Applying Microphone Array to the Quality Monitoring System in Laser Micro Lap Welding

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Abstract

In the micro lap welding, the development of a real-time welding quality monitoring system plays an important role to identify the low strength joint caused by the unreliable contact between two layers of stainless metal sheets. In this study, a microphone array filter is designed and applied to a sound-based quality monitoring system in laser micro lap welding to evaluate the filter's performance to improve the reliability of developed monitoring system when the collected sound signal is contaminated by the noises generated around the welding site. The noise reduction rate by a microphone array was analyzed first without the implementation of laser, followed by the analysis of the relation between sound signal features and welding quality without applying artificial noise in laser micro welding. Finally, experiments were conducted again along with the implementation of artificial noise to evaluate the contribution of the microphone array to the performance of developed monitoring system by comparing the results to the same cases without the implementation of microphone array. In the experimental setup, various joint strengths were generated by controlling the clamping conditions on fixture and changing the welding location. The results show that the noise will contaminate the signal obtained from single microphone and cause the reduction of classification rate up to 25 % when adopting time domain features. By applying the proposed microphone array system to the developed monitoring system, the classification rate of weld quality could be improved and back to the level close to the case without applying artificial noise to the system.

Keywords: Laser micro welding, microphone array, sound, quality monitoring.

1. Introduction

Laser micro welding plays a very important role in manufacturing of products such as electronic devices and battery cells. However, in the micro lap welding, the low strength/failure joint could be generated with the unreliable contact between two layers of thin metal sheets. Therefore, a real time welding quality monitoring system could provide a solution to identify defects on joints and improve the quality of micro welding. A few studies have been reported in past decades for the development of monitoring system in welding processes with different sensors, including the infrared sensor, Acoustic Emission (AE) Sensor, and Microphone [1-2]. Comparing to the other sensors, microphone has the advantage of easy installation and close correlation to the weld pool vibration. Its capability of detecting the weld defect has also been reported before [3-5] . However, how to avoid the contamination of the environmental noise to the system is the key challenge when adopting the sound signal in production line. Microphone array has been studied to reduce the non-stationary noise and provide a promised solution for the noise attenuation in speech recognition [6]. It is also been confirmed to be effective in the tool condition monitoring in turning process [7]. In this study, a multi-spacing configured MEMS microphone array is integrated with the developed weld quality monitoring algorithm to identify the weld joint defect caused by the uncertain contact between two metal sheets in micro lap welding. To simulate the noise generated in production line, artificial noise is generated by speakers during welding, and the sound signal was collected by microphone array simultaneously. In the evaluation of contribution by applying microphone array to the developed system, the classification rate of weld quality was analyzed for both cases with/without applying the microphone array and noise to the system.

2. Experimental Setup

2.1 Equipment and sensors

Laser micro lap welding experiments were conducted on a research platform (Fig. 1) with an integrated MEMS microphone array (Fig. 2, Knowles SPM0408LE5H-TB with frequency from 100Hz to 10kHz). A QCW fiber laser with wavelength of 1.064 um and spot size of 50 um was implemented and a designed fixture (Fig. 3) was used to clamp two layers of metal sheets together for welding. Two 45mmX10mm SUS304 stainless metal sheets with 200um in thickness was chosen as workpiece in this study. It's Thermal expansion (10^{-6}/K), Thermal conductivity (W/m·K), and melting point (^{O}C) are 18.4, 16.8, and 1723, respectively. In the test, a microphone array was installed 10 cm away from the welding location, and a speaker which deliver the broad band noise was installed around welding point as shown in Fig. 4.

To obtain different welding quality from the laser micro lap welding, a number of experiments were conducted with different clamp setup on fixture. For the data acquisition, two NI PXI6132 DAQ card were used to collect sound signals from microphones simultaneously with sampling rate of 50 kHz. The laser delivery parameters for the are listed in Table 1.

2.2 Experiment Design

To quantify the joint condition in micro lap welding, the peeling test was conducted for each weld joint by breaking up each joint on the test equipment designed in Micro Manufacturing laboratory in NCHU. In which, the peeling force to break up the joint was measured by a Kistler 9217A load cell and recorded.

