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ORIGINAL ARTICLE

Condition monitoring of first mode of metal transfer in friction stir welding by image processing techniques

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Abstract This paper discusses a method for online condition monitoring of the friction stir welding (FSW) process using image processing techniques. Many FSW experiments are carried out at different process parameters and images of the first mode of the weld zone are captured. They are subsequently digitally processed and analysed using MATLAB to study the variations in the quality of weld, subjected to various conditions such as pin failure, and pin depth. This facilitates development of a methodology for online condition monitoring.

Keywords Friction stir welding · Image processing · Tool pin failure · Online condition monitoring

1 Introduction

Friction stir welding (FSW) is a low heat input solid state welding technology especially suitable to low melting point metals such as Al and Mg [1–3]. FSW uses a rotating cylindrical tool with a shoulder to heat the metal by friction. The tool pin stirs the plasticized material and therefore joins two pieces together when it is moved along the joint line. This technique has many advantages over conventional welding techniques for joining materials that are difficult to fusion weld; such advantages include low distortion and excellent mechanical properties [4]. Since it is a solid state process there is less joint contamination and a very fine microstructure which increases the tensile strength and fatigue life. Another major advantage of FSW is avoiding the creation of a molten pool which shrinks on solidification. Hence the distortion of the welded plate and the residual stresses are low. Because of these advantages over conventional welding techniques, FSW has found widespread commercial applications in aerospace, shipyards and automobile industries.

It has recently been established experimentally by Muthukumaran and Mukherjee [5] that the metal flow phenomenon in FSW takes place in two modes. The first mode of metal transfer takes place layer by layer and is caused by the tool shoulder, while the second mode is caused by the extrusion of the plasticized metal around the pin. The present paper discusses the image processing techniques to study the changes in the first mode of metal transfer during FSW. The primary process parameters in FSW include tool rotational speed, traverse speed and pin depth. An accidental tool breakage and/or sudden changes in the welding conditions affect the first mode of metal transfer. This decreases the system productivity and degrades the quality of the weld. Hence it becomes necessary to monitor the first mode to ensure that reliable and consistent joints are produced. Online process monitoring facilitates the ability of the machine to adapt to changing process parameters and conditions, thereby

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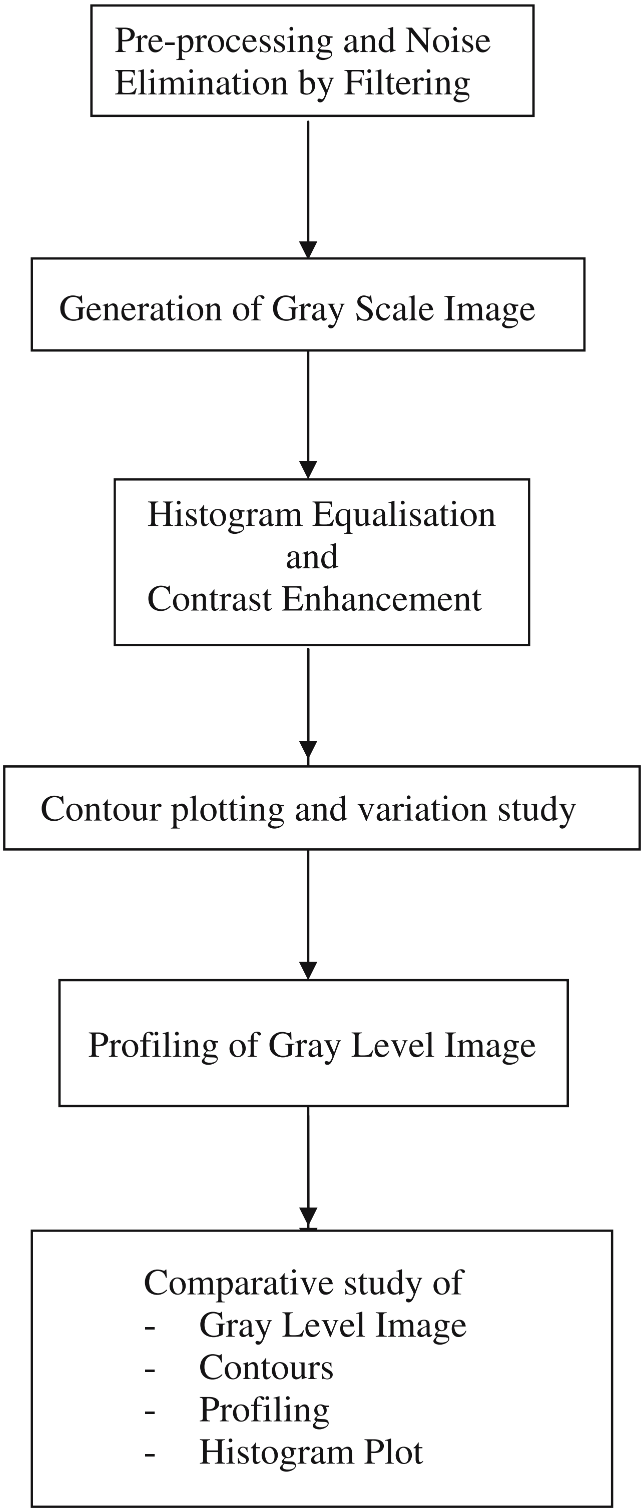

