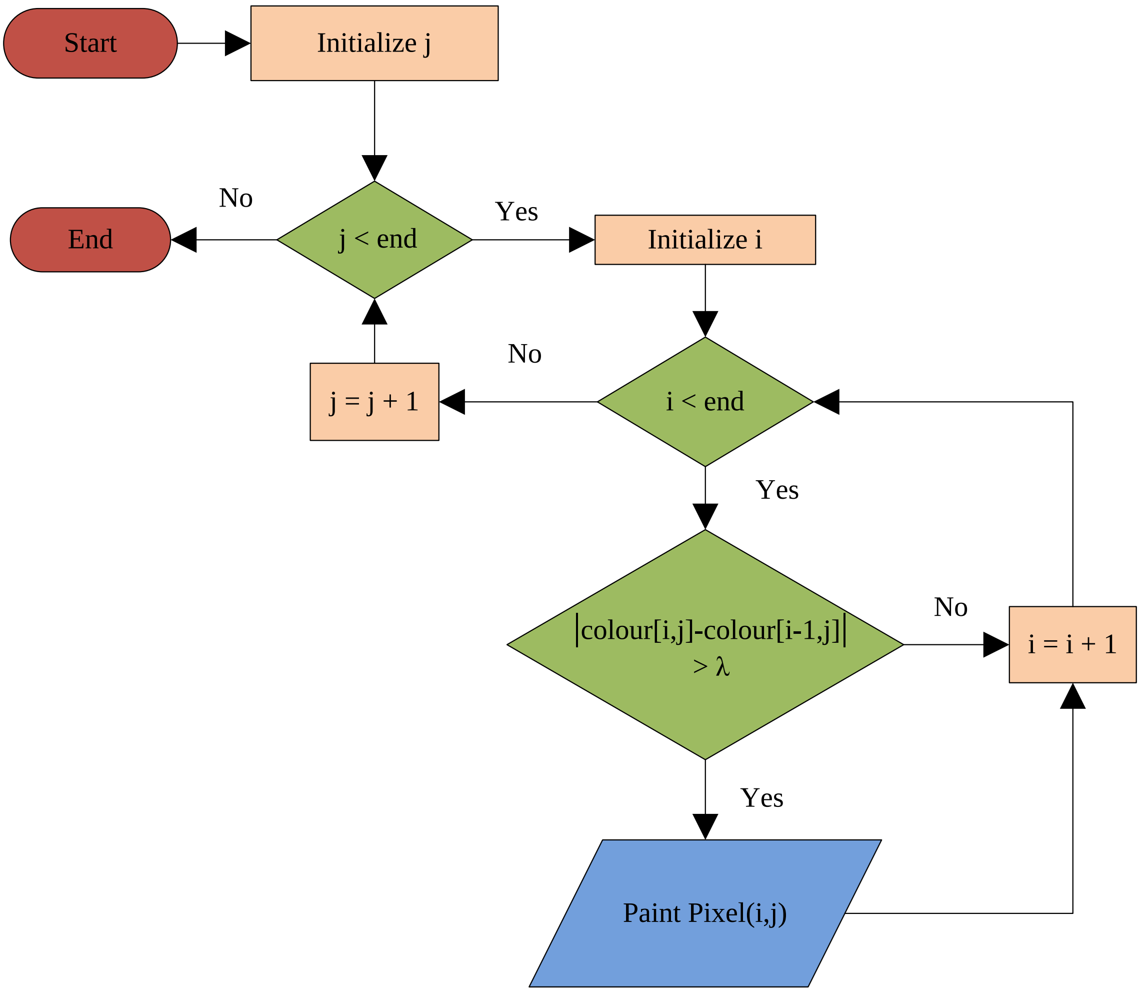


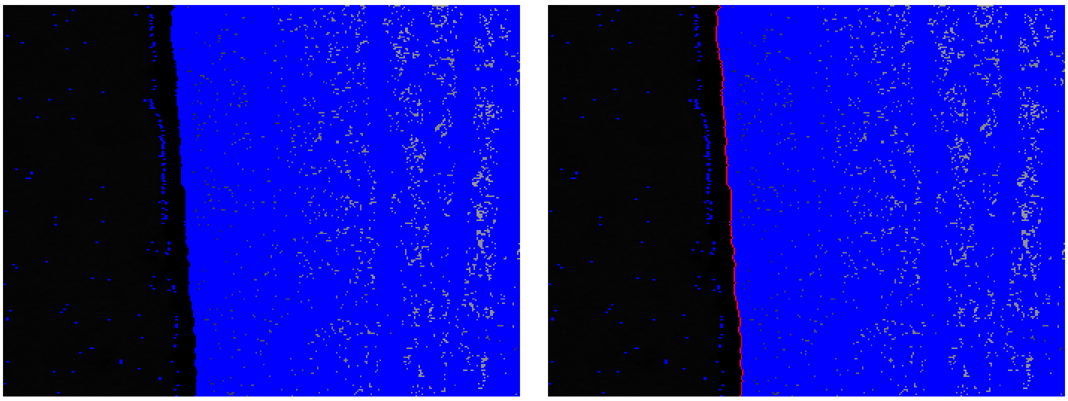
Figure 5. Scheme of the Pre-processing algorithm. λ denotes the colour gap threshold value.

2.3. Boundary Detection

After the pre-processing step, several unwanted edges can still be detected which are marked with pure blue pixels (see the example in Figure 6(a)). These undesirable edges are characterized by thin lines of pixels with large colour gaps, followed by relatively vast spaces of constant colour or changes small enough to not be detected by the pre-processing algorithm. Even in perfectly polished metal sheets, the colour change within the metal occurs in thick lines of pixels. Thus, the boundary will only be detected if a minimum number of consecutive pixels in the same image line presents sufficient colour discontinuity.

The procedure used to detect the exterior edges of the sheet is applied independently to each line (left and right), i.e. it is composed of two sequential, symmetric operations. In the first one, the colour of each pixel is checked from left to right. When a blue pixel is found, the following pixels are analysed and, if the total number of blue pixels found within a predefined range exceeds a minimum value, the first blue pixel is painted with red and the loop breaks (see Figure 7). The second operation is identical but from the right to the left of the same line.

In the end of this procedure, the boundary of the metal is defined with red pixels (see Figure 6 (b)). The total number of consecutive pixels (μ) that will be compared to evaluate if they fulfil the minimum required value (φ) have standard assigned values that may be changed by the user.



a) **b)**

Figure 6. Sheet cross-section: **a)** after Pre-processing were several undesirable edges are visible; **b)** after boundary detection (in red) showing the undesired edges being ignored.

