Journal of Manufacturing Processes 29 (2017) 96–112

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Volumetric defect analysis in friction stir welding based on three dimensional reconstructed images

Chirag Parikh[a], Ravi Ranjan[b], Aaquib Reza Khan[c], Rahul Jain[d], Raju Prasad Mahto[d], Debashish Chakravarty[e], Srikanta Pal[b], Surjya K. Pal[d,*]

[a] Department of Chemical Engineering, Birla Institute of Technology, Mesra, Ranchi, 835215, India
[b] Department of Electronics and Communication Engineering, Birla Institute of Technology, Mesra, Ranchi, 835215, India
[c] Department of Electrical and Electronics Engineering, Birla Institute of Technology, Mesra, Ranchi, 835215, India
[d] Department of Mechanical Engineering, Indian Institute of Technology Kharagpur, 721302, India
[e] Department of Mining Engineering, Indian Institute of Technology Kharagpur, 721302, India

ARTICLE INFO

Article history:
Received 17 April 2017
Received in revised form 30 June 2017
Accepted 5 July 2017

Keywords:
Friction stir welding
Weld defects
Depth map
3D reconstruction
Digital image processing

ABSTRACT

Friction Stir Welding (FSW) is a relatively new technology in welding. The ultimate aim of any welding process is to achieve a defect-free weld. Several defects during FSW can be attributed to various factors and are required to be examined and eliminated if required. The exact severity of a surface defect in FSW cannot be determined by a 2D image, which does not provide any information about the depth of the defect. Thus, this paper aims towards the comprehensive analysis of degradation caused over the weld strength due to surface defect, based on its 3D reconstructed depth map obtained from 3D Optical Microscope. This research work proposed a novel algorithm to determine certain 3D geometrical features like effective length, effective width, average depth and effective volume for giving the severity of surface defects with a precision of around micrometres scale. The depth data were also used to determine the surface textural features like average roughness and RMS roughness. The results obtained by this technique were also experimentally verified by the conventional surface roughness tester machine.

1. Introduction

The weld quality is dependent on the efficient and proper mixing of the materials in the FSW process. Non-uniform mixing of materials is caused due to the improper contact of the tool shoulder, insufficient forging force, rotational speed and other welding parameters. Variations of these parameters from their nominal values, lead to the formation of defects in the weld. Occurrence of defects reduce the strength of the weld. Hence, significant efforts have been put into this field to enhance the weld quality by reducing defect formation. Zhang et al. [1] investigated on the diverse occurrences of pores at various spots in the weld zone with the help of different sets of welding parameters values and proposed a simple mathematical model for choosing suitable values of the welding parameters in order to have a defect free weld. In order to achieve defect free welds, a comprehensive study on the type and severity of defects is necessary. Considerable amount of research is being done in the analysis of surface defects in the FSW process. Defects such as worm-hole, scalloping, flash, surface lack of fill, surface galling could occur due to improper tool design and process parameters [2]. Kim et al. [3] proposed that different types of volumetric defects formed in FSW can be attributed to alterations in rotational and transverse speed of tool. Excessive heat input leads to flash formation on the retreating side (RS) of the weld, while insufficient heat input results in emergence of groove-like defects. They also eluded that cavity or voids are induced due to abnormal stirring.

Analysis of force and torque signals of the FSW process helps to investigate the surface defects. Kumar et al. [4] examine surface defects occurred during friction stir welding by implementation of discrete wavelet transform (DWT) on force and torque signals. They have made use of the fact that defect generation during welding produces abrupt changes in the force signal which falls in the high frequency zone, while the force signal generated during a defect free weld lies in the low frequency zone. The defects are localized based on the locations where these high frequency components are detected, using the detailed coefficients acquired from DWT of the force signals. However, for welds having surface defects over the entire weld region, the force signals will consist only of abrupt signal variations and in such case the detailed coefficients of DWT fails

* Corresponding author.
E-mail address: surjya.pal@gmail.com (S.K. Pal).

http://dx.doi.org/10.1016/j.jmapro.2017.07.006
1526-6125/

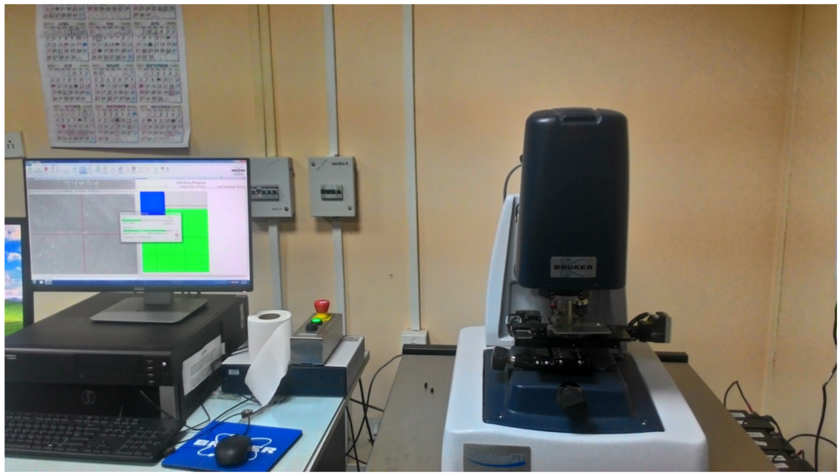

Fig. 1. Bruker's Contour GT-K 3D Optical Microscope machine.