Fig. 1 Methodology flowchart for image processing

producing defect free welds under all conditions. Previously the acoustic emission technique has been adopted for in-process monitoring of the FSW process [6].

Image processing is an emerging technique having wide scope for process automation in the manufacturing applications. In this paper an attempt has been made to adopt image processing techniques for the FSW process automation. The digital images of the first mode are analysed after processing, to detect any defects or abrupt changes. This facilitates development of a method for online condition monitoring.

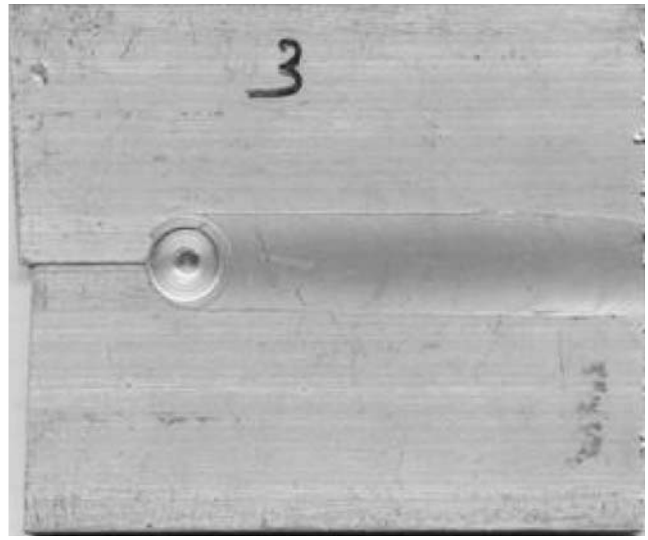

Fig. 2 Processed gray level image of a uniformly welded plate

2 Experimental work

The FSW is performed with a modified milling machine and the tool material is tool steel with 16 mm shoulder diameter and a M6 threaded pin. The tool is provided with 1° rake angle for all the experiments. The rotating speed of

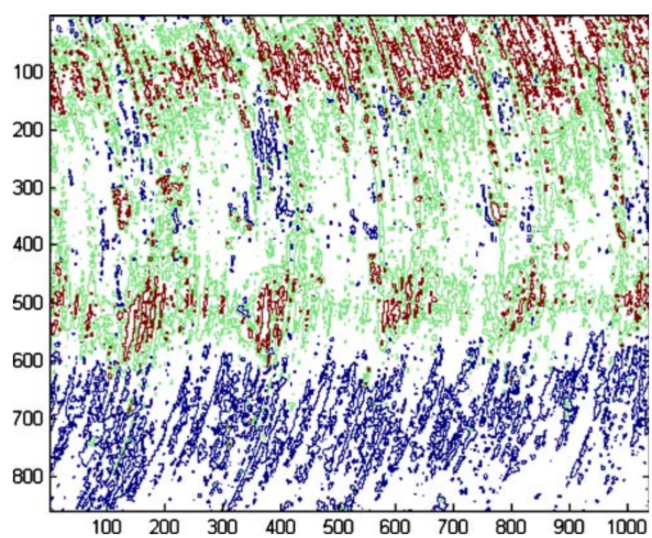

Fig. 3 Even contours shown by the processed image of a uniformly welded plate

the tool and its traverse speed are fixed at 1120 rotations per minute (rpm) and 200 mm/min, respectively.

