ACCURATE METROLOGY FOR PLASMA ARC CUTTERS

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Abstract- Plasma arc cutting is a popular fabrication technology that has numerous process parameters with complex interaction effects. Current methods are limited to cutting standard shapes for ease of measurement when assessing these interaction effects. This work presents a novel and accurate method for plasma arc cutting metrology using computer vision. The metrology is applied to the cutting of 3mm thick mild steel plate. The repeatability of the method is excellent and the edges of the cut are measured to an accuracy of 100 microns. This metrology provides a platform for future investigation into the phenomenology of Plasma Arc Cutting.

Index terms- computer vision, metrology, plasma arc cutting.

I. INTRODUCTION

Plasma Arc Cutting (PAC) has been used industrially for many years but is regarded as a somewhat crude cutting process (compared with water-jet or laser cutting) because of the difficulty in measuring cut accuracy [1-7]. Traditionally cut pieces are measured with calipers, but this is difficult for non-standard shapes [3, 8]. Researchers have derived empirical relationships between process parameters and cut features [1, 3, 6] but little is known about factors such as the variation in kerf thickness with the radius of curvature of the cut. For thin plates, the variation is likely to be very small but for thicker plates, it is reported, anecdotally, that the deviation of the cut around curves can be significant in PAC.

Computer vision assessment of the quality of both 2D and 3D parts is common [9-12] and includes applications to solve optimal cutting of material stock into parts [13]. However, researchers agree that no generalized computer vision system for the metrology of manufactured/fabricated parts exists [11, 14, 15]. Nemchinsky identified two areas of research in the field of PAC that have been neglected, namely, the use of computer vision to assist in the development of models describing the process, and an accurate model of the PAC process [1]. This work describes an accurate metrology system for PAC based on computer vision.
The goal of the research is to measure cut edges to an accuracy of one hundred microns or better. With this accuracy, the position of the kerf edge, being an aggregate, is rather more precisely known. The edge detected is the intersection with the edge of the kerf and the top surface of the plate. A vertical section through the kerf does not have parallel sides; generally the kerf is narrower at the bottom of the plate than at the top. However, this effect is small for thin plate. Therefore, this research uses PAC on thin (3mm thick) steel plate and develops an accurate metrology system using computer vision.

II. METHODOLOGY

A. Experimental System

A CNC Plasma Arc Cutting System (Fig. 1) with a Hypertherm Powermax45 power supply was used to cut 3mm thick, 550mm square mild steel plate. Images were taken using a Logitech c920 HD Pro Webcam mounted 200mm above the cut surface and attached to the cutting head (Fig. 2). The cut parameters are listed in Table 1.



Figure 1. CNC Plasma Arc Cutting system with test cut piece.

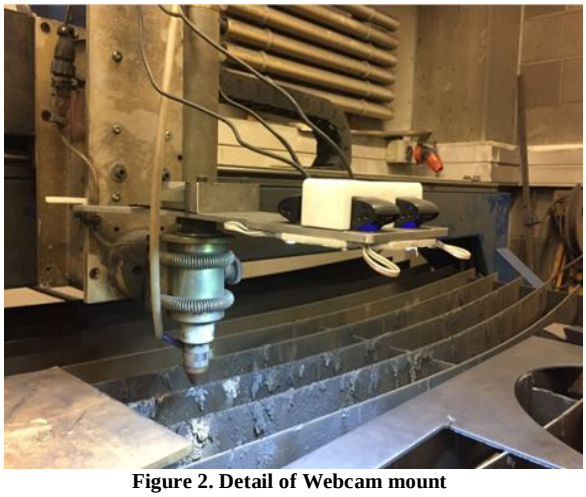

Figure 2. Detail of Webcam mount

Table 1 Values of the cut parameters

Cut parameter	Setting
Cut speed	2800 mm/min
Voltage	115V
Current	45A
Torch height	3.8mm

The cutting system was positioned using servo-motors with encoders, driving toothed belts. Positional repeatability was within 100 microns but true position was only within about one percent from the datum. This is typical for this class of PAC system. The method developed here uses techniques to avoid these errors in the metrology system.

The test cut template (Fig. 3) was selected to provide information on straight lines, corner fillets of several different radii (from 1mm to 24mm) and also on an Euler curve, where the curvature varied smoothly. Two sets of plate were cut in order to assess the repeatability of the methodology.

