Weld defect identification in friction stir welding using power spectral density

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Abstract. Power spectral density estimates are powerful in extraction of useful information retained in signal. In the current research work classical periodogram and Welch periodogram algorithms are used for the estimation of power spectral density for vertical force signal and transverse force signal acquired during friction stir welding process. The estimated spectral densities reveal notable insight in identification of defects in friction stir welded samples. It was observed that higher spectral density against each process signals is a key indication in identifying the presence of possible internal defects in the welded samples. The developed methodology can offer preliminary information regarding presence of internal defects in friction stir welded samples can be best accepted as first level of safeguard in monitoring the friction stir welding process.

Keywords. Power spectral density, Periodogram, Welch periodogram, Defect, Friction stir welding, Vertical force, Transverse force

1. Introduction

Real-time monitoring of friction stir welding (FSW) process was targeted by few researchers integrating different sensors to the physical process. Among different real-time process signals acoustic emission signal, vertical and transverse force signals [1-3] were reported to be most capable in monitoring the FSW process. Subramaniam et al. [4] attempted monitoring of FSW process thorough acquisition of acoustic emission signal during the welding process. Effect of different pin profiles were investigated and concluded that square pin profile yielded maximum tensile properties of the joints. Acoustic emission signals were processed with wavelet transform by Chen et al. [5] for monitoring of FSW process. The objective was to detect in-process gap during FSW process. It was reported that acoustic emission signals processed with wavelet transform can lead to effective monitoring solution of the process. Boldsaikhan et al. [6] acquired vertical and transverse force signals during FSW process. Applying discrete Fourier transform to the signals and with artificial neural network, classification was performed to segregate defective welds from defect free welds. Monitoring of FSW process for defect identification was achieved by Das et al. [7] through fractal characterization of tool rotational speed signal. Fractal dimension of the signal was presented as an indicator for classifying defective welds from defect free welds. Fleming et al. [8] presented the in process gap

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detection methodology during FSW process. Frequency analyses of force signals were performed in order to detect gaps during the welding process. Automatic gap detection during FSW process was also reported by Yang et al. [9] using force signals. Discrete Fourier transform analysis was performed on signals to extract salient features for indicating in process gaps during welding process. Wavelet transform of acoustic emission signals acquired during FSW process was presented by Soundararajan et al. [10]. Power spectrum density analysis was carried out to investigate the role of different process parameters on FSW process. Vertical force signals during FSW process were analyzed with combined wavelet packet-Hilbert Huang transform by Das et al. [11]. In the work defect identification and modelling of weld quality were achieved using force signal features.

Aforementioned literature survey fetched that process force signals analysis can be effective in monitoring FSW process. In the present study the ideology of analyzing force signals for monitoring of FSW process in terms of defect identification has been attempted. Power spectral density estimate can be a useful indicator to monitor the process behaviour with relatively less complicacy as compared to other signal processing techniques [12-14]. This indicator provides a direct indication regarding the conditions of the process under inspection. Classical periodogram and Welch periodogram are the two approaches used for estimation of the spectral densities. The computed spectral densities are then correlated for identification of defects in the welded samples.

2. Experimental Investigation

Square butt joints are obtained with AA1100 material having plate dimension 110mm×160mm×6mm in a knee type vertical milling machine modified for FSW process. A total of nine experimental runs are performed by varying tool rotational speed, welding speed and shoulder diameter. The experimental runs with parameter setting can be seen in Table 1. A non-consumable rotating tool made of SS316L is used with pin length of 5.7 mm and pin diameter of 6 mm. After the completion of the experiments one tensile coupon is cut from each weld for tensile testing as per the standards provided in ASTM E8M manual. A hydraulically operated and servo controlled universal testing machine (make: Instron; model: 8801) is used for the tensile test to obtain the ultimate tensile strength (UTS) of the joints. During the welding experiments force signals are acquired using a strain gauge based force measuring system developed in house [15]. The developed setup is compared with piezoelectric based dynamometer (make: Kistler; model: 9202). The accuracy of the developed setup as compared to the dynamometer is found to be 98.73%, 98.94% and 99.04% for vertical force, traverse force and torque respectively. Integration of selected hardware and computers for data recording and processing are established through standard cables and MATLAB software. Signals are acquired using a data acquisition device (make: National Instruments; model: NI-USB-6259) at a rate of 10 kHz.