The material used in the present study is 6.3 mm thick 6063-T4 aluminium alloy with the following chemical composition: Al-Si0.4-Fe0.35-Cu0.1-Mn0.1-Mg0.7-Cr0.1-Zn0.1-Ti0.1. The plates are cleaned and butt welded by the FSW technique. The images of the welded zone are captured by a digital camera during the process in progress.

3 Methodology for image processing

The preliminary pre-processing stage consists of applying filtering techniques to eliminate the noise from the acquired images. Then the color image is converted to a grayscale intensity image for further analysis. Subsequently contrast enhancement techniques are adopted and a histogram of the graylevel image is generated, which shows the distribution of intensities in the range 0–255.

A transverse section is taken across the graylevel image and a plot of the variation of the pixel intensity along a profile or line segment is generated. Finally the contouring of the graylevel image is performed to display a contour plot of the data and extract prominent features from the image. A contour is a path in an image along which the image intensity values are equal to a constant. The image processing methodology flowchart is shown in Fig. 1.

4 Results and discussion

FSW is performed under different welding parameters and images are captured using a digital camera and analysed. Different image processing techniques are adopted as discussed in the methodology for the following welded plates:

1. Uniformly welded plate
2. Pin failure while welding
3. Lesser pin depth

4.1 Uniformly welded plate

The first mode of metal transfer takes place layer by layer over the second mode, thereby offering compactness to the weld. Thus it is the first mode [5], of metal transfer that is critical and responsible for the soundness and strength of the weld. In the uniformly welded plate all the process parameters and conditions are even and a sound, consistent weld is obtained (Fig. 2). Histogram equalization, contrast stretching and various filtering techniques are adopted for processing the images. Such processed images show minimum variations in the pixel intensities along a selected line segment

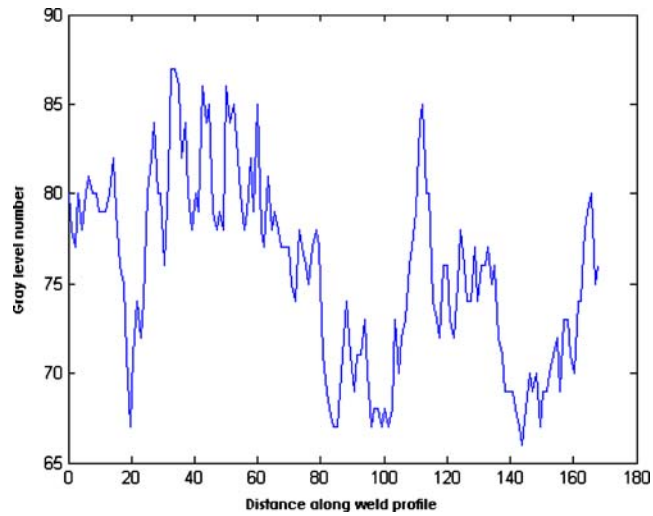

Fig. 4 Gray level variations along a profile observed in a uniformly welded plate

and consistency in the contouring data. The contour lines are continuous and uniform throughout the welded zone (Fig. 3). The pixel intensity differences along a line vary in the narrow band of 20–30 in the grayscale range (Fig. 4). Also the generated histogram does not have any pixels below the gray level number of 50 (Fig. 5). This is indicative of the defect free first mode and the soundness of the weld.