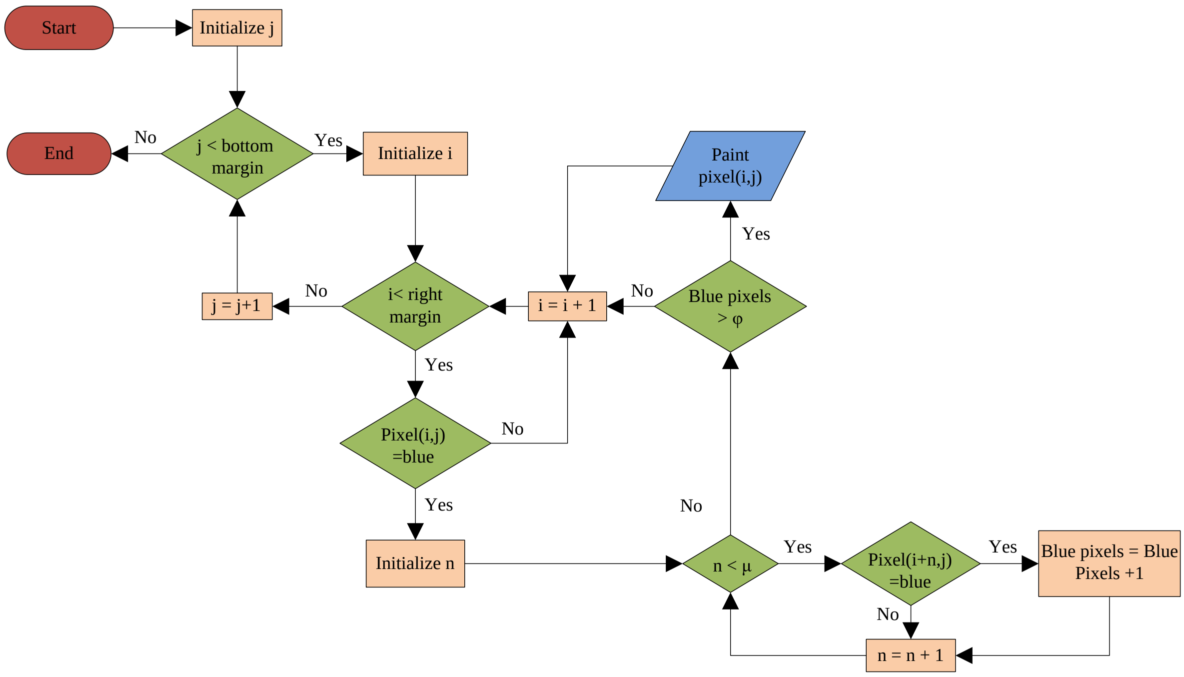


Figure 7. Scheme of Sheet Boundary Detection Algorithm (scheme for the step from left to right). μ stands for the total number of consecutive pixels, which will be compared in this process; while φ denotes the minimum number of blue pixels required to consider that the edge corresponds to the transition between the resin and the metal sheet border.

2.5. Thickness Measurement

After identifying the border of the sheet by red pixels, the last step is the thickness measurement along the height direction. The measurement can be performed either in each line of pixels or dividing the height of the examined region in constant intervals. For each line of pixels, the position of the first and last red pixel is registered, allowing to evaluate the number of pixels in a horizontal direction defining the metal sheet edges. Nevertheless, there is no guarantees that the cross section of the metal sheet is completely aligned with the vertical axis in the image. This may lead to thickness measurements in directions apart from the normal to the metal surface. In some cases, the angle between the metal surface and the vertical direction may be considerably large (as shown in Figure 8). To suppress this drawback, the angle between the metal edge and the vertical direction is measured. The procedure stores the column of the first and the last red pixel in the left edge, allowing to evaluate the required angle, as shown in Figure 9. The attained angle will be used to calculate the thickness of the sheet as follows

$$a = \cos(\alpha) \times \mathrm{h} \qquad (1)$$

where a denotes the thickness value, α is the correction angle for the normal direction to the sheet surface and h defines the distance measured along the horizontal line of pixels (see Figure 9).

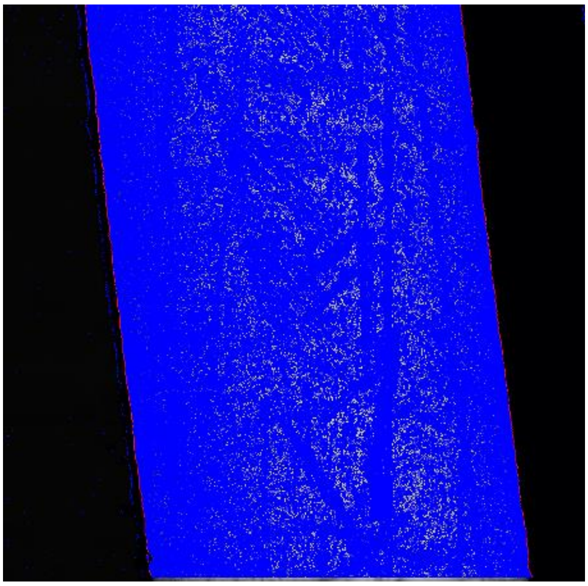


Figure 8. Example of a cross-section highly misaligned from the vertical direction. Ignoring the misalignment would lead to severe errors in thickness measurements.

