Advances in Engineering Software 85 (2015) 43–50

Contents lists available at ScienceDirect

Advances in Engineering Software

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

Defect identification in friction stir welding using discrete wavelet analysis

Ujjwal Kumar [a], Inderjeet Yadav [b], Shilpi Kumari [b], Kanchan Kumari [c], Nitin Ranjan [b], Ram Kumar Kesharwani [c], Rahul Jain [c], Sachin Kumar [c], Srikanta Pal [d], Debasish Chakravarty [e], Surjya K. Pal [c,*]

[a] Department of Electronics and Communication Engineering, Birla Institute of Technology, Mesra, Ranchi 835215, India
[b] Department of Electrical and Electronics Engineering, Birla Institute of Technology, Mesra, Ranchi 835215, India
[c] Department of Mechanical Engineering, Indian Institute of Technology Kharagpur, 721302, India
[d] Department of Electrical Engineering, Shiv Nadar University, Gautam Budh Nagar 201314, India
[e] Department of Mining Engineering, Indian Institute of Technology Kharagpur, 721302, India

ARTICLE INFO

Article history:
Received 19 December 2014
Received in revised form 29 January 2015
Accepted 8 February 2015

Keywords:
Discrete wavelet transform
Friction stir welding
Weld defect
Force signal
Torque signal
Variance
Square of errors

ABSTRACT

This article discusses on the detection of fault occurred during friction stir welding using discrete wavelet transform on force and torque signals. The work pieces used were AA1100 aluminum alloys of thickness 2.5 mm. The plates were 200 mm in length and 80 mm in width. Presence of defect in welding causes sudden change in force signals (*Z*-load), thus it is easier to detect such abrupt changes in a signal using discrete wavelet transform. Statistical features like variance and square of errors of detail coefficients are implemented to localize the defective zone properly as it shows better variations (in defective area) than the detail coefficient itself.

1. Introduction

The friction stir welding (FSW) is comparatively new welding technology. It is a solid state welding process, invented by The Welding Institute (TWI) in 1991 [1]. This process is simple, environment friendly, energy efficient and has become most prominent area for automobile, aircraft, and aerospace industries. The FSW joints have high strength as near as to the base metal. It helps in considerable weight savings compared to other joining processes. In contrast to other welding process, there is no liquid state for the weld pool during FSW; the temperature rise in the FSW is nearly 0.5–0.6 times the melting temperature of the metal. Thus, most of the problems related to the solidification of a fused material are avoided [2]. Due to stirring action of the FSW tool, the material at the nearby edges gets transformed into plastic stage. The material flows plastically to fuse and a friction stirred weld is formed after solidification.

Several researchers have worked on measurement of forces in FSW process. Mandal et al. [3] measured the axial force while attempting welding of AA2024. They observed that there is a high rise in axial force when plunges into work piece. This further increases when the shoulder makes contact with the work piece. Thereafter, when the tool advances, the axial force comes down and becomes stagnant. Several systems have been reported to measure the tool torque, traverse force and axial force during FSW process. The traditional load cells were used to measure the tangential load and tool torque while welding on the aluminum alloy sheets [4]. Cui et al. [5] used a specially designed low stir device to measure the tool torque, and developed a model correlating the tool torque with the tool rotation speed and welding speed. Kumar et al. [6] used load cells to measure the axial force and traverse force, and the tool power was measured by measuring the spindle motor current. Trimble et al. [7] used the rotating component dynamometer to measure the torque and the forces along the *X*, *Y* and *Z* directions. Pew et al. [8] measured the tool torque by monitoring the motor torque output. The methodology proposed by Mehta et al. [9] could also be employed to measure the torque and axial force from the electrical power and current usage by the FSW machine. It looks more compact and cheap in terms of indirect monitoring of tool torque and forces during FSW process. Su et al. [10] also measured tool torque, traverse force and axial force

* Corresponding author. Tel.: +91 3222 282996; fax: +91 3222 255303.
E-mail address: skpal@mech.iitkgp.ernet.in (S.K. Pal).

http://dx.doi.org/10.1016/j.advengsoft.2015.02.001
0965-9978/

during FSW process as they were very important to understand process mechanism and the optimization of the process parameters. They concluded that higher is the tool rotation speed, lower is the tool torque, while the impudence of the welding speed on the tool torque is negligible. The higher is the tool rotation speed, larger is the traverse force. The axial force is significantly larger than the traverse force. Rose et al. [11] performed the FSW of AZ61A magnesium alloy. They determined the effect of the welding force (varying from 3 kN to 7 kN) on the mechanical properties of the FS joints. They concluded that in comparison to others, the FS weld joint produced by 5 kN axial force had good mechanical properties. The reason may be because of the grain refinement with finer size and higher hardness in the stirred zone. Kumar et al. [6] studied about process parameters in AA5083 friction stir welds. They proposed that axial thrust (*Z*-force) largely depends on tool diameter, rotational speed and welding speed. *X*-force is mostly influenced by the welding speed, pin diameter and interaction of tool diameter and rotational speed.