4.2 Tool pin failure

In this case, the sudden changes in the first mode of metal transfer after tool pin failure are indicated by pattern, graylevel, contour and structural variations easily identified by image processing techniques. Many such samples are analysed to get a clear comparative study on tool pin failure. The processed gray level image of a sample welded plate with pin failure is shown in Fig. 6. Subsequently various image processing techniques as discussed are

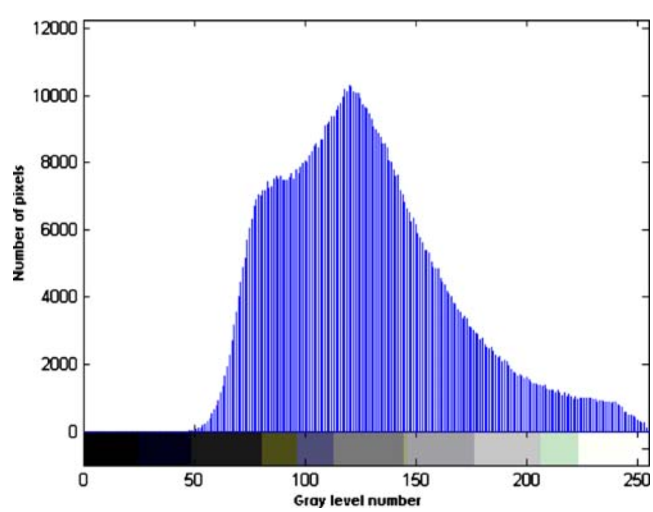

Fig. 5 Histogram plot of a uniformly welded plate

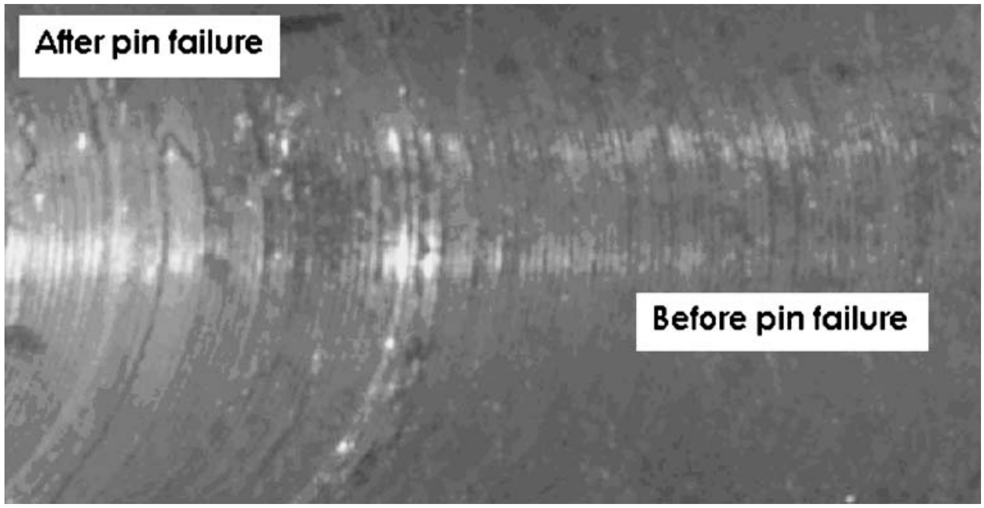

Fig. 6 Processed image shows the defects in the welded plate after tool pin failure

implemented and compared. Figure 7 shows the abrupt changes in the first mode of the welded plate after pin failure. These changes are also reflected as large variation in pixel intensities along a profile in the transverse section, indicated by the sharp peaks and valleys (Fig. 8). However, small grayscale intensity variations in the range of 20–30 are observed in the first mode before tool pin failure occurs (Fig. 9). It can hence be inferred that before the failure of the pin, metal transfer takes place by two modes, but after pin failure the first mode gets affected due to absence of the second mode. This variation in first mode is clear from the processed images shown in Figs. 6 and 7.

4.3 Lesser pin depth

In the third case the welded plate with lesser pin depth (Fig. 10) is critically analysed. Similar image processing techniques are adopted and the results show that the contours are broken and discontinuous over the entire welded zone (Fig. 11). The intensity profile taken along the transverse section reveals abrupt crests and troughs. The pixel intensity values fluctuate between the grayscale ranges of 150–200 (Fig. 12). This indicates the discontinuity in the weld zone and inconsistency in the first mode. Because the gap between the bottom pin face and the base plate is large, the heat generation is insufficient and hence incomplete first mode is obtained. Also the statistical analysis of the generated histogram plot reveals that a number of pixels are having grayscale numbers less than 50 (Fig. 13). This is indicative of the presence of defects and imperfections in the weld quality.