Table 1. Design matrix with responses

Exp. No.	Tool rotational speed (rev/min)	Welding speed (mm/min)	Shoulder diameter (mm)	Ultimate tensile strength (MPa)
1	815	36	16	92.00
2	1100	36	16	69.56
3	1500	36	16	88.42
4	815	36	24	85.48
5	1100	36	24	76.30
6	1500	36	24	92.22
7	815	132	16	88.05
8	1100	132	16	95.95
9	1500	132	16	80.29

3. Defects in friction stir welded sample

Once the experiments are over, each welded samples are cut perpendicular to welding direction to observe the presence of defects. Out of the nine experiments, Exp. No. 2 and Exp. No. 5 yielded defective welds. From the cross section analysis of the welds the defects formed are found to be tunnel defect. Specimens are cut and prepared according to standard procedures and macrographs of the defective samples are captured using optical microscope (make: Leica; model: S6D). The macrographs of the defective welds are shown in Fig. 1. It is to note that the parameters setting against Exp. No. 2 and Exp. No. 5 are same except for the shoulder diameter. High shoulder diameter results in high heat generation under constant tool rotational speed and welding speed. The high heat generated in the welds results in excess softening of the material inside the weld zone and constant stirring action of the tool expels the plasticized material out of the weld zone in form of flash. This leads to loss of material for completely filling the cavity formed by the rotating tool and results in voids inside the weld. Since the process is continuous the voids extends along the length of the weld forming tunnel defect. Again, it is observed that both the defects are formed towards the retreating side of the weld. Flow of plasticized material in FSW process occurs from advancing side to the retreating side towards the trailing edge of the tool. The heat and constant rotation of the tool forge the plasticized material towards the retreating side and is deposited in the retreating side filling the cavity formed behind the tool. Since, due to expulsion of the excessively soften material under high heat condition there is no sufficient material behind the tool towards the trailing edge to fill the cavity leading to defects inside the weld.

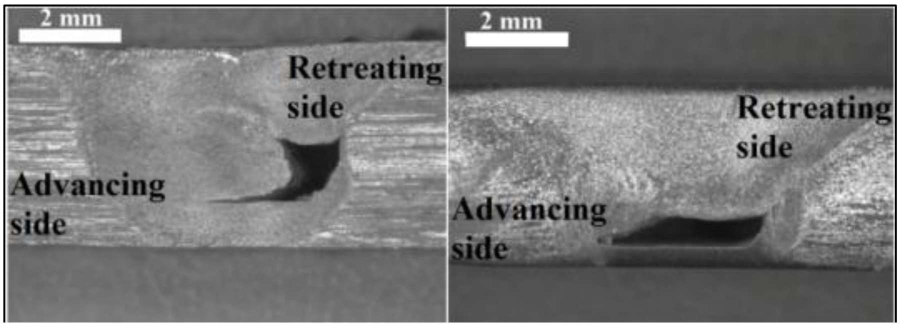

Figure 1. Defects found in welded samples of Exp. No. 2 and Exp. No. 5.

4. Analysis of force signals

Vertical force signal and transverse force signal are acquired during the FSW process against each experimental run mentioned in Table 1. For representation purpose these signals against the defective welding cases (Exp. No. 2 and 5) along with experimental condition with maximum UTS (Exp. No. 8) are shown in Fig. 2. From the respective figures for forces it is evidential that both trend and magnitude of these signals differ for defective and defect free welding cases. The information retained in the signal needs to be extracted for better representation of defect behaviour of the signals. In fault diagnosis of systems power spectral density (PSD) estimator are found to be quite useful as reported in relevant technical articles [12-14]. With the motivation of extending the use of PSD estimator in defect identification of friction stir welded samples; the acquired signals are analyzed with two mostly used PSD estimation algorithm namely classical periodogram and Welch periodogram [16, 17]. Both the algorithms are tested for real time force signals acquired during welding process to estimate the PSD of the signals and further correlated for differentiation of defective welds from the defect free welds.