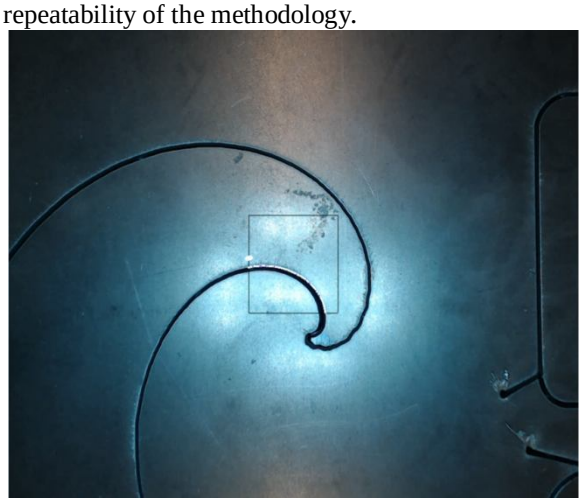

Figure 4a. Portion of test cut. The square shows the section of the image that is used, the white circles show the starting point for the propagation of the edge

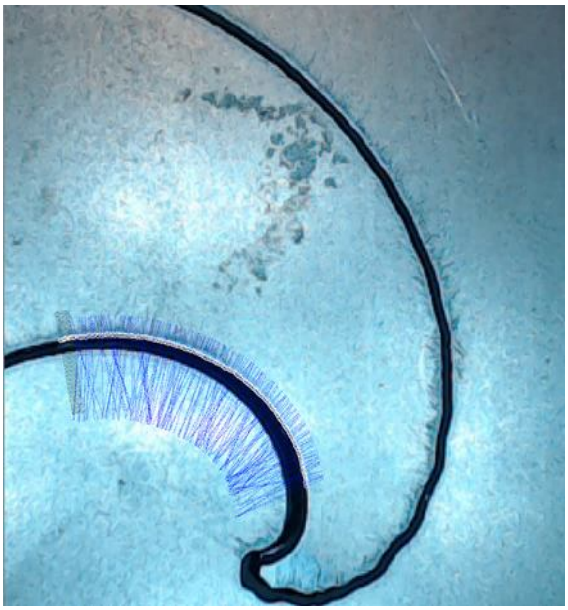

Figure 4b. Magnified view showing the edge profile points plotted in blue, and the edge points found plotted in white

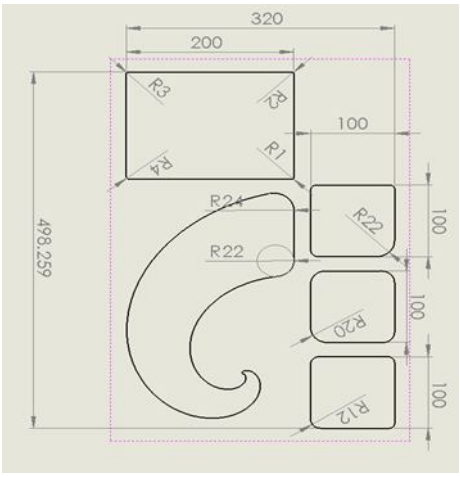

Figure 3: Test cut template.

B. Process for Data Collection

The process for the data collection is:

1. Parse the G-Code data, with an assumed kerf width, to generate a set of edge coordinates for the cut pieces.
2. Take a succession of images at a spacing of 10mm around the cut pieces. Record the position of the cutting head (with camera attached at some x- and y-offset) for each image.
3. Use an edge follower routine on the optical image to find the intersection of the cut with the top surface of the plate. This operates on a window, 200 pixels square, in the centre of the image. This produces a 50% overlap between adjacent images.
4. The first ten edge points are found using the G-Code (shown in Fig. 4a) to estimate where an edge point will lie. This provides the angle of the initial cross section, perpendicular to the kerf. Thereafter, this orientation is determined from the optically measured edge. The angle is determined to within 15 degrees but this tolerance does not degrade the measurement (which is interpolated in both x and y directions in the image). The blue lines in Fig. 4b show the sections through the visual data that are used to find the kerf edge.
5. These edge points are then transformed from the image reference frame into the G-Code's reference frame with the following transformations:
    a. Translation of the edge coordinates by an amount in δx and δy corresponding to the encoder recordings of cutting head position for each image. These points represent camera position with offset.
    b. Rotation of the edge coordinates by the known orientation of the

camera which was -0.75 degrees for this rig. This angle was determined in a calibration procedure.

c. The x and y edge coordinates are then scaled to convert them from pixels to millimeters. These scaling factors (pixels per millimeter in x and y) are calculated in the calibration procedure to be 4.70 mm per pixel.