4.4 Analysis of power consumption

The motor output power is calculated by detecting the electric current and voltage signal of the motor shaft [7]. The power consumption during a better weld is found to be approximately 3.5 kW whereas the power consumption in the absence of the pin is around 2 kW. This power consumption reading can also be used to detect any disparity in the standard weld parameters. Any variations in the standard process parameters are reflected in the real time power consumption data. This variation coupled with the contouring of the captured images can be used

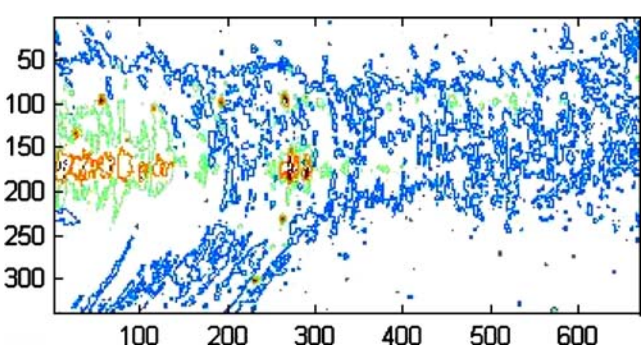

Fig. 7 Variations in the contour plot of a welded plate with pin failure

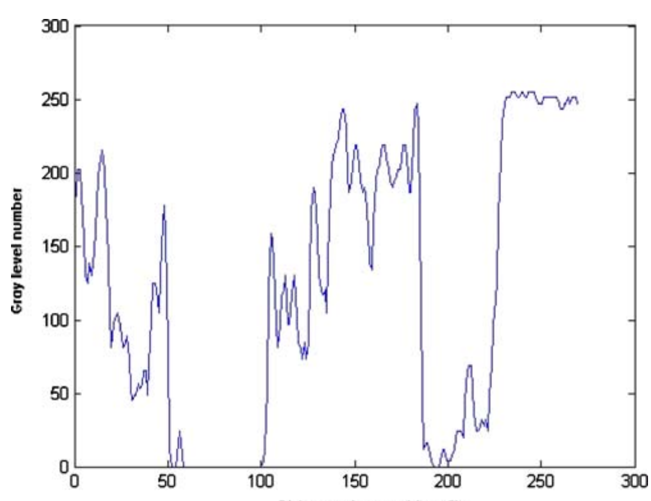

Fig. 8 Large gray level variations along a profile observed in a welded plate after pin failure

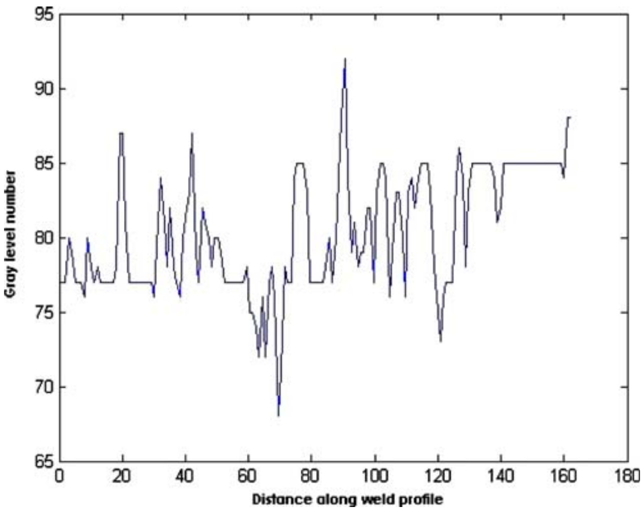

Fig. 9 Small gray level variations along a profile observed in a welded plate before pin failure