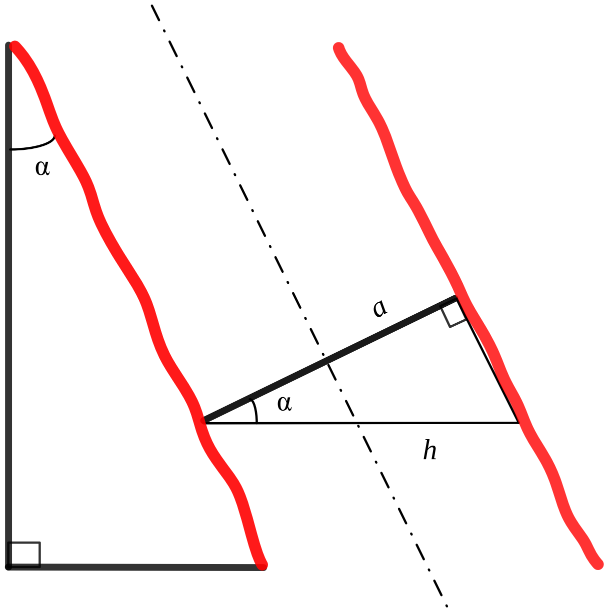


Figure 9. Trigonometric relation used in the algorithm. The real thickness (a) equals the product of the measured thickness (h) by the attained angle (α). On the right, the rectangle triangle whose adjacent (the biggest) and opposite (the smallest) sides are used to obtain α from the arc tangent.

Note that the size of the high definition images can reach millions of pixels; most of them are away from the metal sheet edges. Besides, the slope of the metal sheet is not constant over the image, presenting bends or curves due to the geometry of the component. Therefore, it is

necessary to confine the application of the algorithm used to evaluate the angle to the proper portion of image, i.e. with an almost constant vertical angle to ensure memory/time savings.
The procedure described counts the number of pixels located between the two red pixels, along each horizontal line of pixels, as shown in Box 1. However, the physical dimension of a pixel depends on the scale used to take the picture. Thus, the picture should contain the scale. This allows to algorithm to evaluate the length defined by a pixel from the picture scale, i.e. defines the proper scale factor to convert the total number of pixels into *h*. The real thickness is obtained applying Eq. (1) if necessary.

```
Procedure Get_Thickness
 While i < vertical margin do
    inside=False
    While j < horizontal margin do
       if pixel.color(j,i) = Red then
          pixel_counter = pixel_counter+1
          inside = True
       Else if pixel.color(j,i) = Red and inside = True then
          exit
       Else if pixel.color(j,i) != Red and inside = False then
          pixel_counter = pixel_counter + 1
    loop
 loop
```

Box 1 Logical steps to count the number of pixels located between the two red pixels, along each horizontal line of pixels.

3. CASE STUDY

The image processing algorithm presented was tested in the measurement of the wall thickness of an aluminium cylindrical cup. The thickness was measured along the cup wall in different directions, to highlight the material anisotropic behaviour.

3.1. Experimental Procedure

The cylindrical cup was obtained by deep drawing an AA3104 aluminium blank (0.274 thickness). The cup was imbued in resin powder and cured to allow an easy handling and fixation during the image acquisition process. The geometrical centre of the cup was identified and three directions (0º, 45º and 90º) with the rolling direction (RD) were marked on the base. Then, the sample was cut following the marked lines using a band saw. Cuts were made in normal direction to base, allowing to define the thickness as a function of the cup height (see Figure 10).
The cup parts were polished with a 600μm roughness sand paper, until reaching the marked directions. To improve the surface quality 800μm, 1000μm, 2500μm and 4000μm sandpapers

were used. Diamond polishing cloth was not used because it would bow the sheet surface changing the light exposition of the cross-section.