6. Once all the edge points of the part have been acquired and transformed into the frame of reference of the transport system, allowance must be made for the fact that each piece will probably move relative to the edge calculated from the G-code. Each cut piece will therefore have a rotational error and two translational errors (in the x- and y-direction). These are determined using the Nelder and Meade simplex regression [16] minimizing the error between the actual edge points and the edge points calculated from the G-code.
7. Using these three values, the cut piece edge points are transformed back to provide the best fit for each cut piece within its G-code.
8. This data can then be used to estimate the accuracy of the cut and to assess the accuracy of the measurement technique.

RESULTS AND DISCUSSION

The accuracy of the transport system was typical of this grade of machine. The distances travelled in the x and y directions were dilated because they were referenced to the tooth spacing of the belts. However, in service, the belts must be stretched tight and this leads to an increase in tooth spacing. This factor was measured to be 1.0064 in the x-direction and 1.0069 in the y-direction. An analysis of hysteresis in position indicates that it is asymmetrical as the carriage approaches the end of a belt. The problem was resolved by imagining that a measuring device with this dilation was used in x and another in y. In that case, all measurements would correspond to the specifications in the G-code and, provided the camera was calibrated according to these measurement devices, the system would work seamlessly. This works because the camera position suffers exactly the same deviations as does the cutting head. Ultimately, the measured deviations (of the order of millimetres at most) of the kerf from the G-code would have this error but it would probably be smaller than the error band and could, at need, be scaled. It would be a proportional error rather than a difference error.

The test cut was run twice and the error at each point around the part edges was found. Two of these parts, with their corresponding errors are shown in Fig. 5a and Fig. 5b. The images show the error between where the edge should be, for constant kerf and perfect movement, and where it was measured to be. The error is shown magnified. Specifically, in each image there is a cross, where the length of the bars is one millimetre. It is apparent that the measurement errors are of the order of one hundred microns or less. The regressions for all five pieces returned a standard deviation of the order of 50 microns. The only way in which these results could be obtained is if, for this plate, the kerf width is accurately constant, which would be expected. Note that the curvature of the cut varies considerably but, for this thin plate, there is no deviation from the expected cut path. This accuracy validates the technique.

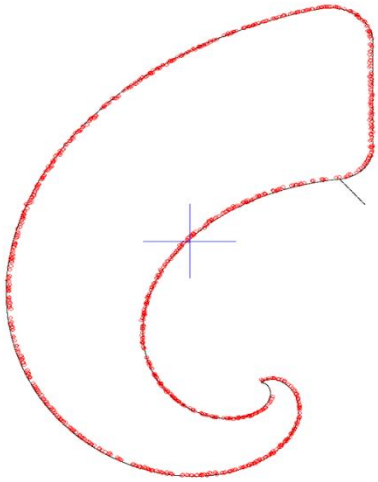

Figure 5a Cut piece # 1

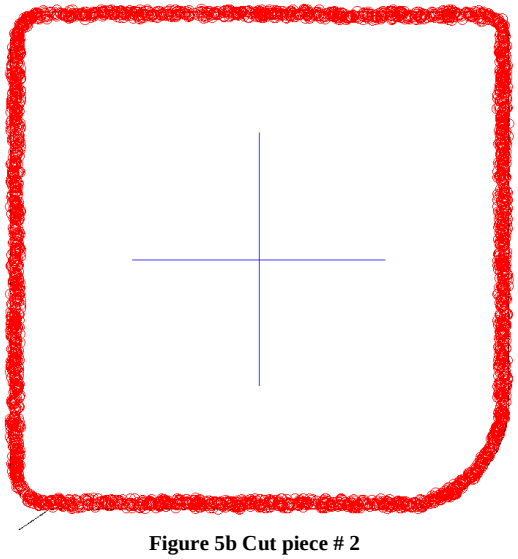

Figure 5b Cut piece # 2

Although the results are not reported in this preliminary work, it is possible to measure the cut edge in the plate from which the pieces were cut. This measurement is somewhat easier than that of the cut pieces because the plate remnant does not move, so regression is not required to mate it to the G-code. Once both edges of the kerf are accurately known, it is possible to go forward with a phenomenological model of kerf width, particularly as it relates to curved cuts in thicker plates.