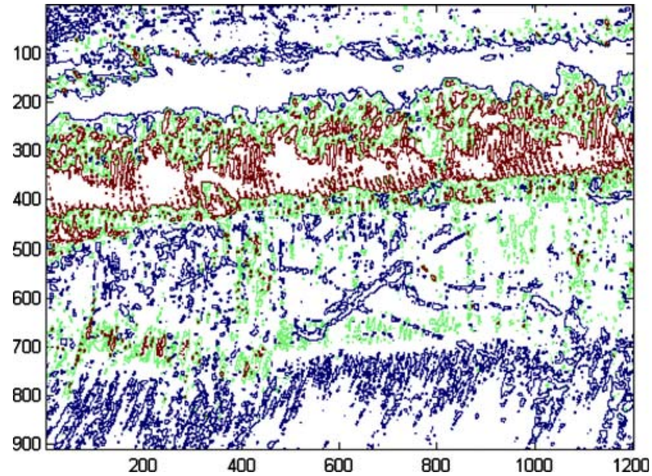

Fig. 11 Highly fractured contours of a welded plate with lesser pin depth

effectively to monitor the changes in the first mode due to pin failure.

5 Proposed procedure for online condition monitoring system

Analysing various welded plates and subsequent digital image processing of the welded zones indicates that

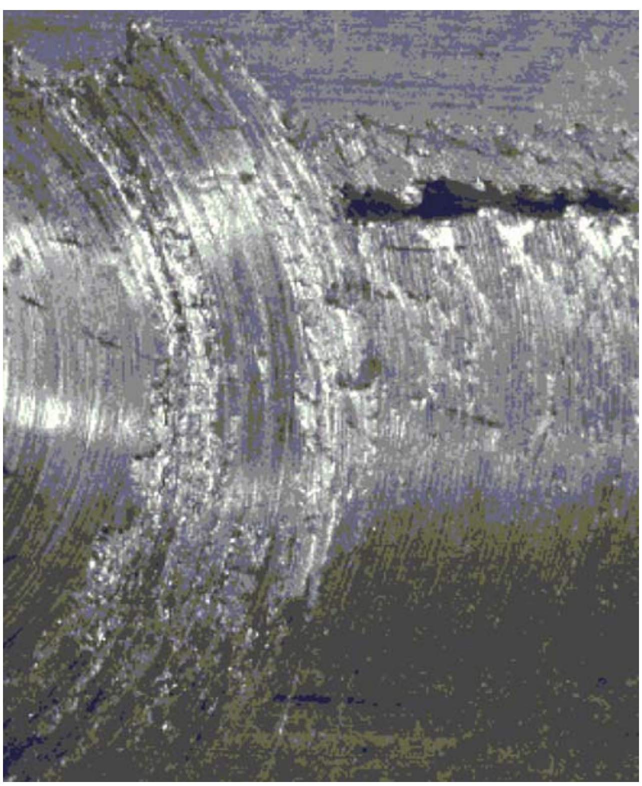

Fig. 10 Processed gray level image of a welded plate with lesser pin depth

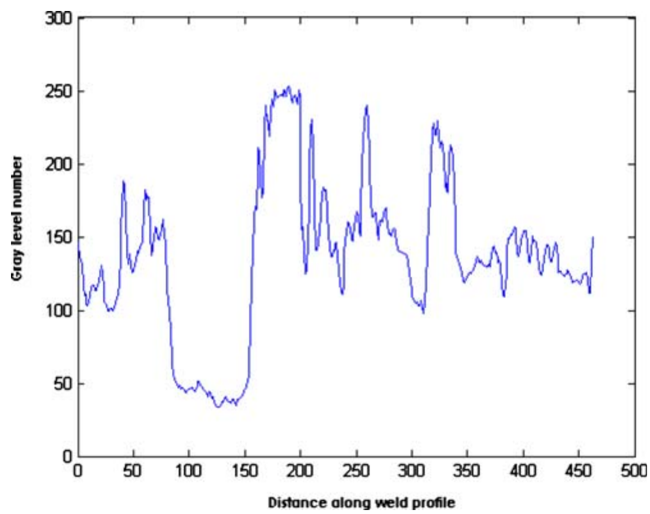

Fig. 12 Gray level variation along a transverse section of a welded plate with lesser pin depth