Finally, each sample was accommodated in the microscope and pictures were taken with a Leica® DM4000 M LED camera, using a 200x zoom. During this procedure, several light conditions were tested to check if the algorithm parameters could be used to surpass unfavourable adjustments. In fact, the tests performed showed that the light adjustments in the microscope are more important than the sample polishing process to guarantee good quality images. Moreover, the zoom used in the microscope was also changed, to check its influence in the image processing algorithm.

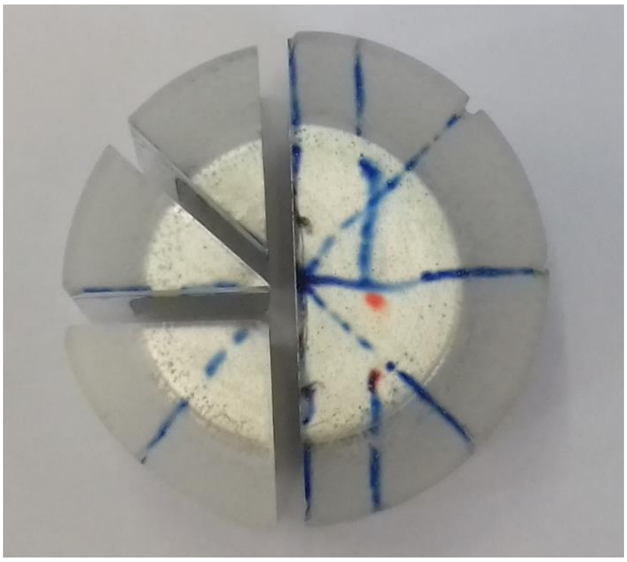


Figure 10. Cup imbued in resin with the cut directions drawn. The cut parts are also represented clockwise sense: 0º left, 90º, 45º and 0º right directions.

In order to validate the image processing algorithm proposed, the thickness distribution was also determined with the manual method. This was done using Zeiss® AxioVision SE64 Rel 4.9.1 software, with an interval between measurements of 500 μm. This software allows to measure the distance between two cursor positions, which must be defined respecting the normal direction of the sheet outer edges. When using the proposed algorithm, the measurements were performed in intervals of 30 μm, defining approximately 500 positions in 15.64 mm of the cup wall.

3.2. Image Processing Parameters

As previously mentioned, the developed algorithm requires some controlling parameters: (i) the total number of consecutive pixels compared in the edge detection procedure (μ) and, accordingly, (ii) the minimum number of blue pixels required in the previous range to detect an edge (φ); and (iii) the threshold for the difference in RGB data to place a blue pixel (λ). Based on the study performed, this last one is the more relevant, since it is also related with the sample preparation and the image acquisition. The light conditions used in the microscope image significantly affect the pre-processing procedure. For some arrangements, it was impossible to determine a proper value for λ, i.e. a value that allowed a proper pre-processing step and, consequently, a successful edge detection. In fact, smooth transitions between the resin and the sheet are required in order to guarantee a successful application of the procedure. Once a proper value for λ is selected, the algorithm shown no problems using the standard values for (φ=6 and μ=10).

3.3. Results and Discussion

In order to obtain the thickness distribution along the cup wall it is necessary to define the vertical coordinate for each measurement. The cup base defines the origin of the vertical axis. Due to the curvature in the punch corner, measurements start only in the straight region of the cup wall.

In this work, the thickness distribution along two different directions, namely 0º and 90º with RD, is presented. For the direction at 90º with RD, since the resin did not stick firmly to the cup in wide region, powders were trapped in the rift during the polishing process. This disables the image processing process it that region.