Fig. 6a shows the corner of a plate and Fig. 6b shows the detail of the measurement at that corner. It is in fact a montage of three separate camera images, each at a different position. As may be seen, there are no perceptible errors in the estimation of the plate edge as the cut traverses a sharp corner.

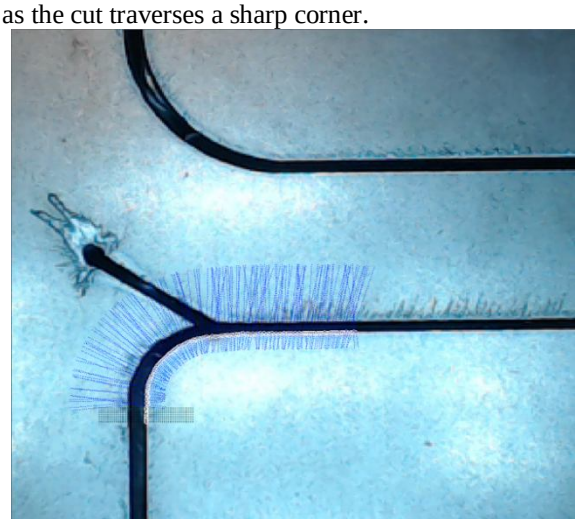

Figure 6a Corner of plate

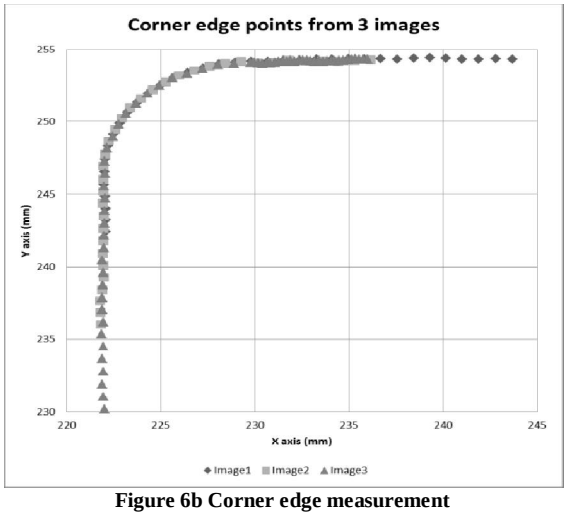

Figure 6b Corner edge measurement

The measurement technique was not simple in execution. It required care and delicacy to obtain the accuracy reported here. The central assumption is that, as the cut is traversed, pixel by pixel in the camera image, the greatest difference in the values of neighbouring pixels, in the direction of the orthogonal section, will correspond to the actual edge. In order to obtain sub-pixel accuracy (pixels were about two hundred microns wide), it was necessary to go to some length to fit a curve to the section data and to find the point of greatest slope by mathematical approximation. In fact, the great accuracy reported here resulted both from careful technique and the fact that astronomical numbers of pixel values were distilled down by a factor of about ten thousand to yield the final data points.

Anecdotal evidence for PAC suggests that cuts deviate when traversing curved sections and this is of concern, though accurate information has not been reported. It might be expected that, at higher cutting speeds and thicker plates, the problem will become more apparent. The basis to this prediction is that the inside edge of a curved kerf will be subject to greater photon radiation from the flame than the outer edge because each area element is exposed for longer. Therefore more material will melt off the inner edge of the kerf.

Nemchinsky reported a first-order analysis of the cutting phenomenology based on limited data [1]. With this technique, it is hoped that a more sophisticated model can be developed. The slope of the kerf edge can be measured at each point by sectioning the piece.

CONCLUSION

The results demonstrate that the PAC metrology system is capable of reading the kerf position to 100 microns despite the inherently inaccurate transport system of the PAC. The system can now be used to explore cuts made in thicker plate and with faster cutting speed in an investigation of the deviation of the cut around corners.

A technique to measure, very accurately, the edges of pieces cut by plasma arc cutting has been presented and validated. It is assumed, for cuts in thin plate at low speed, that there would be almost zero deviation of the cut as a consequence of curvature. The fact that the reported measurements substantiate this assumption can only mean that the measurements are very accurate. It is extremely improbable that the optical measurements would deviate in the same way that the cutting would deviate.

It is concluded that this technique can be used to obtain data upon which a phenomenological model of curved cuts in thicker plates can be based.

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