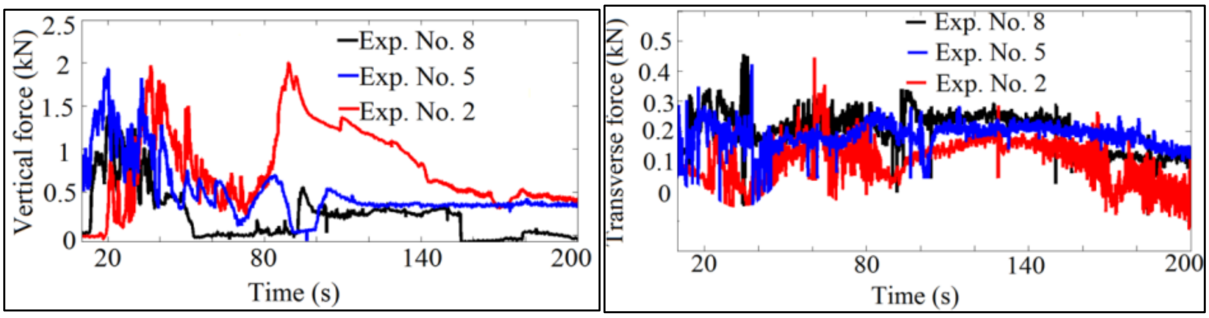

Figure 2. Vertical force and traverse force signals against defective and defect free weld.

5. Results and discussions

Signals acquired during the welding process are fed to both the PSD estimation algorithm and PSD of each signal is estimated using MATLAB software package. The PSD obtained for vertical force and transverse force signals shows notable difference between defective welding conditions and defect free welding conditions. PSD of the signals acquired using classical periodogram approach is represented in Fig. 3. From the figures it is evidential that PSDs of vertical and transverse force signals show appreciable deviation for defective and defect free welding conditions. PSDs of vertical force signals yields a maximum percentage deviation for defective and defect free welding conditions as 62.46% and minimum percentage deviation as 26.08%. The average percentage deviation for defective and defect free welding cases from PSDs of vertical force signal is 45.35%. The same for PSDs of vertical force obtained from Welch periodogram approach are 59.74%, 15.77% and 15.54% respectively. The similar percentage deviations for transverse force signal are represented in Table 2. Similarly PSDs computed from Welch periodogram approach for vertical force and transverse force signals are represented in Fig. 4 and respective percentage deviations for defective and defect free welds are furnished in Table 2. From the percentage deviations furnished in Table 2 it can be inferred that apart from the PSDs computed from vertical force signal, PSDs from transverse force signals also contribute appreciably in differentiating the defective welds from defect free welds. However, vertical force signal contribute maximum percentage deviation from both classical periodogram approach and Welch periodogram approach in differentiating defective welds from defect free welds. This indicates that PSDs obtained from both the two approaches from vertical force signal show appreciable deviation for defective and defect free welding cases and the computed PSDs can be implemented as a level of safeguard for identification of defects in FSW process.