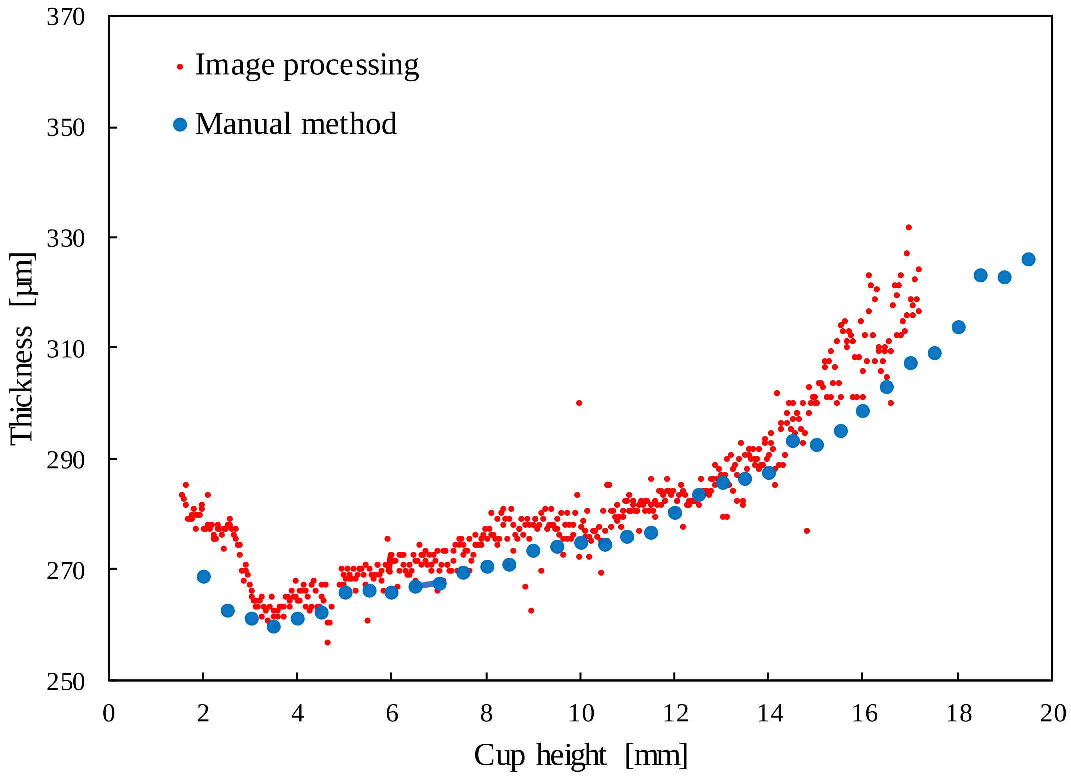


Figure 11. Results for measurement at 0º with RD.

Figure 11 presents the comparison of both methods in the measurement of the thickness distribution along the RD. Globally, both methods present identical thickness distributions. However, a small discrepancy occurs due to the lower definition of the image in the boundary zones (accumulated powders). This problem can be overcome by using of a sticking resin. The difference between the two methods is larger in the region close to the top edge (height > 15 mm), because the top edge got blurred and some of the accumulated resin powders were identified as part of the sheet, which leads to an artificial thickness increase (see Figure 12).

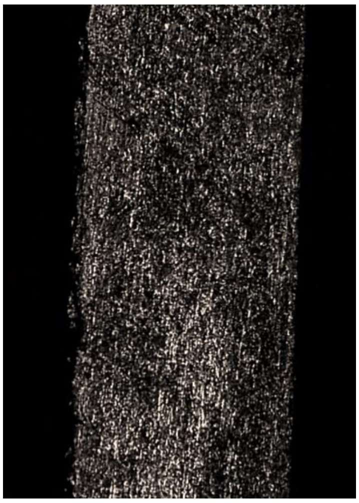


Figure 12. Cross-section of the sheet were the right edge is obviously blurred.