Chen et al. [14] studied about formation of defects in FSW of 5456 aluminum alloy especially at weld nugget zone by varying the tool tilt angle. They demonstrated that tool tilt angle, an important parameter to obtain defect free weld. Tool tilt angle has an essential influence on the heat input into the material and the position of the defects in the weld. At low tilt angle flash formation occurs at retreating side. Further at large tool tilt angle a channel type defect is observed in the weld zone. Some other researchers also studied about the weld defect in FSW and proposed that geometric parameters had a wide role in formation of defect free welds [15,16].

Ramulu et al. [17] studied on optimization of process parameters to obtain a defect free weld and they developed a criterion of variation of force and torque with process parameters to predict a defect free weld from a defected weld. Their work did not focus on signal processing techniques and thus they have to depend on human observation for defect detection for different process parameters. This tends to produce the errors as they are considering the weld as defected or defect free just by observation. Macias et al. [18] studied vibro-acoustic signals generated from FSW and implemented statistical tools on the original signal and detail coefficients of the wavelet transform of signal. They extracted these features from acoustic signal to train their neural model to predict process parameters. They applied these statistical features in their model and predicted tool rpm, tool profile, travel speed and tensile strength. This article focuses on wavelet analysis of force signals for localization of different kind of defects which arise due to various reasons. Chen et al. [13] studied the acoustic signals generated in friction stir welding to analyze the induced gap defects. They applied wavelet transform on acoustic signals and then found the energy bands over different regions. They showed sudden change in band energy when tool traverses over defected regions. The acoustic emissions are generated because of mechanical stresses caused due to deformation of materials but it is very difficult to identify irrelevant emissions which are caused due to internal or external stresses. The extraction of valuable features out of acoustic signals is very difficult which was also discussed in their article. Chen et al. [13] showed band energies of decomposed signals as one of the feature for defect analysis. They showed the presence of sudden changes in signal but those changes can also correspond to some other stresses as well as they have not shown the exact location of defects. Soundararajan et al. [19] showed that acoustic emissions produced are time variant only during plunge phase but is steady during welding. They have applied FFT, STFT, and wavelet transforms on signals but found difficult to correlate the frequency of the signal directly to various interactions that occur during the process. Only the frequency corresponding to loss of contact between the tool and work piece was observed. They showed the effect of variation of different parameters on acoustic signals. The exact positions of defects were not localized. Kleiner and Bird [12] studied about the usage of signal processing in FSW for weld quality determination. They proposed a mathematical model to compare the noise level in the weld. They inspected quality of weld to determine whether weld has been forged properly or not.

Available literatures showed mostly the study of signals for defect localization on acoustic signals, and a very few works have been done on processing of force signals particularly to localize the defects during welding. The work presented in this article focuses the study of force signals using discrete wavelet transform and then implementation of statistical tools like square of errors to exactly localize those defects. This work has an advantage that all kind of defects can be found and the exact positions of even small defects are localized which is sometimes not visible by bare eyes. These defects affect the strength of weld.

2. Experimental procedure

The work pieces used in this research work were AA1100 aluminum alloys of the thickness 2.5 mm. The chemical composition of AA1100 is given in Table 1. The plates were 200 mm in length and 80 mm in width. Tool and fixture used are made of hardened steel and H13 Steel respectively. The tool shoulder was made flat having 16 mm diameter. The pin used was of straight cylindrical shaped, with a diameter of 5 mm and a height of 2.1 mm. The welding parameters used in this research work are as follows: rotational speed 500 rpm, 1000 rpm and 3000 rpm on a single weld for two halves, welding speed 50 mm/min and 75 mm/min and a 0° tool tilt angle. The plunge depth was kept constant of 0.05 mm.

The experiments were conducted on a 2.0 ton FSW NC machine manufactured by ETA Technology Pvt. Ltd., India. The machine consists of load cell which is able to measure the forces along *Z* direction. Servo motor has been used to drive the worktable along *X*-axis. *Z*-axis vertical motion of the tool is controlled by servo hydraulic cylinder. A three-phase AC induction motor is installed to drive the main spindle and tool rotation. (During FS welding, the output parameters in terms of forces along *Z* direction is plotted on the computer screen attached to the machine by the internal correlations of the electrical parameters and recorded in real-time.) The machine is also equipped with industrial PLC based control system with industrial PC and LabView software for real time data acquisition.

3. Theory

The concept of wavelet was given by geophysicist Jean Morlet in 1981. In 1984, Morlet and a physicist Alex Grossman invented the term wavelet. Wavelet transform is based on small wavelets with limited time duration. The concerned localization is done by translation of wavelets. The scaled version of wavelet allows the study of wavelets in different scales i.e. frequency ranges [21].

Table 1
Chemical composition of the workpiece (AA1100).

Element	Al	Fe	Si	Mn	Mg	Zn	Ga	Na	Others
(wt%)	98.7 (min)	0.831	0.705	0.013	0.004	0.003	0.0118	0.0024	0.05 (max)