to generate peaks at the defected regions as the entire force signal lies in the high frequency range. Researchers have also classified the quality of weld using certain statistical features like linear profile plot and contour plots extracted from an image with the help of image processing techniques [5]. Rajashekhar et al. [6] analysed the weld texture by extracting first and second order statistical image parameters of the grey level co-occurrence matrix which showed clear variations in their intensities distinguishing smooth and rough texture regions. Ranjan et al. [7] used different image processing techniques like image pyramid, image reconstruction for identification and classification of surface defects. However, exact information about the severity of each classified defect cannot be computed without having knowledge about its 3D structure. Shao et al. [8] proposed an image processing algorithm for monitoring the size of the liquid droplet in laser enhanced GMAW. Again, this estimation gives only 2D information about the size of the droplet while in the proposed research work, the defect has been analysed in 3D to obtain its volume. Dhanasekar and Ramamoorthy [9] determined the roughness parameter R_a of a weld surface by evaluating the contrast between two adjacent pixels of a 2D image obtained from a CCD camera. However, the average roughness parameter R_a cannot be determined precisely unless the exact variations of the depth of weld surface is known.

Among the published literature in the field of 3D reconstruction of the weld surface, few works have been done regarding the reconstruction of weld pool surface in GTAW [10]. Wang et al. proposed a 3D reconstruction method based on the intersection of incident and reflected laser light whose equation was calculated using mirror and camera. The work successfully reconstructed the weld pool surface, but it lacked the accuracy achieved in other reconstruction algorithm [11]. Moreover, the accuracy of results is very much affected by the initial calibration of the system which is not the case in this research work. Zhang et al. [12] proposed an analytic reconstruction algorithm to measure the 3D weld pool surface based on the slope field of the reflected laser pattern in real time for Gas tungsten arc welding (GTAW). Wang et al. [13] used an improved multi-frequency phase shift profilometry to reconstruct 3D surface images. This method gives good measurement accuracy but was not sufficient enough to give a proper estimate of the volume of surface defect.

In FSW, the defects have only been analysed in 2D using image processing techniques which gives only a superficial idea. The 2D surface image is just the top view of the weld zone, while there is no such information about its depth. Thus, a 3D reconstructed surface of the weld zone is required to exactly quantify the depth of the defect. A 3D reconstructed data of any weld sample helps in determining that how the defects have progressed through the weld surface which gives an idea about the quality of weld. The reconstructed depth image obtained by 3D Optical microscope cannot be directly used to estimate the impact of defects on weld quality and hence, post-processing of this data was required. Therefore, this research work proposes a novel algorithm to determine the volume of defects in any welded sample by using its raw reconstructed data obtained by 3D Optical microscope. Also, the depth data of the weld surface has been used to evaluate their average roughness Ra effectively and root mean square (RMS) roughness Rq parameter as well, which give a very precise knowledge about the texture of the weld surface, as well as the weld quality.

2. Experimental setup

2.1. FSW using NC controlled machine

A 20 kN capacity NC controlled FSW machine was used to butt weld AA1100 work-pieces with the dimension of 100 mm × 50 mm × 2.5 mm by using a tool made of tool steel with a shoulder diameter of 16 mm, pin diameter of 4 mm and pin height of 2.2 mm, respectively. The purpose of this research work was to correlate surface defects with the weld images. Thus, process parameters were chosen in a way such that surface defects may occur, i.e., at 800 rpm with 50 mm/min and 125 mm/min. Also, to compare the results obtained from a defective weld, process parameters were chosen in a way so as to produce a good weld, i.e., at 2000 rpm and 70 mm/min. In all the above experiments the plunge depth and tilt angle were kept constant at 0.05 mm and zero degrees, respectively.

2.2. 3D optical surface measurement

A portion of the welded surface was scanned under the Bruker's Contour GT-K 3D Optical Microscope machine whose experimental setup is shown in Fig. 1. This microscope is based on the principle of white light interferometry (WLI) to obtain the 3D reconstructed surface. A closed-loop scanning in the Z-axis is done to provide sub-nanometer (0.26 μm) vertical resolution. At a particular time the machine scans over a single window of an area of 3.45 × 2.59 mm^2 i.e. 1286 × 966 pixels with 1.5X zoom lens and 3X speed. As mentioned in the introduction, there is another technique of 3D reconstruction namely multi frequency phase shift profilometry. The accuracy of which was improved to 0.65 mm by Wang et al. [13] using angle and pattern modelling methods for system calibration. However, the surface measurement accuracy of 3D optical