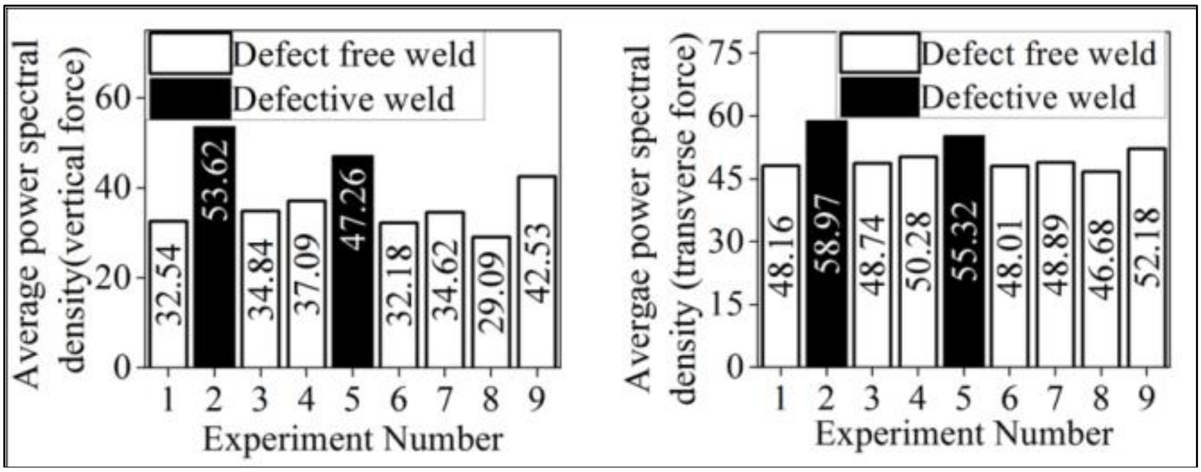

Figure 3. Power spectral density computed through classical periodogram approach

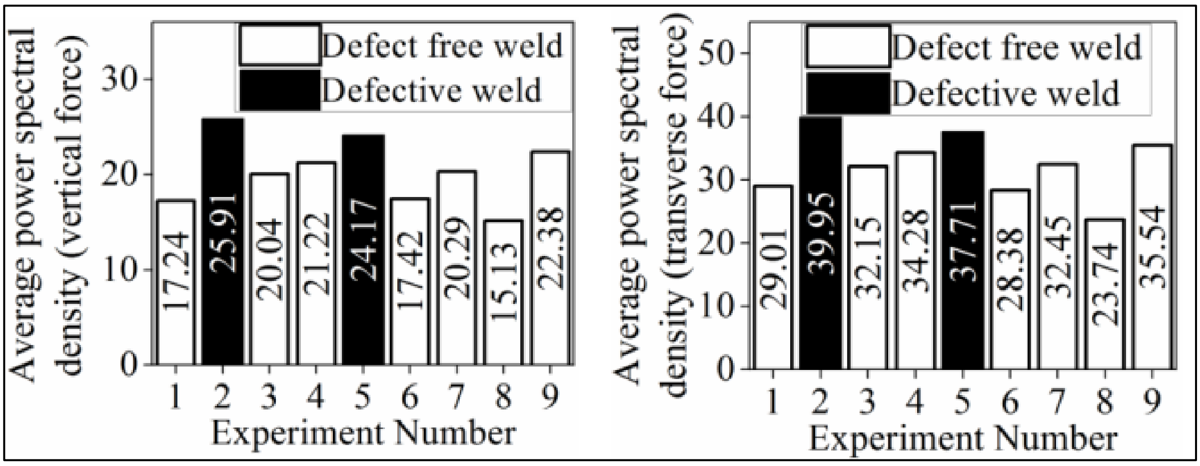

Figure 4. Power spectral density computed through Welch periodogram approach

Table 2. Percentage deviations of computed PSDs for defective and defect free cases

Percentage deviation	**Classical periodogram approach**		**Welch periodogram approach**	
	Vertical force signal	**Transverse force signal**	**Vertical force signal**	**Transverse force signal**
Maximum	62.46	18.5	59.74	58.84
Minimum	26.08	13.01	15.77	12.40
Average	45.35	16.64	15.54	26.11

6. Conclusions

Experimental investigation leads to the impression that similar process parameters setting may sometime lead to welds with different characteristics. Depending only on process parameters to monitor the outcome of the process may not be a suitable option for error free decision making process. Incorporation of real time process signal information in monitoring and decision making process can be an effective alternative. In the current research work vertical force and transverse force signals acquired during FSW process is analyzed for the estimation of PSD. Classical and Welch periodogram algorithms are implemented for the PSD estimation. It is observed that signals acquired against defective welding case results in higher PSD than that for signals against defect free welding cases. Power spectral densities obtained with vertical force signals reveal a higher average percentage deviation of 45.35% against defective and defect free welding cases. This brings the notion that PSD of vertical force signal can be an effective indication towards identification of internal defects in friction stir welded samples. Even though process parameters fail to depict actual process outcome; the computed PSDs can contribute appreciably in describing the process condition in terms of identification of internal defects.

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