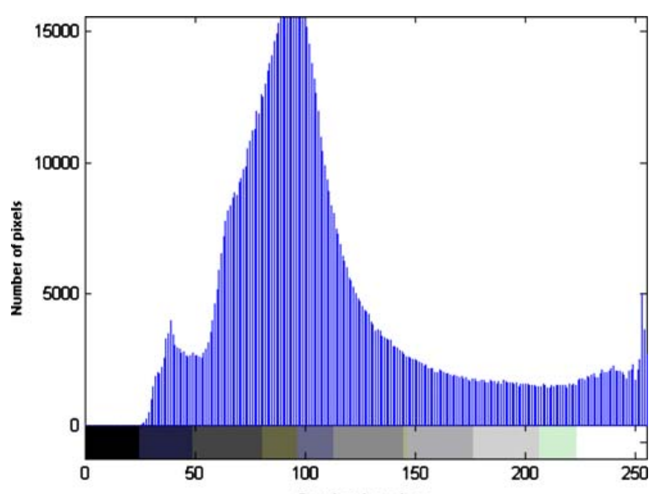

Fig.13 Histogram plot of a welded plate with lesser pin depth

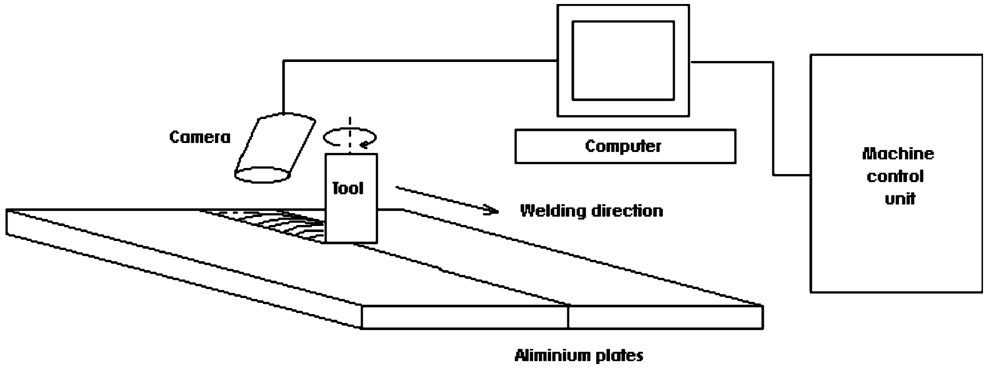

Fig. 14 Experimental set-up for online condition monitoring of the friction stir welding process

continuous monitoring of the first mode in FSW is required for automation. Hence an online condition monitoring system should be employed to detect the welding state and evaluate the weld quality. A camera is to be mounted adjacent to the tool head at a suitable height to capture the images of the welded portion in real time, and then the images are sent back to the computer for analysis. It should be interfaced with the computer system by means of connecting cables (Fig. 14). The online image processing toolbox of software such as MATLAB can be used for processing the acquired images.

The histogram equalization, filtering techniques, contrast stretching and standard deviation techniques should be adopted to delineate the defected structures and monitor the first mode. Accordingly the machine control unit should modify the process parameters or indicate the tool pin failure.

Thus the scalable and open features of the architecture for real-time monitoring lead to an advanced high performance control system. The tool condition and product quality can be monitored by employing online monitoring coupled with image-processing techniques which provide a more flexible automation in manufacturing.

6 Conclusion

The digital image processing techniques are adopted to compare the variations in the first mode of metal transfer in FSW. The changes in texture, pattern, graylevel and contours indicate variation in such welding conditions as pin failure and pin depth. Hence, automation of the FSW process, if adopted by means of an online monitoring system, can improve the productivity and quality of the weld. The proposed vision system incorporated in the form of a camera may be used to capture the images. Then various image processing and computer vision algorithms are to be applied to recognize the defects or any variations in the first mode of metal transfer. Subsequently, the system makes acceptance decisions according to prescribed standards. Thus the system learns to identify and test the main types of welding defects and variation in the first mode of FSW. The proposed method, if implemented, may be used to easily identify defects and reduce the error during the process. This online condition monitoring system can be used for estimation of process parameters for unknown materials. Also, it may provide cost benefits.

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