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Manufacturing Letters 7 (2016) 6–10

www.elsevier.com/locate/mfglet

Research Letters

Defect detection in friction stir welding process through characterization of signals by fractal dimension

B. Das, S. Bag *, S. Pal

Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, Assam, India

Received 11 February 2015; received in revised form 11 November 2015; accepted 21 November 2015
Available online 27 November 2015

Abstract

An attempt has been made in this investigation to explore the possibility of quantifying the dynamic spectrum of signals in friction stir welding process using the concept of fractal dimension. A series of scan with a fixed span of time signals is characterized by computed fractal dimension. Difference observed in the computed fractal dimension for defective welding condition. The factual change in fractal dimension is indicative the initiation of defect for a specific welding condition. The analysis reveals the fact that fractal dimension can be an independent indicator for the prediction of defect formation in friction stir welding process.

Keywords: Monitoring; Fractal dimension; Signal; Defect; Friction stir welding

1. Introduction

The process of friction stir welding (FSW) involves complex physics and too many process parameters make it difficult for accurate phenomenological modeling of the process. The assumptions made in modeling techniques to integrate all physical phenomena may not be feasible in actual welding conditions. This motivates to implement real time data based analysis of the process, which is the outcome of the actual process conditions experienced during welding. Apart from the monitoring of FSW process, real time data can also be effective in identification of defects. In FSW process, the identification of defects is a challenging task as most of the defects are internal or subsurface where visual inspections techniques are not feasible.

In metal cutting and other welding processes, sensor data was effectively used for the monitoring of the respective processes. Current and voltage signals [1], force signals [2,3], acoustic emission signal [4–7] were few competent signals, analyzing which different researchers proposed different monitoring methodologies for different manufacturing processes [8]. In FSW process, detection of gap in the base plate was attempted in [9,10]. Real time force data were analyzed using Fourier transform for detection of possible gaps during the welding process. Identification of internal defects in FSW process was attempted by few researchers [11,12] that are mostly focused on non-destructive methods. Available non-destructive methods demand high operational cost and time. Hence, an attempt has been made to develop a methodology based on real time data acquired during FSW process for identification of internal defects in the welds which is relatively faster and of low cost. Literature review reveals the fact that processing and analysis of signal is effective route in monitoring of different manufacturing processes. However, very limited work is reported in the field of FSW process where monitoring of the process is performed using signals.

Welded joint in FSW is achieved by combined effect of tool rotational speed and welding speed. Tool rotational speed is mainly responsible for generating the frictional heat required to plasticize the material which facilitates the

* Corresponding author.
E-mail address: swarupbag@iitg.ernet.in (S. Bag).

http://dx.doi.org/10.1016/j.mfglet.2015.11.006
2213-8463/

welding process. Thus, rotational speed is decided to monitor using a laser tachometer. The well-established fractal theory is extended in this work as a tool for analysis real time signals acquired during FSW process. Most widely used signal processing techniques in defect identification such as Fourier transform, short time Fourier transform suffers from limitations as inability to analyze non-stationary signal and fixed window size, respectively [13]. Wavelet transform provides a solution to the limitations with Fourier transform methods but too limited by the selection of suitable basis and optimum level for efficient signal decomposition [13]. Realizing the drawback with the available and widely used methods, fractal theory is implemented in this study for the analysis of signals. The theory suggests that no pre-processing on the signal is required. It is a data driven approach and more importantly, fractal theory results in finding a single indicator termed as fractal dimension, sufficient to describe behavior of the signal in time domain. The acquired signals are segmented based on three salient stages during friction stir welding process namely plunging which includes pin and shoulder plunge, dwell period and welding period. Fractal dimensions for each segment from each speed signals were computed using well-known Higuchi's method [14]. The computed fractal dimension form the welding period of the sensorial data were presented as an indicator for the detection of defects in the welded samples.

2. Experimental set up

Single pass welding procedure is carried out on AA1100 aluminum alloy plates with dimension $160 \times 110 \times 6$ mm in butt joint configuration. The welding experiments are carried out by varying tool rotational speed, welding speed and shoulder diameter as shown in Table 1. Mechanical sectioning method is used to section the welded samples to observe the presence of defects inside the welds. In present work, an attempt has been made to find the presence of defects by analyzing the tool rotational speed signals. A non-contact type laser tachometer (accuracy: $\pm 0.1\%$) is used for acquiring the speed signal and the signals are sampled at a sampling frequency of 10 kHz using a dedicated data acquisition hardware. This signal data was used for detecting the occurrence of defects using fractal dimension.

3. Fractal dimension method

The concept of fractal dimension was introduced to the world from the work of Mandelbrot [15]. Since then, this was used in many field of science and engineering and many researchers has found its significance in analyzing the output of different processes. Relevant works on process analysis using fractal dimension can be found in [16–18]. Fractal dimension of waveforms was reported by Katz [19]. It was concluded that fractal dimension of waveforms can be computed and the dimension should be in between 1 and 2. The algorithms used for the computation of fractal dimension do not differentiate between fractal and non-fractal objects. The algorithms deliver a fractional number irrespective of the nature (whether fractal or not) of the object under consideration. This provides the strength to implement the fractal dimension algorithms to waveforms and correlate the physical behavior of the system. In this work, one of the well-established fractal dimension algorithm known as Higuchi's method was implemented to compute the fractal dimension of tool rotational speed signals acquired during FSW process. This algorithm is more accurate, robust and computationally economic as compared to other algorithms [14].

The idea of fractal dimension is extended to characterize the signals in FSW process by segmenting the original signals into three subdivisions which is related to three characteristics stages in FSW process. In plunging stage, the rotating tool is plunged into the workpiece up to a depth called as the plunging depth. During this period, the frictional heat is generated due to relative motion between tool and the workpiece that aids plasticization of the material. Once, the desired depth is achieved, the rotating tool is retained in that position for a predefined span of time. This time length is termed as dwell period and the material gets heated sufficiently for better plasticization of the material ahead of the tool by the rotating tool. The rotating tool is then traversed in welding direction and this stage is known as welding period. The welding stage is more significant since it provides the precise information about the process output and the formation of any defects inside the weld. As visual inspection methods cannot be implemented to detect sub-surface defects and high cost associated with non-destructive testing motivates to put effort in developing simple yet effective defect detection methodology.

Fig. 1(a) shows the welding period data for tool rotational speed signal against the defective cases. The signals show clear deviation as compared to the signal against the defect free welding shown in Fig. 1(b). The change in the amplitude and trend of the signal for defective cases are clear indication of process anomaly during welding

Table 1
Experimental design matrix with welding conditions.

Exp. No.	Tool rotational speed (rev/min)	Welding speed (mm/min)	Shoulder diameter (mm)	Remarks on the welds
1	1100	36	24	Defective
2	1100	36	16	Defective
3	1100	132	16	Defect free
4	815	98	20	Defect free
5	1500	63	28	Defect free