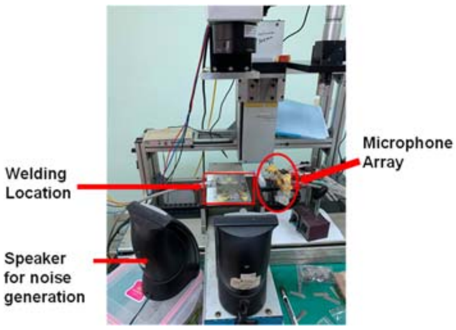


Fig1. Experimental setup with microphone array installation.

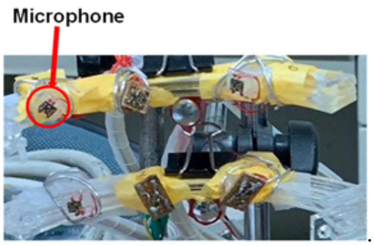


Fig. 2. Microphone Array.

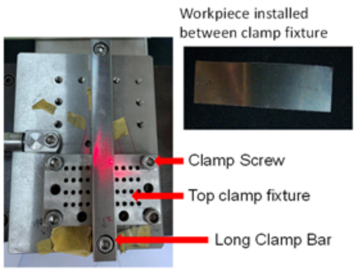


Fig. 3. Fixture for workpiece installation.

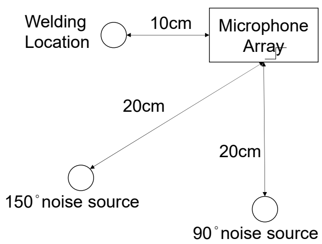


Fig. 4. Microphone Array and artificial noise source installation.

Table 1 Welding parameters

Laser Deliver Parameters	
Power(w)	40
Scan Speed(mm/s)	200
Power deliver Frequency (Hz)	10
Beam deliver interval (ms)	2
Spot size (μm)	50

To simulate the conditions with proper and lost contact between welded metal sheets, two workpiece holding conditions and selected welding locations were designed as shown in Fig. 5. To increase the chance of generating the gap between welded metal sheets, the remove of central clamp bar along with low level torque applied to the screw were chosen in the setup. At the same time, the welding location was also moved to the central parts of fixture as show in Fig.5(b), compared to the case in Fig. 5(a) for the proper contact design. The summary of setup is listed in Table 2.

For the microphone array design, various spacing between each MEMS microphone was setup to cover various frequency span of interest [7]. Fig. 5 illustrates the arrangement of MEMS microphone on a fixture. The spacing between microphone and corresponding designated frequency band (based on the cut-off frequency) is shown in Table 3.

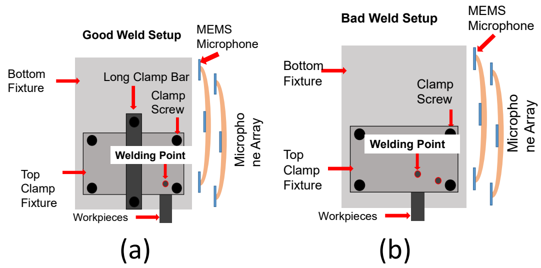


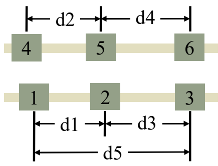
Fig.5. Set up for various contact condition in Welding (a) proper contact (b) loss of contact.

Table 2 Parameter for the generation of proper and lost contact

	Proper Contact	Loss of Contact
Torque for screw	8N	1N
Extra Central Clamp	Yes	No
Welding Location	Close to the clamp screw	Close to central Line of fixture

Table 3 Spacing for multi-spacing microphone array

	d1	d2	d3	d4	d5
Microphone Space (mm)	23.8	28.4	33.5	42.5	57.2
Effective Frequency (kHz)	7.0	6.0	5.0	4.0	3.0



3. Results and Discussions

3.1. Artificial noise and noise reduction by microphone array

To evaluate the noise reduction performance, experiments were conducted when the artificial noise was implemented without laser power delivery. The noise was delivered by speaker located at 90 degree and 150 degree respective to microphone array as shown in Fig. 4. The time and frequency domain environmental background noise and the artificial noise generated from a single speaker is shown in Fig. 6. The amplitude of the artificial noise is higher than the environmental noise, and it could cover the frequency range up to 10kHz. The noise reduction rates with implementation of microphone array and noise from different locations is shown in Fig. 7. The results show that more than 50% noise could be reduced with frequency higher than 3kHz. Moreover, the higher noise reduction rate could be observed in the high frequency range.