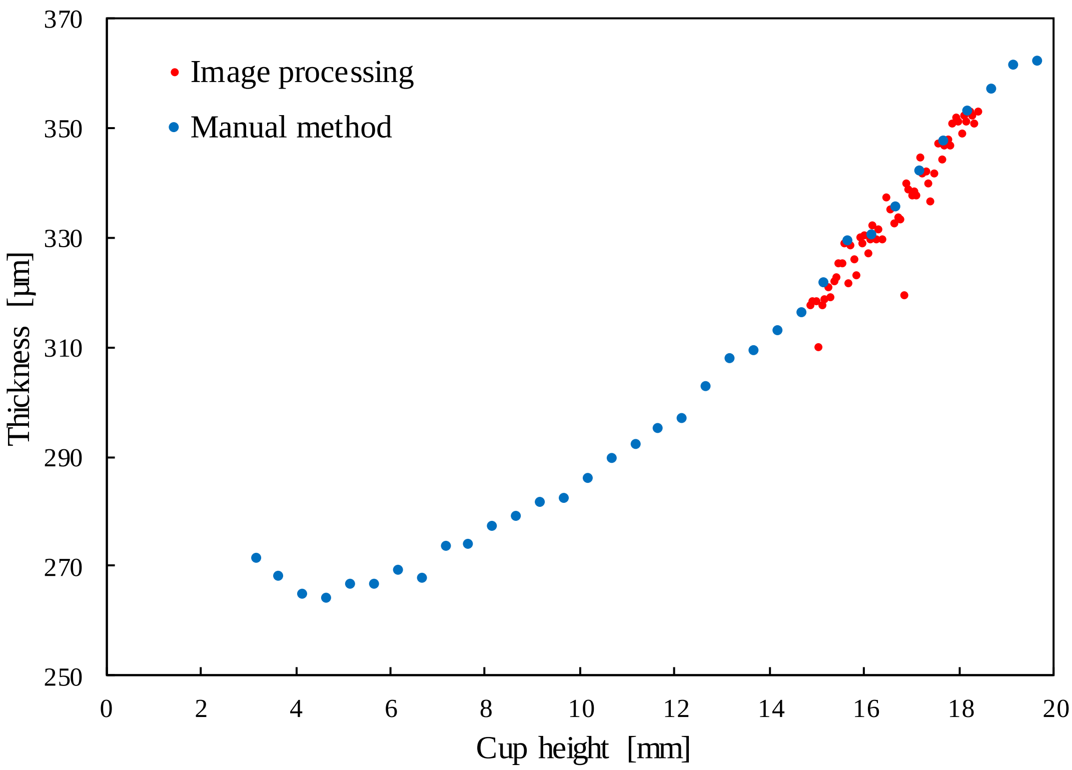


Figure 13. Results for measurement at 90º with RD.

Figure 13 presents the thickness measurement at 90º with the RD, comparing the proposed method with the manual measurement. As previously mentioned, it was only possible to performed approximately 60 measurement with the proposed method, in a region of approximately 4 mm of height. The difference between both methods in this direction is significantly lower than the one observed along the RD. This may be explained by the fact that this sample suffered fewer polishing steps. This prevented the application of the algorithm in a wider range, but since in the zone of application the edges remained perfect, the results were closer to the manual algorithm.

The accuracy of the thickness measurement using the proposed method is affected by several factors, but the more relevant ones are connected with strange variations in the colour of the sheet near the edges, leading to errors in edge detection step. A non-continuous or pixelated border is a characteristic of this situation. Also, intrinsic defects of the blank may lead to superficial holes in the sheet, which may also be due to problems in the polishing process.

4. CONCLUSIONS

The thickness measurement of thin metallic sheets is important for validating finite element codes, through the comparison between experimental and numerical results. This study presents a simple digital image processing technique for thickness distribution measurements using high-resolution images from microscopy. In this procedure, the image of the cross-section section under analysis is defined by a matrix of pixels, which allows identifying the RGB colour code is each one. The edges are identified by strong gradients in the colour, allowing to measure the thickness of the sheet in the surface normal direction. The results obtained from both manual method and image processing techniques are close, i.e. the overall thickness distribution is globally identical. The image processing algorithm is very sensitive to quality of the images acquired with the microscope, when the user should avoid the presence of strange variations in the colour of the sheet near its edges.

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