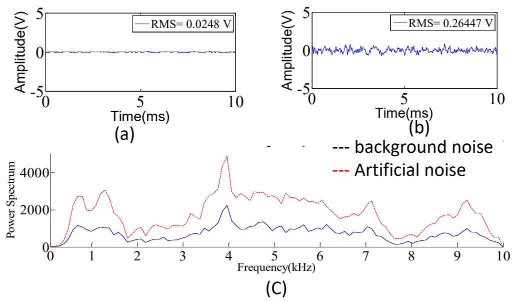


Fig. 6. Background noise(a) environmental noise (b) artificial noise by speaker (c) frequency domain environmental and artificial noise by speaker.

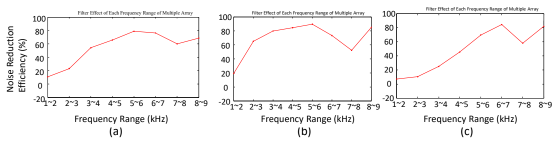


Fig. 7. Noise reduction performance by microphone array(a)90°+150° noise (b) 90° noise (c) 150° noise.

3.2. *Welding quality and sound signal analysis*

For the evaluation of the joint condition on welded samples, the peeling tests were implemented for each sample (with only one joint performed) to determine the joint strength. The surface condition was investigated by the optical microscope as well after the peeling test. The surface conditions with respective to the top and bottom surface of both layers of metal sheets after peeling are shown in Fig. 8. Surface condition in Fig. 8(a) is defined as good weld with peeling force higher than 9N. In which, the clear tearing of material and a hole on the bottom sheet could be observed. In this situation, the removed part of material is adhered to the bottom surface of the top sheet. In contrast, the surface condition in Fig. 8(b) is defined as bad weld with very low peeling force. No such material removed from the bottom sheet is observed, and the larger heat effect zoom observed on the two surface of the top sheet because the more heat energy trapped on the top sheet caused by the gap generated between two layers of metal sheets.

The sound signals collected from the cases with good and bad weld are shown in Fig. 9. Different patterns between two cases could be observed. It might be caused by the different size of weld pool generated on the top metal sheet due to different level of heat accumulation.

Similar to our previous work for the feature extraction in micro welding [4], the time domain signals in all welding process is divided to 10 sections for feature analysis in Fig. 10. The root mean square (RMS) and standard deviation obtained from 40 samples (Joints) for each section are illustrated in Fig. 11 and Fig. 12. The difference of both feature values between good and bad weld cases could be observed for all four sections. In this study, the frequency domain features for all welding process are analyzed as well. The different feature pattern could be observed in Fig. 13, especially in the high frequency range.

To quantify the capability of features in identifying the bonding condition, the index J (Fig. 14) which is calculated based on the ratio of between-class distribution to in-class distribution was implemented to the three types of features discussed above for each section or frequency band [4].

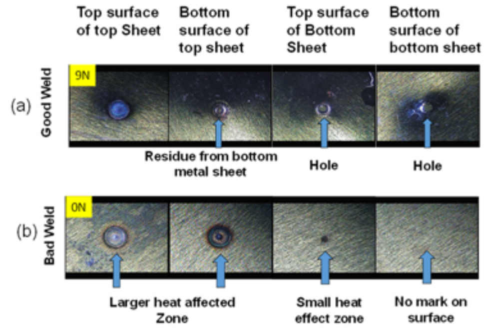


Fig.8. Surface condition of welded sample after peeling test.

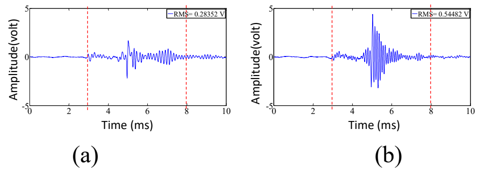


Fig.9. Sound signals collected during laser micro lap welding (a) normal joint strength (b) low joint strength

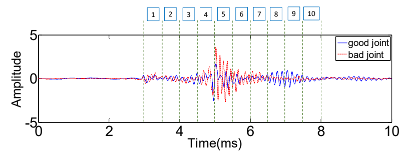


Fig.10. 10 sections of sound signals.

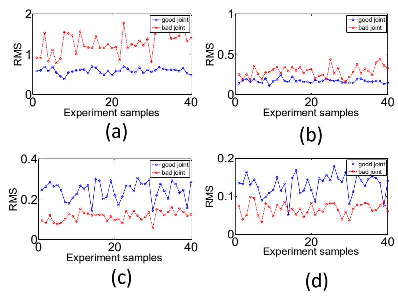


Fig.11. RMS values for each selected section with proper and low bonding strength (a) 5th section (b) 6th section (c) 9th section (d) 10th section.

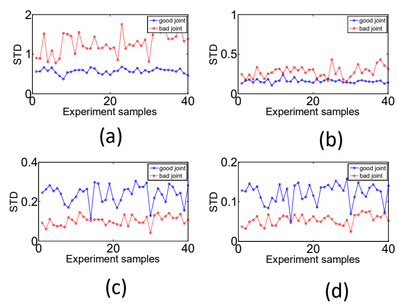


Fig.12. Standard deviation values for each selected section with proper and low bonding strength (a) 5th section (b) 6th section (c) 9th section (d) 10th section.

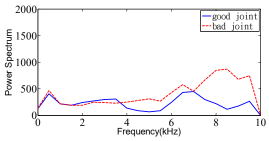


Fig.13. Chip forms with various experimental setup of depth of cut (a) 1μm (b) 10μm(c) 35μm (d) 60μm

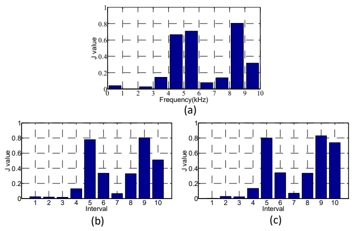


Fig.14. Classification Index for each section (a) RMS (b)Standard Deviation (c) Frequency features.

3.3. Evaluation of weld quality monitoring perforce improved by the microphone array

To evaluate the contribution of the developed microphone array to the weld quality monitoring system, an HMMs based classifier integrated with microphone array and feature selection module was implemented in this study. In the HMMs model training, 20 set of data were used to develop the model. Another 20 set of data were used in the system evaluation. The system performance with three operation conditions were conducted in this study and the results are shown on Table 4. Three conditions implemented include, (1) no artificial noise is generated and the microphone array is on, (2) noise is generated in welding but no microphone array filter is on, (3) noise is generated in welding, and the microphone array filter is on.

Table 4 Classification rate for developed weld quality monitoring system

Noise input	Microphone array filter	Selected features	Noise Input direction 90°	150°	90°+150°	Average
NO	YES	3 RMS	90%	90%	90%	90%
		3 STD	97.5%	97.5%	97.5%	97.5%
		3 RMS slope	95%	95%	95%	95%
		4 Frequency	100%	100%	100%	100%
		fusion of RMS, STD, RMS slope	100%	100%	100%	100%
YES	No	3 RMS	55%	60%	55%	56.67%
		3 STD	60%	75%	70%	68.33%
		3 RMS slope	60%	70%	65%	65%
		4 Frequency	92.5%	92.5%	92.5%	92.5%
		fusion of RMS, STD, RMS slope	72.5%	80%	77.5%	76.67%
	Yes	3 RMS	77.5%	85%	77.5%	80%
		3 STD	97.5%	97.5%	97.5%	97.5%
		3 RMS slope	82.5%	85%	85%	84.17%
		4 Frequency	97.5%	97.5%	97.5%	97.5%
		fusion of RMS, STD, RMS slope	97.5%	97.5%	97.5%	97.5%

Based on the data presented in Table 4, 90% to 100% classification rate could be obtained with different selected features without applying the artificial noise to the system. However, over 25% drop on the classification rate is observed for the case with the selection of time domain features when the artificial noise is applied to the system in welding. At the same time, the drop could be improved to less than 10% by selecting the frequency domain features. It might be caused by some of the frequency band of signals contaminated by noise have been removed during the feature selection process. For the third conditions by applying the noise and microphone array filter to the system simultaneously, the classification rate of system could be improved dramatically. 97.5% classification rate could be obtained, and this result suggests that the application of proposed microphone array filter could reduce the noise effect on the monitoring system significantly.

4. Conclusions

Laser micro lap welding experiments were conducted along with the implementation of artificial noise and microphone array to evaluate the performance improvement of weld quality monitoring system contributed by the proposed microphone array filter. The results show that the noise will contaminate the signal obtained from a single microphone and cause the reduction of classification rate up to 25 % when adopting time domain features and 7.5% when adopting frequency domain features. By applying the proposed microphone array filter, the classification rate of weld quality could be improved from lower than 60% to 97.5% by adopting time domain features, and from 92.75% to 97.5% by adopting frequency domain features.

Acknowledgements

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